Analysis of design options and trade-offs for road tunnels incorporating suppression systems

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Abstract
The possibility of trade-offs in road tunnel design incorporating suppression has been evaluated. Different tunnel configurations and ventilation conditions considered to identify potential trade-offs, offering options of design alternatives for future substantial cost-benefit estimates. Suppression systems are regularly used in Australia and Japan. The interest regarding suppression systems in tunnels are growing in the rest of the world and slowly getting implemented in tunnels in Europe and other continents. There is a possibility of introducing trade-offs in tunnel design incorporating suppression. Possible trade-offs have been identified using an event tree approach as part of a qualitative risk assessment, where scenarios has been evaluated after best practice and judgment of the profession. Reliability of suppression systems is shown to be an important aspect, as well as the behavior of tunnel users. One may argue that suppression systems should always be considered as a primary option in tunnel design. As additional benefit suppression systems offer the opportunity of potential trade-offs, opening a window of opportunity for more innovative solutions and cost-benefit approaches in tunnel design. Residual value of this evaluative report and its conclusions shows that aspects like 'point of no return', visibility and consequences of trade-offs in the event of suppression system failure must be addressed from a fire engineering and risk management point of view.

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Foreword

Peter Johnson, Arup Fire Melbourne, made this thesis possible and provided me with the idea of the subject Thank you. Peter has been an extraordinary knowledgeable, supportive and professional supervisor. Much appreciation goes to my supervisor Jimmy Jönsson, Arup Fire Madrid, for great support, patience and understanding. I would also like to give my thanks to my supervisors Patrick Van Hees and Henrik Tehler at Department of Fire Safety Engineering and Systems Safety at Lund University for relevant advice and guidance. My big gratitude goes to my colleges at Arup Fire London, Nathan Hewitt for believing in me, Barbara Lane for showing me my potential, Rachel Taylor for interesting work and friendship as well as all other work colleges at the Arup that contributed with valuable knowledge and references upgrading this thesis.

Further I would like to thank Ricky Carvel for valuable discussions and contribution of material from his research regarding design fires and suppression systems in road tunnels. Also big thanks to Haukur Ingason at SP for interesting discussions about the interaction of water droplets and wind velocity in tunnels. Further I'm grateful to Pasi Vuolle at Marioff Corp. for providing me with research material and technical data of their suppression system applications for road tunnels.

Special thanks go to my family and friends, dad and grandpa for your endless support, mum and Pidde for being there for me whenever needed.

Last but not least much appreciation goes to opponent Mathias Hamrefält as well as examiner Håkan Frantzich for well reflected constructive criticism of the presentation of this report.

Summary

The possibility of trade-offs in road tunnel design, incorporating suppression, has been evaluated. To identify potential trade-offs various tunnel configurations and ventilation conditions is considered, offering options of design alternatives for future substantial cost-benefit estimates or analysis.

Suppression systems in tunnels are regularly used in Australia and Japan. The interest regarding suppression systems in tunnels are growing in the rest of the world and slowly getting implemented in Europe and other continents.

Except for a higher level of fire safety there is a possibility of introducing trade-offs in tunnel design, when incorporating suppression. To identify potential trade-offs and evaluate them, the following has been considered:

- Design fires
- Peak HRR and 'point of no return'
- Tunnel structure
- Ventilation configuration
- Effectiveness of suppression systems
- Life safety of tunnel users
- Fire brigade intervention
- Design options

It should be noted that to be able to use trade-offs in a suitable matter it is crucial to have chosen an acceptable fire safety level compared to a 'standard' design and to use relevant design parameters in the right matter. For the purpose of this report different guidelines in tunnel fire safety around the world have been studied to get a full understanding of the concepts of tunnel design

Possible identified trade-offs have been evaluated using an event tree approach, as part of a qualitative risk assessment, where scenarios has been evaluated after best practice and judgement of the profession.

Ventilations systems used for road tunnel design that have been considered are longitudinal-, transverse- and semi- transverse systems. There are different strategies concerning time for activation of a suppression system, related to what type of ventilation system is used. Type of traffic conditions is also an important aspect to take into account.

Commonly used design fire size requirements for smoke control and evacuation design have a peak heat release rate (HRR) between 30-50MW for tunnels with cars and trucks as well as heavy goods vehicles (HGV's). Although resent research shows that fires involving HGV's and multiple vehicles may reach maximum HHR's of 100-200MW.

Design of tunnel structure and fire protection of tunnel linings are based on standardized Temperature-Time curves, where the severity of the curves used, are varying for high risk versus low risk construction. The required fire resistance in road tunnels are commonly 4 hours, and 2 hours to the more critical areas, however it vary slightly with different design objectives, assessments and design guides.

Reliability of suppression systems is shown to be an important aspect, as well as the behaviour of tunnel users. One may argue that suppression systems should always be considered as a primary option in tunnel design to reach an acceptable fire safety level. As additional benefit suppression systems may possibly offer potential trade-offs, opening a window of opportunity for more innovative solutions and cost-benefit approaches in tunnel design.

Conclusion of this evaluative report and its residual value is: Trade-offs has a great potential in road tunnel design when adopting suppression as a design concept. However aspects like ventilation influence on design fire size, early activation and reliability of suppression, behaviour of tunnel users, visibility, consequences of trade-offs in the event of suppression system failure and the ‘point of no return’ have to be incorporated in the design from a fire safety and risk management point of view. These have been evaluated here as an attempt to provide guidance in future tunnel design and research in tunnel fire protection internationally.

Sammanfattning

Potentiella tekniska byten i samband med projektering av brandskydd i vägtunnlar då släcksystem används, har identifierats och utvärderats. Varierande vägtunnel konfigurationer och ventilationsförutsättningar har studerats för att möjliggöra identifiering av potentiella tekniska byten. Tekniska byten kan bidra till substantiella besparingar. Denna rapport kan utgöra underlag för framtida kostnad-nytta skattningar eller analyser i samband med tunneldesign.

I Australien och Japan används släcksystem i de flesta vägtunnlar, vilket generellt inte har varit fallet i resten av världen. Intresset för släcksystem i tunnlar har dock ökat världen över de senaste åren och konceptet implementeras i Europa och andra kontinenter.

Förutom ett förhöjt brandskydd föreligger möjligheter med släcksystem i tunnlar. Dessa möjligheter omfattar så kallade tekniska byten i projekteringen. I identifieringsarbetet av potentiella tekniska byten för tunnel projektering har följande aspekter analyserats och utvärderats.

- Dimensionerande brand
- Maximal effektutveckling och 'gränsen utom återvändo'
- Tunnel konstruktion
- Ventilationens utformning
- Effektiviteten av släcksystem
- Personsäkerhet för tunnelanvändare
- Räddningstjänstens säkerhet
- Projekteringsmöjligheter

För att nyttja tekniska byten på ett korrekt och vetenskapligt sätt är det är essentiellt att det valda ursprungliga utförandet har en acceptable nivå på brandskyddet. Därför är det viktigt att relevanta parametrar används på korrekt sätt. För att få en övergripande förståelse av projektering av brandskydd i tunnlar har riktlinjer från olika länder världen över studerats, som underlag till denna rapport. Identifierade tekniska byten har utvärderats med hjälp en kvalitativ risk analys omfattande ett händelseträd. Olika scenarier har analyserats efter erkända metoder och vetande i branschen samt fakta presenterat i denna rapport.

Studerade ventilationssystem är longitudinella, transversella och semi- transversella system. Det förekommer varierande strategier gällande tid för aktivering av släcksystem beroende på typ av ventilationsstrategi samt vilka trafikförhållanden som föreligger.

För tunnlar med bilar, lastbilar och långtradare är vedertagen storlek på dimensionerande brand är en maximal effektutveckling av 30-50MW. Den dimensionerande branden utgör underlag för dimensionering av brandgasventilation och utrymningsstrategi. Senare forskning visar dock att en brand som involverar långtradare och eventuellt flera andra fordon kan uppnå maximal effektutveckling av 100-200MW.

Projektering av tunnelkonstruktion och dess bärighet i händelse av brand baseras generellt på standardiserade Temperatur- Tid kurvor där konstruktion i hög- respektive lågrisk områden designas efter olika kurvor med varierande maxtemperatur och tillväxt.

Tillförlitligheten av släcksystem i tunnlar har visat sig vara en viktig faktor och så även beteendet av tunnel användare. Släcksystem bör alltid beaktas som ett primärt val i projektering av vägtunnlar för att uppnå en acceptabel nivå på brandskyddet. Utöver det ger släcksystem möjligheten till potentiella tekniska byten eller ökade möjligheter för

analytisk dimensionering, vilket öppnar för innovativa och mer kostnadseffektiva lösningar där kostnad-nytta konceptet kan komma spela en stor roll.

Kontentan av denna utvärderande rapport och dess slutsatser; då släcksystem som designkoncept anammas är att tekniska byten medför stora möjligheter till besparingar i delar av brandskyddet. Aspekter som ventilationens påverkan på dimensionerande brand, tillförlitligheten och tidig aktivering av släcksystem, beteendet av tunnelanvändare, sikt, konsekvenser av tekniska byten i det fall ett släcksystem fallerar samt aspekter kopplade till ”point of no return” skall beaktas utifrån ett brandskydds- och riskhanteringsperspektiv. Utvärderade designmöjligheter och tekniska byten kan utgöra en initial internationell vägledning i framtida tunnelprojektering.

Abbreviations

To assist comprehension of this report, the following abbreviations are used within the report have been collated for ease of reference.

AFFF	Aqueous Film Forming Foam
BLEVE	Boiling Liquid Expanding Vapour Explosion
CCTV	Closed-Circuit TeleVision
CFD	Computational Fluid Dynamics
FFFS	Fixed Fire Fighting Systems
HGV	Heavy Goods Vehicle
HRR	Heat Release Rate
LCC	Life Cycle Costs
NATM	New Austrian Tunnel Method
NFPA	National Fire Protection Association
MTBF	Mean Time Between Failure
MTTF	Mean Time to Failure
MTTR	Mean Time To Repair
PIARC	Permanent International Association of Road Congresses
pp-fibres	polypropylene fibres
TBM	Tunnel Boring Machine
TNO	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek
TT-curve	Temperature-Time curve
UPTUN	Cost-effective, sustainable and innovative UPgrading methods for fire safety in existing TUNnels

Contents

Tables

Figures

1. Introduction

This chapter provides the background of the thesis, outlines the purpose and researched questions, defines limitations and explains methods used.

This master thesis is the concluding part of the Master of Science Programme in Risk Management and Fire Safety Engineering at the Faculty of Engineering, Lund University, Sweden. The thesis has been written in association with the Department of Fire Safety Engineering and Systems Safety in Lund and Arup Fire (in Melbourne – Australia, Madrid – Spain as well as London – UK). The project corresponds to a period of 20 working weeks.

1.1 Background

The inspiration to engage in the subject presented in this project plan derives from a year of working as a consultant at Arup in Melbourne, Australia, during a mid university internship. After discussions with my supervisors at Arup Fire and at Lund University as well as attending the 3rd International Symposium on Tunnel Safety and Security (ISTSS) in Stockholm Sweden, questions and problems forming the base of this thesis where identified. The major interesting point was the different use of suppression systems in tunnels within Europe compared to other continents and countries. For instance Australia generally seems to use suppression systems in their tunnels, whereas it is not so common in Europe. However there is a large interest growing in Europe of the possible benefits of using mist systems in tunnel design, due to cost savings in fire risk reductions. Interesting questions are raised, like what effect suppression systems may have on various tunnel designs, the cost of them, the planning process, the safety as well as the benefits and limitations for future use in tunnels. These aspects make the decision of what systems to use quite complex.

Several countries have included principles, or are preparing them, for fire-safe design in their tunneling recommendations. Some of which are based on the PIARC committee on road tunnels report from 1987 (PIARC 2004). Thereafter several fire tests has been conducted, included in the overall view and the tunneling industries best practice. Further there is a great need to fully understand the concepts and benefits of suppression systems in tunnels. A selection of research programs carried out to date and findings from fire incidents related to tunnels are presented in Appendix C and D respectively.

This thesis will constitute an overview of problems, benefits and effects of suppression systems in tunnels applying a holistic approach. The reason for addressing the problem with a holistic approach is due to the complexity and interdependence of a number of technical systems as well as human interfacing. All with an attempt of designing safe tunnels associated with acceptable risk for all affected by or dependent on them.

A simple attempt to visualize mentioned aspects and how they are linked is presented in Figure 1.

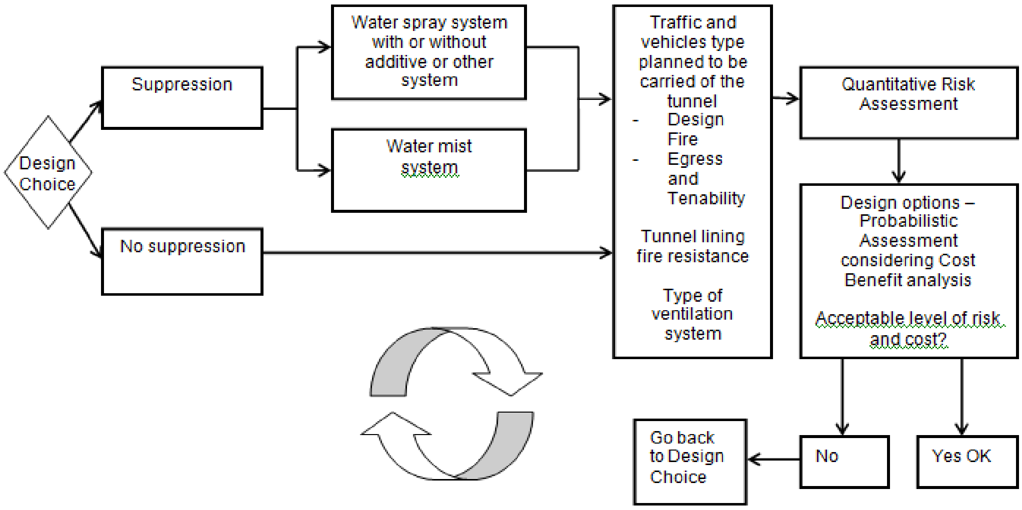

Figure 1 - The author's initial view of tunnel design of long road tunnels in a simplified model

The complex interconnected systems and choices, shown in Figure 1 in a simple manner, may be analyzed and associated with certain costs and benefits. Tunnel design often comes with a major planning process and requires a substantial budget. Therefore it is crucial to be able to perform an extensive fire risk assessment and associated cost-benefit analysis in the initial phase of such a project regarding associated risks. This to ensure the level of safety of the tunnel, the ability to recover from a potential accident or fire as well as to ensure that systems installed are designed for excepted worst credible scenarios. The latest is directly linked to renovation costs and loss of profit due to the tunnel being out of order after an incident. A cost-benefit analysis also allows the tunnel developers to see the value of their investment in fire safety through reduced potential losses. Design fires and fire scenario selection are crucial in the design process, due to the significant effect they have on all design parameters.

An interesting aspect is that, tunnels built all over the world to meet the need of modern society differ in design approaches, regarding egress strategy as well as passive and active systems for fire protection. Differences often derive from legislation used, the design complexity and even the specific engineering design team in question. Differences don't necessarily mean that the designs or approaches are wrong. The question to ask is probably how many of these differences are derived from real differences in the hazards and actual level of risk, and how much comes from a lack of knowledge from designers and authorities. Further it is interesting to view how well established design scenarios and design fires have been researched and investigated, to ensure that the design team is not just using them because "everyone else seem to use them".

In Australia, the tunnel length usually has an impact on what mitigation measures need to be considered. This is based upon the RTA's (Roads and Traffic Authority) design guides. However the Fire Brigade may still require provision of additional mitigation measures. Australia and Japan clearly use a different approach and attitude for suppression systems compared to Europe and other continents. It is only during recent years mist systems have been installed in tunnels Europe. Supposedly mist is chosen over deluge systems in an attempt to reduce costs and water supply.

One aspect in consideration when using suppression (especially mist) systems in tunnels is the effects that may come from interaction with ventilation systems. Problems like water being carried by air with high velocity may arise as well as turbulence mixing smoke affecting tenability of occupants. There are several suppression systems on the market, which include water mist, water cannons, sprinkler systems, foam and one of the most common, sprinkler deluge systems. Sprinkler deluge systems are generally used in Australia and Japan designed to extinguish small fires before reaching large fires. Suppression systems are often manually activated via control room operators often combined with an automatic detection and activation system. Manual operation is carried out via 24hr CCTV which requires manpower and it is therefore subject to major operational costs.

Consequently there are substantial amounts of questions to be raised to identify the most efficient system and how they may be used in a sufficient way. There is not only a possibility to make tunnels safer by installing suppression, but there is also a opportunity to cut costs. For instance costs associated with construction, excavation due to less required ventilation and business continuity. With a suppression system a smaller design fire could potentially be used resulting in smaller ventilation ducts which comes with a great cut in excavation cost. Further a suppression system may limit the extent and damage of a fire, shortening the time for repair. Resulting not only in cut in reparation costs but also allowing for improved operability. Further loss of revenue may be limited as well as other traffic complications that may arise with a tunnel that is closed for a longer period of time, not to mention loss of properties and life's.

There is an urge and trend in the industry to work towards united international guidelines to ensure the level of safety in road tunnels. Upgrading programs as UPTUN in Europe is one example. Further suppression is slowly being incorporated in tunnel design not only in the few countries that require them by regulations but also in other countries. In lack of detailed code requirements the reasons are often issues like insurance aspects and business continuity in case of a fire incident, rather than life safety. There is a possibility to use suppression not only for life safety, insurance, asset protection, and business continuity purposes but also in regards to potential reduction in costs associated with possible trade-offs. To assist the decision making in a design process of a tunnel design it is suitable a cost-benefit analysis to evaluate aspects related to fire.

1.2 Objectives

The maim aim of this thesis is to investigate the possibility of incorporating trade-offs in tunnel design when using suppression systems, also known as FFFS (Fixed Fire Fighting Systems). As mentioned previously there are differences between approaches and guidelines regarding the use of FFFS in tunnels in Australia and Japan, compared to Europe. On the basis of these differences this thesis is to form the base for future probabilistic approaches in designing tunnels with FFFS's. The long term aim is to work towards a probabilistic decision tool, involving cost-benefit analysis regarding tunnel design, with a holistic approach.

The objective is thereby to analyze differences of approach in using suppression systems in tunnels and identify possible design fires for different set ups and FFFS system. This to investigate if and when certain potential trade-offs could be suitable for a variety of tunnel design options.

1.3 Definition trade-offs

The purpose of this thesis is to investigate the possibility of trade-offs in tunnels when using suppression systems or so called FFFS's.

In building design, sprinklers are not used in isolation but are considered as part of the complete package for fire safety measures that complement each other (Bafsa 2006). The use of trade-offs are common in building design incorporating sprinklers (NFPA 101 2006) (Blomqvist and Isaksson 2002), however the concept seems not to be as well established for road tunnel applications. Fredrik Nystedt explains the concept of trade-offs; the goal in a trade-off situaiton is the overall safety remaining constant, as shown in Figure 2 explaining the principle.

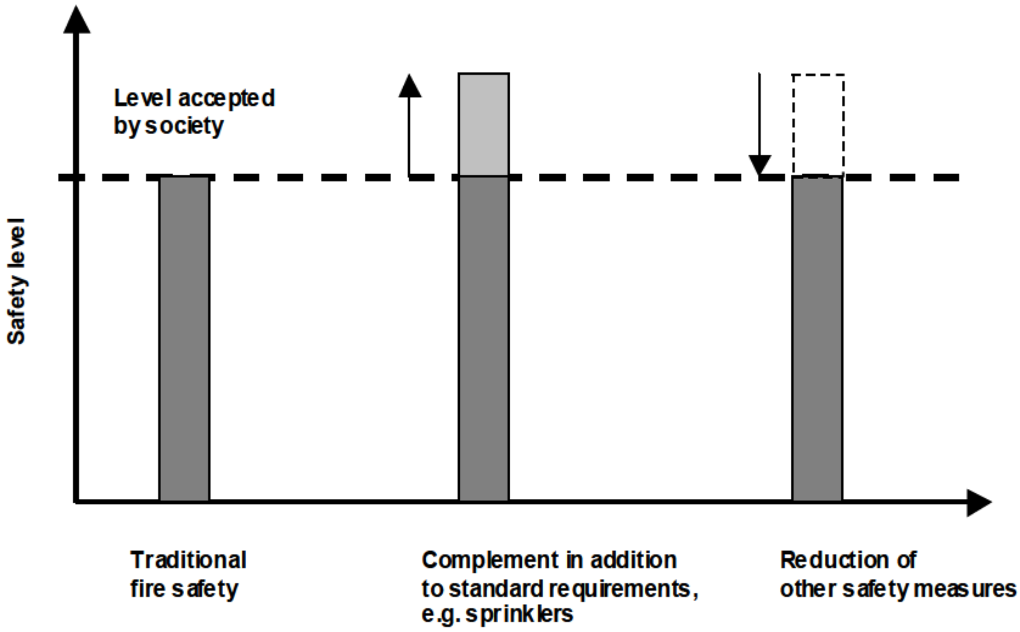

Figure 2 – The principle behind trade-offs (Nystedt 2003)

It should be noted that use of trade-offs may only be motivated in a satisfactory manner if the tunnel fire regulations used provide an acceptable level of risk. Further combinations of trade-offs should be considered with care (Nystedt 2003). The use of suppression systems in tunnels may open for the possibility of trade-offs in tunnel design. Although always subject to verification showing that the relevant performance requirements stated in the relevant regulations are complied with.

1.4 Identification of problems and questions at issue

Identification of problems and investigation of questions at issue, have followed a hermeneutic circle (Ejvegård 2003). A hermeneutic circle was used to enable new information and research, covered by the author and feedback from the supervisors during the research period, to be incorporated in a systematic manner.

Questions at issue are:

1. What are the effects and benefits of using suppression systems in road tunnel design?
2. To what extent may a suppression system control (suppress) a fire in tunnel?
3. What design fires are commonly used and are they adequate?
4. What would be an adequate design fire and scenario to use when considering trade-offs depending suppression in road tunnels. This would include the time to detect a fire as well as activation time of suppression.

5. What are the benefits? Are certain ‘trade-offs’, applicable when considering suppression systems in tunnel design? Which trade-offs, may be appropriate?
6. For what conditions in construction type and ground condition as well as location in relation to the surroundings may trade-offs be considered, if any?

Tunnel design is a complex process with several stakeholders and technical challenges. Therefore the means of risk assessment and analysis is considered a necessary tool. Potential trade-offs identified in this thesis will further be viewed from a risk perspective.

Key aspects for further research to enable trade-offs will be identified for potential trade-offs, when incorporating suppression systems in tunnel design.

1.5 Methods

The general scientific methodology used in this report is based on a literature study approach (Ejvegård 2003) (Backman 2008). The subject in question was expected to be quite onerous and a holistic view and understanding have been anticipated to be necessary. After initiating the literature search it was found that large amount of research is available, associated with tunnel design. However limited research related to the specific subject of the thesis, focusing on trade-offs, could be identified. The intent was to select only highly relevant research material from the tunnel design field, for the purpose of the thesis. Relevant conclusions of the subject, requires a broad understanding of all systems and performance requirements, associated with tunnel design and the view on suppression systems worldwide.

A reasonable approach has been used in the selection of relevant information where the latest publications, if considered reliable, have been valued higher than earlier publications addressing similar issues. Method of selection and evaluation of research is described by (Ejvegård 2003) and considered a valuable method in literature studies.

A qualitative risk approach using an event tree was chosen as a tool to systematically identify trade-offs suitable for tunnel design incorporating suppression. The approach was chosen to help visualise the various potential options where trade-offs could be subject to evaluation. Tunnel design systems regarding fire protection are not only dependent on each other, but also on other parameters like; type of traffic, the surrounding environment and ground conditions as well as designers choice related to cost-effectiveness. Therefore an event tree presentation of the problem was adopted to visualise the options discussed systematically to identify acceptable and non-acceptable outcomes.

1.5.1 Information resources and databases

To allow for experience of fire engineering skills in tunnel design the writer spent half a year as a consultant for Arup Fire in London working on tunnel projects including metro, rail as well as road tunnels. This lead not only to a greater understanding of fire engineering in tunnel design but also experience to identify potential issues that may arise when incorporating suppression systems in tunnels with focus on trade-offs in the overall fire safety.

This thesis have been carried out on the basis on the research and experience of other relevant parties as well as discussions with consultants experienced in tunnel design within Arup Fire globally. Also relevant material from tunnel conferences has been used and the author attended the ISTSS Tunnel conference in Stockholm 2008 (ISTSS 2008).

The method to gather relevant experimental material, standards/codes and research information/papers are presented in Table 1. A substantial amount of research material, standards and guidelines were provided by Arup Fire directly as well as Lund University.

However in order to get an overview of available research material to date, in the wide range of topics this thesis cover, a wide search of publications has been done.

Since the technical fire safety applications in tunnels are likely to have been applied in a multiple of research fields, the search was made in two different databases. The databases used were Science Direct[1] - Engineering, Elin[2] - Electronic Library Information Navigator a registered trademark of Lund University Libraries, Head office. Further relevant local research material available at Lund University – Fire Safety Engineering and System Safety[3] as well as Edinburgh Research Archive[4] - University of Edinburgh, have also been used.

Table 1- Search results in the form of hits of search terms in the databases used.

Database	Tunnel	Tunnel design fire	Tunnel Detection	Tunnel Fire Detection	Tunnel Suppression	Tunnel Mist	Tunnel Deluge	Tunnel sprinklers	Search field
ScienceDirect[a] - Engineering	7836	25 (2)	57 (5)	6 (1)	29 (2)	49 (8)	5 (1)	34 (4)	Title, Abstract, Keywords
Elin [b]	3192	0	5 (0)	0	1 (0)	1 (1)	1 (1)	1 (1)	Title, Abstract, Keywords

[a] Search was carried out in November -08 and again in March -09.

[b] Search was carried out in March -09. Search hits are presented and the numbers of articles deemed relevant are marked in brackets.

After scanning the relevant search hits from the databases presented above the articles deemed relevant to the topic have been marked in brackets in the table. It is not considered suitable to add the number of articles together since some of the hits on different search terms resulted in a few of the articles appearing more than once.

Some references may have sources with an angled view of some sort and therefore factors like the authors interest should be considered when reviewing research material (Ejvegård 2003). This has been taken into consideration where reasonably possible. When the author or financer is a company often with the main goal of distribute and market their products (such as suppression manufacturers), it may be more obvious than for other more subtle angled research results.

Research and upgrade programs for tunnel safety that has been identified and used are presented in Appendix D.

1.6 Focus

Due to the complexity and dependability of several technical systems working together in tunnels a holistic approach is preferable. This will result in the thesis being an overview of problems, benefits and effects with using suppression systems in tunnels rather than research in depth of investigated areas that form part of the thesis. The

[1] http://www.sciencedirect.com
[2] https://hugin.lub.lu.se/cgi-bin/pclient?url=http://elin.lub.lu.se
[3] http://www.brand.lth.se/english/publications/
[4] http://www.era.lib.ed.ac.uk/handle/1842/96

reason for addressing the problem with an overview is the verity of solutions and configurations in tunnel design. For example it is not certain that a trade-off which is possible for one type of tunnel is suitable for another.

The thesis will focus on road tunnels leaving rail tunnels for future investigation. Since suppression systems are the subject in question, only long and/or heavy trafficked tunnels with varying types of vehicles and cargos will be considered.

The following limitations applies:

- Detailed technical design issues in general tunnel design related to of affected by potential trade-offs identified will not be considered.
- The design process will be considered holistically, however briefly, to allow for an general understanding of fire safety in tunnels and tunnel design.
- The risk analysis used will only be qualitative due to absence and/or uncertainties of relevant data.
- Natural ventilation configurations in tunnels have not been considered in this report due to the limitations in applicability to long tunnels.

Research have been carried out over the recent years as experiments, CFD modelling and full scale modelling. Some finalised and others still ongoing on the behaviour if fires in tunnel and the effects of potential suppression systems. However there is not enough research material available to support any final conclusions regarding trade-offs. Therefore the findings summarised in this thesis should only be seen as interim results, working towards a better understanding of tunnel fires and the effects of incorporating suppression systems in tunnel design.

On the basis of tunnel design being a broad area covering an extensive amount of research fields and technology, this thesis will solely present an overview and identify the specific fields in need of more research. This with the aspiration to enable trade-offs in a more general matter. Examples and models presented in this theses are only to be seen as guidance and summary and will require further detailed work, comprising fire strategy and risk analysis, before being adopted into tunnel design.

1.7 Disposition

To fully understand the benefits and issues with suppression systems in tunnels hence their possible contribution to a tunnel design it is important to understand the fire safety strategy in tunnels and how fire safety measures may be incorporated in a design. Therefore it is relevant to investigate and comprise information on general fire safety measures in tunnel design that may be affected by a suppression system being incorporated. For preparation general investigation on fire safety in tunnels has been conducted to highlight design issues related to the following measures:

- Tunnel lining and passive fire protection solutions.
- Ventilation solutions for tunnel fire safety.
- General technical information on suppression systems used in tunnels.

A structure of the work has been carried which was divided into two tasks, shown below. Two more tasks was identified as required to enable the concept of trade-offs creating four tasks in total. However task 3 and 4 was left for further work. The reason for choosing the first two tasks was that 1 and 2 forms the base for tasks 3 and 4.

- Part 1: Summary for comparison and understanding the efficiency of deluge sprinkler, water mist and other fire suppression systems in road tunnels.

- Part 2: Investigation and identification of possible trade-offs when designing tunnels with suppression systems.

Further part 3 and 4 has been identified as further work to be carried out in the process where the industry work towards the use of and adoption of trade-offs in tunnel design. These will simply be discussed briefly leaving assessment for future studies.

- (Part 3: A potential base for a probabilistic approach for estimation of design scenarios using risk analysis as a tool in tunnel design when choosing suitable trade-offs.)
- (Part 4: Cost-Benefit solutions for tunnel design related to part 1-3.)

A discussion in the majority of the chapters has been incorporated to summarise specific findings. At the end of the report a final discussion chapter has been included to evaluate the thesis work and methods used. The overall findings have been presented in final conclusions followed by recommendations for further research work and testing.

2. Fire safety in tunnels

This chapter will briefly cover the integrated fire safety components in tunnels.

2.1 Fire incidents - history

As mentioned before there has been several major tunnel fires in recent years, which has raised the importance of efficient fire safety in tunnels and the lack of sufficient fire safety in many road tunnels. Fires like the Mont Blanc disaster 24th Mars 1999 where 39 people died and the Tauern tunnel fire 29th of May the same year resulting in 12 deaths, made the focus on tunnel fire safety increase drastically (Beard and Carvel 2005).

Alfred Haak states (A. Haak 2005, A. Haak 2008) that fire in traffic tunnels can result in real catastrophes as learnt from recent incidents also referring to fires in tunnels like the Mt. Blanc Tunnel, The Tauern Tunnel, Gothard tunnel, the Baregg tunnel, the Frejus tunnel, as well as the the Viamala Tunnel among others. He underlines that these large incidents have cost too many lives and thought us new aspects, neither known nor expected before (except for in the Nihonzaka road tunnel in Japan 1979, with 189 involved vehicles). Lessons learnt where:

- Extremely fast development of the fire combined with a tremendously fast increase of temperature (up to 1000˚C) as well as the enormous emission of masses of smoke from the very beginning of the fire.
- The fire jumps from one car to another even over sections longer than 200 m with no vehicle in between (Mt Blanc Tunnel).
- Most shocking fact and the by far most tragic experience, was the behaviour of tunnel users. Many of them did not realise the danger and felt safer in their cars (possibly right for the very first minutes), not wanting to leave their property behind. Once (if ever) they realised the extreme danger they were in, it was too late.

Haak further stated:

"Against this background every proposal for any improvement in the direction of avoiding a vehicle fire especially in a tunnel, easing the escape conditions, rescuing tunnel users, and automatic fire combating is welcome. There never is a stupid idea in this field"

It was also underlined the importance of systematically evaluating new ideas as well as testing under conditions as reasonable as possible.

A list of major tunnel fires and damage estimations produced by ITA (ITA 2004), with additions made by the author, is presented in Appendix C of this report.

The dramatic fires which occurred in European road tunnels in 1999-2001 have led to development of new regulations and recommendations taking into account that tunnel safety is not only determined by the infrastructure but also by operation, emergency intervention, users and their vehicles (Lacroix 2008). To implement these new concepts a new EC-Directive (2004/54/EC 2004), responsibilities of the major players, safety references, including minimum technical requirements and provisions of analysis has been defined.

2.2 Fire safety objectives

Fire safety objectives for road tunnel safety has been identified as:

- Life safety
- Prevention of fire growth and fire spread

- Asset and business continuity
- Protection of relevant adjoining facilities above or in the surrounding of the tunnel
- Protection of the environment

2.3 Active and passive fire safety measures and evacuation

Fire protection equipment used in road tunnels is briefly described here. A more detailed investigation related to the fire safety systems specially related to the objectives of this report is presented in chapters 3 to 6 of this report.

2.3.1 Detection

Detection used is often automatic fire detection with linear heat detections devices. Smoke detection systems are often combined with video monitoring (CCTV) and/or incident detection for smoke and flame detection and early warning. There are available systems adopted for tunnel environment for detection of stationary vehicles, CCTV-systems, visibility measurement for presence of smoke and linear heat sensor detection. It has been concluded that two or more automatic detection systems are always required to ensure detection. (PIARC 2008). Up to date detection usually spot incipient fires with an accuracy of a few meters. (SOLIT 2007), or even up to 10 m from the actual fire location (Liu, Kashef, et al., Symmary of International Road Tunnel Fire Detection Research Project - Phase II 2008).

2.3.2 Self rescue of tunnel users

An evacuation strategy enables tunnel users to take shelter in a safe place prior to the arrival of the fire brigade. This is done by clearly marked emergency exits or special shelter rooms provided at adequate intervals. These have to attract attention even of poor visibility despite persons situation of evacuatio medför n. The UPTUN research has shown that it's most important to inform tunnel users how to behave in case of fire.

2.3.3 Ventilation

There are two categories of tunnel ventilation; natural and mechanical. Natural rely upon air movements induced by temperature or pressure gradients and those induced by tunnel traffic. Mechanical system configurations for tunnel design are longitudinal ventilation, fully transverse, semi transverse (and reversible semi- transverse) and partial- (or pseudo-) transverse. (Beard and Carvel 2005). According to (PIARC 2004) natural ventilation can be used only in tunnels of less than 240m-1000m, depending on the location (country, urban area or not) of the tunnel and the justification.

2.3.4 Fire fighting

Portable fire extinguishers are provided to enable fast suppression of a fire when it is still small. Water pipelines with discharge points (hydrants) for the fire brigade to use are available in many tunnels as well as hose reels when required. (PIARC 2004)

2.3.5 Tunnel structure fire protection

Protection of tunnel structure is either adding substances to the concrete for construction which also is used for renovation, or the use of additional protection lining. The means of structure fire protections may be concrete with the addition of polypropylene fibres, sacrificial concrete in conjunction with a mesh or additional fire protective panels attached to the concrete of the tunnel lining. For more detailed information about tunnel structure fire protection the reader is referred to chapter 3 and Appendix A of this report.

2.3.6 Fixed Fire Fighting Systems (FFFS)

Fixed Fire Fighting Systems (FFFS) or suppression systems may be incorporated in tunnel design to control fires i.e. limit the HRR and high temperatures that may arise as well as fire spread until fire brigade succeeds in extinguishing the fire. Examples of fixed fire fighting systems are sprinkler, deluge and mist systems.

There have been contradictory views upon the use of suppression in tunnels. For instance PIARC recommended against it back in 1983 and 1987. At the 1995 congress an investigation on the use of suppression in Europe, Australia, Japan and the United states was carried out, showing that suppression systems where not generally used in Europe, nor in the United states, except for a few tunnels carrying hazardous cargoes. However used in Japan for tunnels of important length or traffic to cool down vehicles on fire. (PIARC 2004). At the time for the FIT (FIT 2004) research program there were no requirements for fixed fire suppression systems in Europe. Only the UK and Netherlands had some normative information.

In recent years the view on using suppression in tunnels have slowly taken a more positive matter. Also the new concept of using mist systems instead of conventional spray sprinkler systems has opened a whole new debate with both pros and cons (NFPA 502 2008) (PIARC 2004, PIARC 2008) (SOLIT 2007) (UPTUN 2006). Detailed information and findings about suppression systems may be found in chapter 6.

This report focus on suppression systems for tunnels from now on, referred to as FFFS.

3. Passive fire protection

This chapter will briefly cover the design requirements in structural stability in a fire situation for road tunnels.

There are variations in requirements of fire resistance depending on the type of tunnel construction, location of the tunnel (in what type of ground conditions as well as which countries) and what type of vehicles the tunnel may carry.

The road tunnel guideline in Australia (RTA 2006) state that all tunnel constructions should be designed to withstand the ISO834, TT-curve for four hours. Further critical areas of tunnels shall be designed to withstand a hydrocarbon curve (HC-curve) for two hours. Critical areas are: any tunnel structure that may be affected by fire and as a consequence may result in the collapse of a building, tunnel, other infrastructure or utility service supported by the tunnel structure, and/or result in the injury of a person. Other international recommendations available for tunnel construction such as ITA tunnel guidelines (ITA 2004) give somewhat similar recommendations, however there are other variations in the time recommendations for expected types of vehicles and TT-curves (varies between one to three hours), to be used for design are the more severe HC-curve or RWS-curve. Elements solely for structure shall remain their structural integrity for the required time of the given TT-curve in question. Elements for compartmentation shall provide insulation and compartment integrity, as well as its structural integrity (if part of structural elements) for the required time for the given TT-curve (RTA 2006).

Commonly used TT-curves for tunnel design have been summarised and explained by Promat (Promat Tunnel), for comparison presented in Figure 3. Cellulosic ISO 834 curve developed for building design are the slowest growing curve compared to the more severe RWS-, and HC-curve. The RABT ZTV was developed for both a car and a train with a decay face.

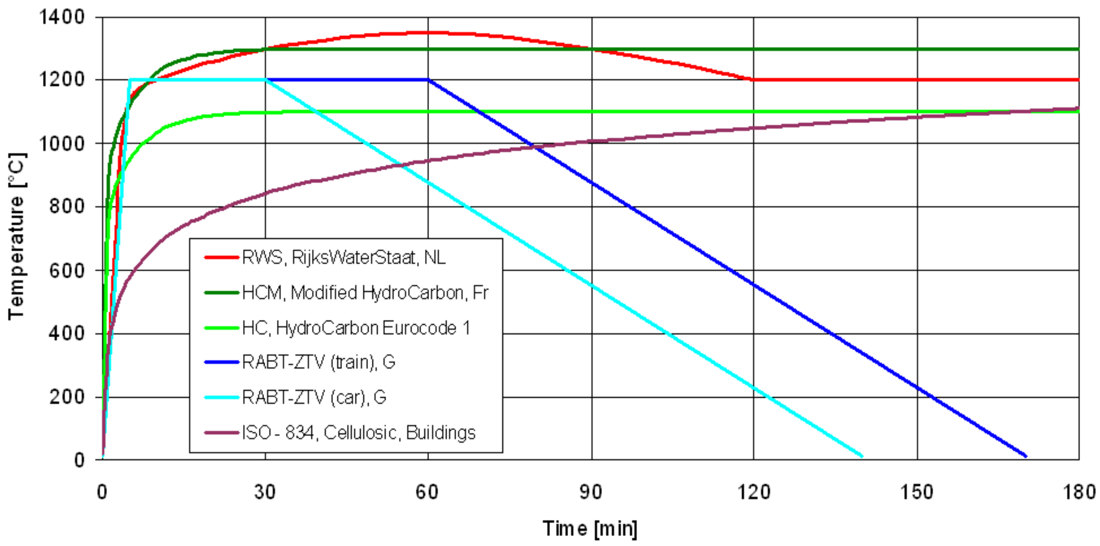

Figure 3 - Temperature Time curves used for tunnel design (Promat Tunnel)

The cellulosic time/temperature curve, is defined in various national standards, e.g. ISO 834, BS 476: part 20, DIN 4102, AS 1530 etc. The cellulosic time/temperature curve is the lowest used in normal practice and, as previously mentioned, is based on the burning rate of the materials found in general building materials and contents. Although the cellulosic curve has been in use for many years, it became apparent that the burning rates for certain materials e.g. petrol gas, chemicals etc, were well in excess of the rate at which for instance, timber would burn. As such, there was a need for an alternative exposure used within the petrochemical industry, and thus the hydrocarbon curve was developed. The HC-curve is applicable where small petroleum fires might occur, i.e. car fuel tanks, petrol or oil trucks, certain chemical trucks etc. The HC- modified curve derived from the HC-curve after request from the French regulation, resulting in a maximum temperature of 1300ºC instead of the 1100ºC.

The RABT curve was developed in Germany as a result of a series of test programs such as the Eureka project. The RABT curve represents rapid temperature rise to 1200°C within 5 minutes, with the temperature drop off starting to occur at 30 minutes for car fires and 60 minutes for trains. A cooling period of 110 minutes is applied to both fire curves.

The RWS curve was developed by the Rijkswaterstaat, ministry of transportation in the Netherlands, based on the results of tests carried out by TNO in the Netherlands in 1979. It is based on a worst case scenario of a 50 m^3 fuel, oil or petrol truck fire with a fire load of 300MW, lasting up to 120 minutes. Recently a Full Scale Tests in the Runehammar tunnel in Norway proved the accuracy of the RWS fire curve as a design fire curve for road tunnels (Ingason, Haukur 2008).

The difference between the RWS and the HydroCarbon curve is that the HC-curve is based on the temperatures that would be expected in a relatively open space. Whereas the RWS-curve is based on temperatures you would find when a fire occurs in an enclosed area, such as in a tunnel. The temperature gradient in the first few minutes of curves like RWS, HC and HCM can cause temperature shock to the surrounding concrete structure, with concrete spalling as a result. For failure criteria's the specimens exposed to the RABT-ZTV TT-curve, the reinforcement temperature should not exceed 300°C, with no maximum interface temperature requirement. Whereas for the RWS TT-curve the interface between the concrete and the fire protective lining should not exceed 380°C and the temperature of the reinforcement should not exceed 250°C. (Beard and Carvel 2005) (Promat Tunnel) (PIARC 2004)

Promat further states that the following countries has adopted the RWS standard, either as their local legislation or specified for specific projects:

- USA (NFPA 502, Standard for road tunnels, bridges and limited access highway's)
- Italy (UNI 11076)
- Austria (OVBB)
- Singapore (KPE project)
- UAE, Dubai (The Palm Jumeirah development)

There are numerous unwanted effects of fires in tunnels, especially extremely large ones, since they are problematic to control and difficult to approach. Some of the effects on concrete, which is usually used in tunnel construction, being exposed to high temperature is the phenomena of spalling. When concrete is exposed to high temperature, chunks of the concrete may shoot off, which is normally referred to as explosive spalling (Shuttleworth 2002). Spalling and heat damage to concrete in a tunnel construction may lead to decrease in the structural strength of concrete that may result in the tunnel construction loosing it's structural capacity.

Depending on the type of tunnel construction, location and it's use, the fire resistance of lined tunnels in many cases are possible and must be examined according to certain objectives (FIT 2004). Appendix A explains the phenomena of spalling in more detail as well as possible passive fire protection measures available for road tunnels.

4. Ventilation

Short review on mechanical systems used in road tunnels.

Emergency ventilation systems and tunnel operating procedures shall be developed for the removal and control of smoke and heated gases resulting from fire emergencies in tunnels. The operational procedures shall be designed to assist the evacuation and rescue of tunnel users (NFPA 502 2008).

Objectives for ventilation of fire and smoke control and the view of safety is to:

- Control the spread of smoke to create a smoke-free environment for tunnel users in relevant parts of the traffic room as long as possible.
- In any case provide tunnel users with a possibility to reach a safe place in reasonable time and distance.
- Ensure that ventilation is able to keep clear of smoke in unharmed structures like escape routes, twin traffic tube etc.
- In case of petrol fire, avoid secondary explosions due to incomplete combustion. Therefore the ventilation system must be able to deliver enough air for complete combustion or dilution of explosive gases. Also suitable drainage facilities should be in place to limit the area of fuel evaporation.

As mentioned before there are two categories of tunnel ventilation; natural and mechanical. Natural ventilation rely upon air movements induced by temperature, pressure gradients and tunnel traffic, whereas in mechanical ventilation the air is moved by force. Ventilation methods of application are not always distinct, combinations are possible and in some cases, unavoidable. This thesis focus on long tunnels, therefore only mechanical systems will be reviewed further.

Mechanical system configurations for tunnel design are longitudinal ventilation, fully transverse, semi transverse (and reversible semi- transverse) and partial- (or pseudo-) transverse. Longitudinal ventilation is a system that introduces air or removes air or both, at a limited number of points creating a longitudinal airflow. The longitudinal flow is generally performed by axial-flow fans called jet-fans or boosters, distributed along the tunnel (PIARC 2004). Another longitudinal ventilation configuration commonly used is the Saccardo nozzle system shown in Figure 4. The longitudinal ventilation is shown as a single shaft, however there are various configurations with shafts creating sections in long tunnels, two-shaft solutions with a shaft for both supply and exhaust as well as no shafts solutions with jet fans to maintain the ventilation from portal to portal (Beard and Carvel 2005).

Transverse ventilation on the other hand is defined by air being uniformly distributed and/or collected along the length of the tunnel, shown in Figure 5, whereas semi transverse ventilation may provide either exhaust or supply. The partial (pseudo) transverse system is an intermediate system between transverse and semi-transverse, with intermediate characteristics more similar to one or the other transverse type depending on what percentage of the ventilation flow is injected or extracted.

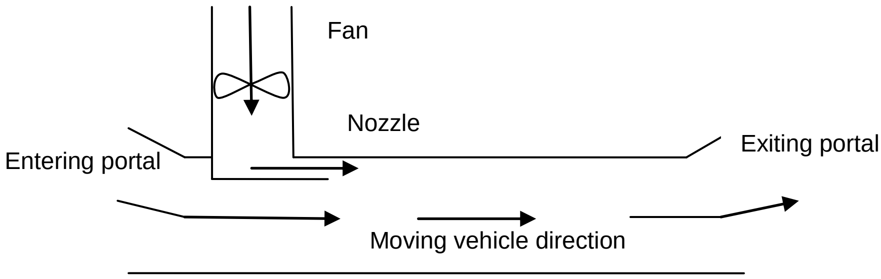

Figure 4 - Saccardo nozzle longitudinal ventilation system, as shown by Beard and Carvel, 2008

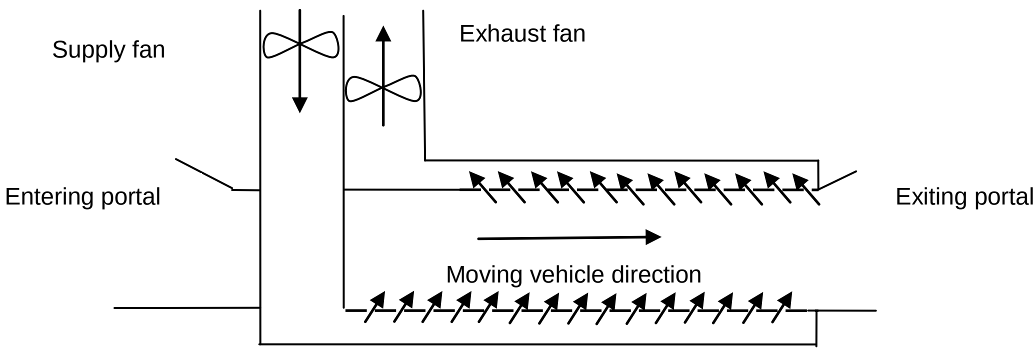

Figure 5 - Fully transverse ventilation system, as shown by Beard and Carvel, 2008

Longitudinal systems have been shown to be most sufficient in dealing with large fires in tunnels[5]. Fully transverse systems may be working satisfactory, however would normally require the section containing the fire to be set on exhaust in combination with the rest of the tunnel system in supply mode. This to be able to deal with large amounts of smoke from a large fire as well as limiting smoke from spreading to unaffected parts of the tunnel. Semi-transverse systems are not as sufficient as the other options however combinations with these has been done in tailored ventilation configurations such as the Sydney harbour tunnel and the restored Mount Blanc tunnel. (Beard and Carvel 2005) (NFPA 502 2008) (PIARC 2004)

Figure 6 and Figure 7 presents examples of semi-transverse systems.

[5] This is probably true when assuming that the system is allowed to work in its full capacity and not limited by the need for delayed activation or decreased exhaust velocity. Delayed activation may be necessary for situations of escaping tunnel users downstream from the fire, deriving from traffic queues or bi-directional traffic conditions.

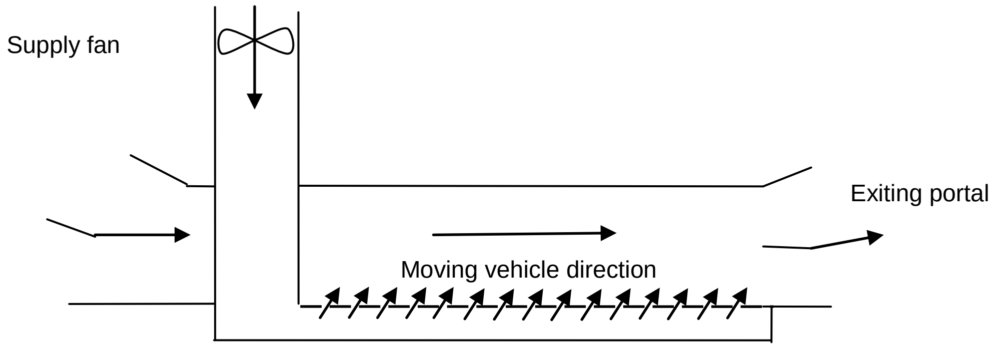

Figure 6 – Supply semi-transverse ventilation system

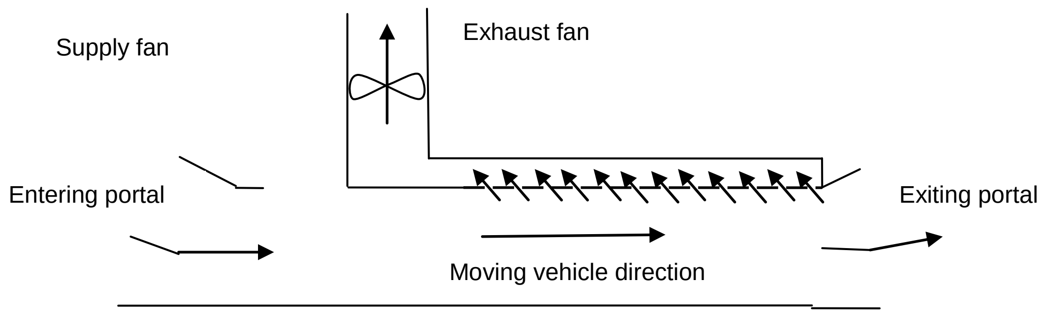

Figure 7 – Exhaust semi-transverse ventilation system

Design fire is measured in HRR which proved the required flow rate of a tunnel ventilation system for smoke control. Design fire size suitable for tunnel ventilation design is only briefly discussed here however investigated further in chapter 9 of this report.

For HRR above 20-30MW the efficiency decreases or needs to be maintained by very large investments in ventilation equipment. An increased flow velocity may result in a intensified fire HRR. State of the art systems may be able to deal with HRR of up to 100MW however approximately design fires of 15-50MW have been considered acceptable during recent years, depending on location and specific design parameters. The industry have started to appreciate that the former estimations of expected fires in tunnels are not necessarily the same as for real up to date tunnel fires which may be much more severe, even up to 100-200MW shown in chapter 8. There is a need for further research since new findings point towards more sufficient ventilation systems are needed, or other fire safety measures should be considered, as for instance FFFS's.

For any chosen design fire and ventilation configuration it is crucial to consider and use design measures to aim for safe evacuation of tunnel users from the fire area or downstream of the fire where untenable conditions may be expected. The strategy of smoke extraction is often affected by the traffic condition. PIARC has suggested three general cases that should be considered:

1. Tunnel designed for uni-directional traffic not designed for queues
    - Can be assumed that drivers downstream from the fire are free to escape by their own vehicles, whilst drivers upstream will not.
2. Tunnel designed for uni-directional traffic designed for queues.
    - People prevented from escaping with their own vehicle can likely stand on both sides of the fire.
3. Tunnels with bi-directional traffic.
    - People prevented from escaping with their own vehicle can likely stand on both sides of the fire.

NFPA (NFPA 502 2008) have set objectives for tunnels with either uni-directional or bi-directional traffic.

NFPA objectives for uni-directional traffic:

1. Longitudinal systems
    - Preventing back-layering by producing a longitudinal air velocity that is greater than the critical velocity in the direction of traffic flow.
    - Avoid disruption of the smoke layer initially by not operating jet fans that are located near the fire site. First operate fans that are furthest away from the site.
2. Transverse or reversible semi-transverse systems
    - Maximize the exhaust rate in the ventilation zone that contains the fire and minimize the amount of outside air that is introduced by a transverse system.
    - Create a longitudinal airflow in the direction of traffic flow by operating the upstream ventilation zone(s) in maximum supply and the downstream ventilation zone(s) in maximum exhaust.

NFPA objectives for bi-directional traffic:

1. Smoke stratification shall not be disturbed.
2. Longitudinal air velocity shall be kept at low magnitudes.
3. Smoke extraction through ceiling openings or high openings along the tunnel wall(s) is effective and shall be considered.

4.1.1 Longitudinal ventilation

To prevent back-layering (smoke moving upstream of the fire) ventilation designers need to consider the critical velocity. The critical velocity is the minimum air velocity required to suppress the smoke spreading against the longitudinal ventilation flow (Y. Wu, M.Z.A. Baker 2000). Scale models and full size scale tests as the Memorial tunnel have shown that HRR affect the critical velocity less than earlier anticipated. Further results tend to show that for HRR < 100MW and a slope of < 4% an airflow velocity of 3 m/s may be sufficient to prevent back-layering [6] (PIARC 2004).

[6] footnote: It should be noted however that the memorial tunnel had quite a large tunnel cross-section area and the results, i.e. critical velocity may be different for tunnels with another tunnel cross-section.

Stated in the SOLIT research report, for HRR above 20-30MW, the efficiency of longitudinal ventilation sufficiently decreases or needs to be maintained by very large investments in ventilation equipment. Also an increased flow velocity results in a substantially intensified fire. (SOLIT 2007)

Other research confirms the assumption of factors like tunnel cross-section affects the critical velocity. However it is suggested that a mean hydraulic tunnel height should be used instead of tunnel height which is often used as the characteristic length in the buoyancy forces expression in tunnel fire studies (Y. Wu, M.Z.A. Baker 2000). I.e. the whole tunnel geometry, which may be accounted for with the mean hydraulic tunnel height[7], affects the critical velocity and not solely the height of the tunnel.

To prevent back-layering, a 50 MW fire may correspond to a critical velocity of approximately 3m/s as a design criteria for a tunnel ventilation system. The approximation is highly sensitive to the tunnel configuration where factors like tunnel gradient and cross-section will have an impact. When altering the HRR to 100MW the required critical velocity may be around 3.5m/s. It is clear that there are higher costs associated with higher critical velocities. Suppose the critical velocity for longitudinal ventilation requires to be increased from 3 to 3.5 m/s, this could result in additional number of jet fans of approximately 40% (Tabarra 2009).

4.1.2 Transverse ventilation and semi-transverse ventilation

As already mentioned the purpose of controlling the spread of smoke is to keep a smoke-free environment for people in the traffic room as long as possible. Therefore in this type of ventilation configuration of stratification must be kept intact leaving tenable conditions underneath the smoke layer. To keep stratification, continuous ducts and extraction points is required. Further it is critical to maintain the longitudinal velocity below 2 m/s and full extraction operation within at least 10 minutes are to be achieved. (PIARC 2004) The latest is based on that stratification needs to be kept intact and no longitudinal velocity or earlier activation of longitudinal velocities up to 2 m/s is present. Earlier activation of longitudinal velocities is used in the case of uni-directional traffic with no queuing.

PIARC further states, fresh air should be entered at floor level and be throttled to a rate of 1/2 - 1/3 of the full capacity. When fresh air is added from the ceiling in normal mode it is important to make the changeover to extraction in the activated zone as soon as possible.

4.2 Discussion

In general longitudinal ventilation should not be used in tunnels with bi-directional traffic flow, since smoke will travel along the tunnel keeping the upstream part clear of smoke and the downstream mixed with smoke. Bi-directional traffic flow allows vehicles to always be situated both upstream and downstream from a fire. Therefore longitudinal ventilation is more suitable for uni-directional traffic flow and not bi-directional traffic flow.

The issue may occur for uni-directional traffic flow as well, if queuing is allowed. The potential of queuing should always be considered in a design and extra measures undertaken if needed to prevent a scenario where hot gases from a fire travels with the ventilation flow to where tunnel users are situated or in process of evacuation.

For instance, it may be reasonable to believe that the critical velocity will be higher for tunnels with a smaller cross-section area.
[7] mean hydraulic tunnel height is defined as the ratio of 4 times the tunnel cross- sectional area to the tunnel perimeter, m

Transverse ventilation may create a stratification layer that allows tunnel users to evacuate underneath it. It should be noted that the efficiency of the same type of system may not be the same for all tunnels since their capacity and nozzles etc. may differ.

Tunnels in Europe are commonly equipped with longitudinal ventilation independent on traffic conditions mostly due to the reduction in cost compared to transverse systems.

Pseudo transverse systems if calibrated well way provide an tailored solution where the beneficial aspects of both longitudinal and transverse systems is represented. However a pseudo transverse ventilation design is associated with high costs and challenging technological solutions.

5. Detection

Review on detection systems used in road tunnels and their ability to detect vehicle fires in tunnels.

There are a few generally common options of fire detection in tunnels:

- Automatic fire detectors
  - Smoke detector[8] (scattered light or ionisation)
  - Heat detector (fixed-temperature or rate-of-rise temperature)
  - Flame detector (ultraviolet or infrared)
  - Incident detection (often combined with one of the detection methods above)
- No automatic fire detectors
  - Fire push- button and/or communication facilities as emergency phone

Generally heat detection seems to be the most acceptable automatic fire detection system in road tunnels. The use of CCTV also exists usually with a combination of one of the options mentioned above and/or with traffic incident control. Flame detectors will detect a fire as long as there is a line of sight, however many fires starts inside or below vehicles. Other systems for detection exists such as CO monitoring, HCl monitoring but these are not yet shown to be sufficient.

To understand the use of detection systems history, application and views on ability to detect fires in tunnels, different systems have been investigated. The detection times of the most accepted and efficient detection systems has been considered.

5.1 Ability to detect fires and incidents

Fire detection ability in tunnels becomes very demanding due to critical ambient conditions, such as dirty and partly corrosive exhaust fumes, elevated temperatures and humid conditions. There are several aspects to be considered to enable a 'fail-safe' and 'false-alarm' safe operating detection system. State of the art fire alarm systems are designed in accordance with standards like EN 54 and NFPA 502. In 2005 fire detection systems were able to detect fast temperature increase from open fires of 1MW with an activated alarm within 30-60 s under ventilation conditions of 0-8 m/s, 60-90 s is allowed for smoke control devices to go into full operation. The same alarm may be used to trigger other essential safety actions such as egress control parameters, CCTV and/or FFFS. (Beard and Carvel 2005) The expected detection time are confirmed by resent testing of tunnel detection systems in the USA (Almand 2008) which shows that state of the art detection generally may detect fires with heat release rates up to 3 MW within 60 s.

Tests in the Benelux tunnel on linear heat detection show the following results (Vasilovska 2006):

1. With a velocity speed of < 1 m/s a slow growing fire will be detected within 1-3 minutes, if right beneath the detection cable.
2. If not right beneath or with a wind speed > 3 m/s no alarm can be expected or an alarm with a time delay of 5 minutes or more.

[8] Smoke detection is however very rare due to maintenance and false alarm issues. Normally heat detection is used.

3. Fast developing fires will nearly always be detected within 3 minutes independent of wind velocity.
4. Location accuracy can be expected to be less than 5 meters.

The SOLIT report state the same, detection used usually spots incipient fires with an accuracy of a few meters (SOLIT 2007). However others say that a fibre optic based linear heat detection system may determine the fire location, within 10 m from the actual fire under a longitudinal airflow. (Liu, Kashef, et al., Symmary of International Road Tunnel Fire Detection Research Project - Phase II 2008)

Another aspect raised as a concern, the ability to detect moving fires in tunnel environment. There is limited research on detection ability of fires on moving vehicles until the international road tunnel fire detection research project in the USA investigated it, with the conclusion that it was difficult for fire detection systems to detect small moving fires. Only an optical flame detector identified a moving fire at a speed of 27 km/h, but non at the speed of 50 km/h in the test. Other detection systems did not respond to moving fires (Almand 2008). [9]

Detection systems have been investigated further for the purpose of this report and presented in Appendix B.

5.2 Discussion

Identification of time for detection is crucial to the estimation of the time for activation of other active fire protection systems. Evidently the time for activation could then vary for different tunnel designs and systems depending on the expected design fires and their growth phase. To focus on general time could be misleading due to similar fires having different growth rate depending not only on the fuel and time after ignition but also ventilation conditions, tunnel configuration and environment.

Carvel (Carvel March 2008) suggested in his research that an estimated HRR should be established which could lead to detection and then a time for activating other systems added to that specific time. The concept should be subject to further future research. Further work could contribute with a minimum accepted detection time required for all types of detection systems used in tunnel environment. Based on a set maximum HRR for when the detection system always detects the fire. In absence of extensive research and the fact that a set HRR for detection may vary depending on fuel type and detector types, a reasonable interval of possible time for detection will be selected and reviewed for the design fire study in chapter 10 of this report.

It may be possible to achieve reduced detection times by combining incident control with state of the art detections systems on the market.

[9] The difficulty with detection of moving vehicles may be an issue and should be considered, however it seems reasonable to assume that in most cases a burning vehicle would be stationary. If not initially stationary then some delay in detection may be possible since detection will most likely be made after a burning vehicle has come to a halt. Last option is if the vehicle continues out of the tunnel which would be the preferred option since the tunnel would then no longer be subject to a fire.

6. Fixed Fire Fighting Systems (FFFS) or suppression systems

This chapter will identify benefits and evaluate efficiency of suppression systems in tunnels based on available research material.

There are various types of water-based systems available for road tunnels, the most common ones presented below:

- Deluge water spray systems - open nozzles installed in sections over the tunnel length
- Deluge water-foam systems
- Low pressure water mist systems
- High pressure water mist systems
- Water curtains

Selected tests and research on these systems are summarised and evaluated in chapter 6.2 of this report.

There is limited research available on water curtains and these are not likely to be associated with potential trade-offs and will therefore not be investigated in more depth.

6.1 Background

Prior the Alpine tunnel fire disasters in 1999 previously mentioned, Japan was the only country to significantly having tested and used sprinkler systems in road tunnels. The view has been divided if the benefits (as reduction of fire) take out the negative aspects (as decreased visibility). Much debate has followed and several research programs such as UPTUN, FIT, SOLIT and PIARC have been investigating the matter. (Beard and Carvel 2005, PIARC 2008, SOLIT 2007).

Generally FFFS's are used for different reasons depending on the local code requirements, type of tunnel, client requirements as well as expected type of traffic. In Australia commonly, if a tunnel is longer than 360 m, suppression (spray deluge) system is required and incorporated in the design (ITA 2004).

Japan as Australia is also a frequent user of FFFS's which normally are required in tunnels of more than 3 km in length carrying 4000 vehicles per day (Mashimo 2002, Liu, Kashef, et al. 2007). There are several full-scale fire tests carried out and published in Japan between 1963-1985 (most of them not translated from Japanese). The general conclusions are that sprinklers are able to reduce fire size and temperature and prevent spread to adjacent objects. (Beard and Carvel 2005) The Japanese fire statistics show about 10 to 16 tunnel fires per year requiring the fire brigade and 2 or 3 cases per year where sprinklers are activated. When used, the fire heard was cooled and fire spread to other vehicles was prevented, because of the sprinkler. Main pipes are filled with water; pipes between valve and heads are not filled, which results in a very short time lag between opening of automatic valve and water discharge from sprinkler heads.

Previously Europe has not used FFFS's in tunnels although there are a few recent tunnel projects, incorporating the means of active fire protection by mist systems, as the M30 tunnel in Madrid and the A86 tunnel in Paris (Marioff/HI-FOG 2008). Further the new Tyne tunnel crossing in the UK is being constructed with a mist system incorporated in the design, for property protection and insurance purposes.

In European tunnels water mist systems is currently more common if any suppression system. Mostly used for property protection and insurance purposes. However mist systems also demand less water than deluge spray sprinkler systems. Deluge systems, common in tunnel installations in Australia and Japan, are mostly incorporated into tunnel design due to code requirements in tunnels of certain length and/or traffic flow (RTA 2006, Vasilovska 2006). However they contribute to both a higher level of life safety as well as improved property protection.

As mentioned previously tunnel fire history have raised the issue of tunnels having inferior fire safety. This seems to result in suppression systems being used more frequently in tunnel design around the world. Due to expected costs associated with incorporating suppression the concept trade-offs is appealing. There is a potential of incorporating suppression systems as part of the design, with the benefit and advantage like reduction in HRR, temperature and toxicity. This may lead to the possibility of incorporating trade-offs in the design for both passive and active fire protection.

6.2 Effectiveness of FFFS's in road tunnels

Some argues that FFFS are not cost-efficient for fires normally expected in tunnels, will not save the life's of road users, but only be helpful in preventing catastrophes like extremely large fires to spread and prevent BLEVE's (Huijben, J.W.; 2005). This view is based on, although fire spread may be prevented or limited, road users lives will not be saved by FFFS because they are expected to have left the tunnel before the fire develops to its maximum. There are however other views and experiences that lead to contradictive conclusions.

Fire engineers in Australia have a more positive view on the effectiveness of FFFS (Johnson och Barber, The Burnley Tunnel Fire - Implications for Current Design Practice 2008) and views of implications for international practice:

"The implications of the Burnley tunnel Fire and the current design practice in Australia is that it appears that if life loss in road tunnel fires is to be minimized, especially after major truck accidents such as occurred in Burnley and Santa Clarita, then some or all of the current practice in Australia will need to be considered in other countries. In particular, further consideration will have to be given to provision of suppression systems."

It was concluded that the Burnley Tunnel fire contrasted strongly with the Santa Clarita tunnel fire in California where lack of fire protection measures resulted in much greater damage.

The effectiveness of FFFS in road tunnels is dependent on aspects as water density, type of system, type of fire and fire growth rate, time for activation of suppression as well as traffic conditions and influence by ventilation. PIARC explains advantages and disadvantages of FFFS, within different traffic conditions and ventilation scenarios, as presented in Table 2. Results and conclusions on the effectiveness of suppression systems have been summarised in 6.2.1 and Appendix E.

Table 2 – Advantages and disadvantages of FFFS within different scenarios (PIARC 2008)

Scenario	Infulence on ambient conditions during self-rescue		Creation of additional risks (b)
	Stabilization (a)	Improvment	
Longitudunal ventilaiton uni-directional traffic, non-congested	Yes	No	No
Longitudunal ventilaiton, bi-directional or congested uni-directional traffic	Yes	depends on the specific situaiton	Yes
Transverse ventilation	Yes	depends on the specific situation	Yes (c)

(a) By limiting e.g. fire growth and heat release rate

(b) By e.g. location error, destratification
(c) Also for uni-directional tunnels

Longitudinal ventilation combined with FFFS and in conjunction with non-congested traffic is an easy option for an uncomplicated design. The other two scenarios probably occur more often for tunnel design since tunnels are often used in urban areas where both long tunnels and congested traffic may be expected. For all scenarios it can be concluded that fire growth and HRR will be limited.

Effectiveness of FFFS may also be measured in different ways. For instance in its ability to limit fire spread, decrease fire growth, keep a fire at constant level, decrease the HRR or even extinguish a fire. Depending on the objective the effectiveness may be interpreted differently.

6.2.1 Conclusions from tests and experience of suppression systems

Several tests and research on various suppression systems has been identified and summarised in Appendix E.

Water Spray:

- Standard values used in Japan are a water volume of 6 L/(min m$^{2)}$, with a discharge pressure of 340 kPa. One spray section is 50 m in length and the water supply lasting longer than 40 minutes (Liu, Kashef, et al. 2007, Mashimo 2002, Vasilovska 2006).
- Flow rates for deluge systems are generally in the range of 10 mm/min/m^2 with an operation pressure between 300-500 kPa (approximately doubled that of an ordinary sprinkler system). With every deluge zone being approximately 30 m. The consequences of higher flow rates are that factors like fluctuations in flow rates, variations in operational pressures, external effects such as wind speeds achieving critical velocities as well as droplet size have minimal effect on the deluge systems. (Vasilovska 2006)
- A major fire incident with a suppression system present is the Burnley Tunnel Fire in 2007, where the deluge system and the ducted semi-transverse smoke controls system were activated rapidly, together controlling smoke volumes to a zone of about 100m downstream of the fire, as designed. (Johnson and Barber 2007)

Foam systems:

- Foam additives for water spray protection against possible flammable liquid fuel or chemical fires are the most common type of suppression systems used in the USA.
- CAF (compressed air foam) systems may extinguish an open diesel pool fire but only control solid fuel fires. (Liu, Kashef, et al. 2007, Mashimo 2002).

Mist:

- The efficiency of water mists systems are satisfactory in respect of temperatures downstream of the fire, heat stresses, toxicity as well as back-layering and visibility upstream of the fire (Opstad and Stensaas 2006) (SOLIT 2007). It has been shown in resent research that mist systems can control fires, decrease temperature and prevent fire spread (Liu, Kashef, et al. 2007).
- Visibility not improved downstream during the first minutes but generally increased as the HRR was reduced. (Opstad and Stensaas 2006) (SOLIT 2007)

- Efficiency of water mist is strongly dependent on the size of the fire, nozzle type, location and water discharge rates. (Opstad and Stensaas 2006, Liu, Kashef, et al. 2007)
- Best results for mist systems was achieved for HRR >20MW for HRR tested in the range of 2-28MW (Opstad and Stensaas 2006)
- High pressure mist systems use less water and suppress fires to a higher degree in the gas phase of the flames, while low pressure systems mainly effects the fire by cooling the fuel surface (Opstad and Stensaas 2006).
- Visibility has been shown to be reduced by water mist systems, which would negatively affect evacuation.
- Cooling of the smoke causes loss of stratification, which somewhat reduces visibility at floor level, compared to un-cooled smoke. An acceptable trade-off considering the alternative. Considering that the water mist cannot remove insoluble toxic gases such as carbon monoxide, improved breathability may be a dangerous overstatement (J. R. Mawhinney April 2002).

General:

- Validation of performance of fire safety equipment like water spraying systems requires full scale testing and cannot be trusted for example by simulations solely (Opstad and Stensaas 2006)
- Japanese authorities has concluded that the activation time of water spray systems for maximum advantages and minimized errors by tunnel operator, are 3 minutes for uni-directional tunnels and 10 minutes for bi-directional tunnels, after a fire is detected. This was based on risk analysis and experimental data. Therefore automatic activation has been adopted in Japanese tunnels. (Liu, Kashef, et al. 2007, Vasilovska 2006)
- No significant steam generation or deflagration resulting in re-ignition has been reported when using foam sprinklers, spray systems or water mist systems, in resent tests with gasoline pool fires, large diesel pool fires and solid fuel fires. (Liu, Kashef, et al. 2007).
- Water spray cooling systems may be used in smoke ducts to minimise the gas temperature at the exhaust fans (Agnew och Allen 2008).

6.3 Reliability of FFFS's

Reliability of suppression systems are a significantly important subject. Reliability of FFFS may vary depending on type of system and its components, the installation, maintenance procedures as well as the type of detection system used.

In buildings, the performance of sprinkler systems in terms of reliability is exceptionally high, compared to other forms of protection. Values for the probability that a sprinkler system will operate successfully on demand in buildings are: maximum: 95% (applicable to new systems in areas where statutory enforcement is in place; typical: 90% (new life safety systems) or 80% (new property protection systems; minimum: 75% (older systems). These values assume that no more than four sprinkler heads operate (Bafsa 2006). Since building and tunnel designs are different in many aspects and the suppression application normally incline a customised deluge type suppression system for road tunnels, specific values for tunnels application should be considered.

For FFFS in tunnels all components shall be properly dimensioned. The reliability of the components used is vital for the safe functioning. Thus the aggressive environmental conditions found in the relevant tunnel must be considered to compensate for effects of salt, humidity, change in temperatures, pollution etc. Third party testing and listing of safety relevant components shall be ensured. Further aspects like expected life time, Life Cycle Costs , Fault Tree Analysis, Mean Time to Failure (MTTF) and cost to recommission the FFFS after a false activation should be considered (UPTUN 2006).

Typical values for Mean Time Between Failure (MTBF) and Mean Time To Repair (MTTR) are (PIARC 2008):

- Diesel pump
    - MTBF=$8.75x10^3$ hours
    - MTTR=2.25 hours
- Electric valve
    - MTBF=$1.04x10^7$ hours
    - MTTR=0.25 hours

There is not extensive research present on the expected reliability of suppression systems in tunnels however Huijben (Huijben, J.W.; 2005) has suggested some probability values shown in Figure 8. He argues that the effectiveness of a sprinkler system depends on the main aspects of:

1. The control of suppression, i.e. detection and switching.
2. The technical system of the suppression, i.e. does it function on demand.
3. The effect of suppression on a fire

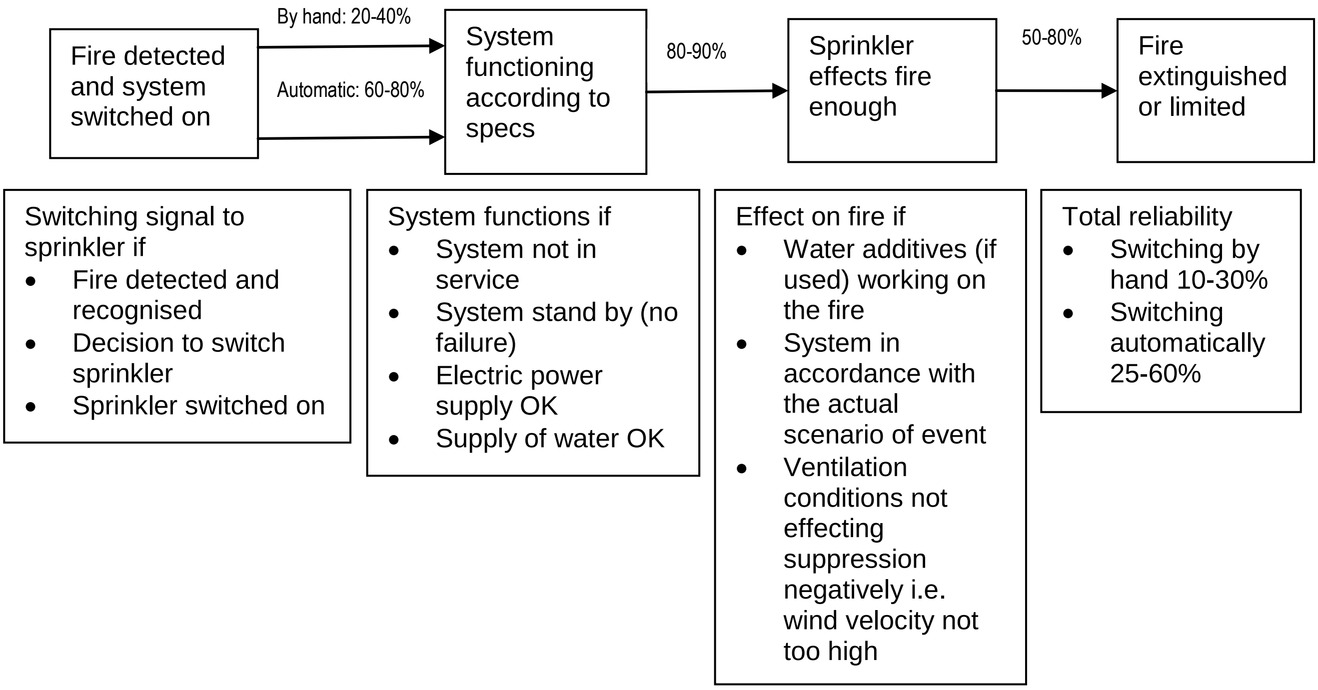

Figure 8 - Reliability of sprinkler systems in a tunnel (Huijben, J.W.; 2005)

There has been no opportunity to check the sources of the numbers stated in Figure 8. Even though the probability statements above are not verified by other sources and should not be taken as the simple truth, it can be concluded that the reliability of automatic switching is higher than the reliability of switching by hand. However the reliability of automatic systems is still quite low. A reliability this low of a suppression system, in a road tunnel associated for trade-offs, should not be acceptable. This aspect needs to be considered carefully and be included in a detailed risk analysis for each project in question and its specific conditions.

There are promising results from already operating systems. Japanese authorities report that sprinklers have been used in two or three fire incidents in tunnels per year, where they have cooled fires and prevented fire spread. No cases are known of false operation, malfunctioning or only partly functioning of sprinklers during actual tunnel fire. The experience with sprinklers during normal tunnel operation has been no malfunctioning of sprinklers during normal tunnel operation. However in Japan, sprinklers for road tunnels do not follow a certification system for quality guarantee. In the first stage of development, new sprinkler types are tested for functionality and water discharge volume, before installation. After that, reliability is established based on actual performance. Up to date, no notable performance defects have been experienced with sprinkler installation in road tunnels. It is stated that regular maintenance and inspection by specialist technicians have been essential for this performance. (Stroeks 2001)

6.4 Discussion

There is still a need for more extensive research on FFFS's in road tunnels. However it may be concluded that implementing FFFS's in road tunnels may result in:

- Safer tunnels for tunnel users and fire fighters, keeping tenable conditions for a longer period of time.
- Minimising damage to the tunnel structure.
- Significant reduced cost associated with asset protection and business continuity due to for instance repairs and lost toll fares after a fire incident.

However, regular maintenance and inspections by specialist technicians are crucial to maintain a high reliability of FFFS in tunnels.

In the design of ventilation systems for tunnels incorporating FFFS, designers may not necessarily account for a reduction of design fire size. Often ventilation capacity is designed for the same peak HRR despite of FFFS present or not. This is specially the case in Europe where tunnel ventilation systems for smoke extraction are commonly based on a prescriptive appointed design fire HRR. It is reasonable to assume that FFFS is capable of limiting the HRR and prevent fire growth. The question is, to what extent this is true for large fires in tunnels? With lower HRR follows less smoke production i.e. reduced required capacity of the emergency ventilation system.

Expected temperatures within a tunnel may significantly be limited by a suppression system. TT-curves which are used for tunnel design show expected temperature for a tunnel fire without a suppression system in place, see chapter 3 of this report. This temperature could be of the same magnitude locally close to a fire, however in a tunnel with a suppression system the temperatures along the tunnel would most likely be much lower.

It is reasonable to say that an acceptable configuration would be, when the mix of smoke and water (from mist or spray deluge) in a tunnel is being moved away from escaping tunnel users. This could be achieved by a longitudinal ventilation strategy preventing back layering, based on a uni-directional traffic condition. A longitudinal airflow with uni-directional traffic condition may be a preferred option in a tunnel environment when suppression and ventilation interactions occur. Although the preferred can be when there is no expected queuing i.e. no tunnel users excepted downstream of the fire. It is still possible that configurations with expected queuing or bi-directional traffic conditions and even other ventilation configuration, also may benefit from a FFFS design approach. This is discussed further in the evaluation of potential trade-offs in chapter 11.

7. Operation

Short review on tunnel operation systems and procedures.

Presented below is an example derived from experience in Japan (Stroeks 2001) concerning activities during tunnel fire incidents. Types of activities as well as their order may be different on a case by case basis. Further a number of activities are carried out parallel:

- Activation of fire detector
- Detection of emergency in tunnel with ITV camera
- Information to tunnel users (traffic signal at tunnel entrance to red; message at tunnel entrance to “Fire ! Do not enter tunnel ! ”; message by speaker and radio to leave tunnel)
- Fire Brigade alerted and it’s intervention
- Activate sprinkler
- Tunnel owner arrival at the incident

It is essential that operation and maintenance follows the fire strategy for the tunnel in question, as well as the authority having jurisdiction.

As mentioned in chapter 6.2.1, Japan highway public corporation, has adopted a new procedure for deluge suppression with an automatic activation on pre-set times. For maximum advantages and to minimize errors by tunnel operator, 3 minutes for uni-directional tunnels and 10 minutes for bi-directional tunnels after a fire is detected is used. In recent tunnel projects in New South Wales (Australia) there is however a uniform position that the operator manually activates the deluge system at a very early stage following detection independent on the type of traffic. (Vasilovska 2006)

7.1 Discussion

Independent of what type of systems used in a design, it is crucial that all parameters are accounted for and the systems are well implemented in the operation. This is to ensure an effective operation. Aspects of design fire size, confirmed ventilation systems response times and the effects of suppression should allow project engineers to develop emergency operation programs that identify the correct operating mode.

8. Design fires

Review on design fires considering the influence of ventilation conditions and the presence of suppression or not.

Key design fire scenarios based on relevant design fire objectives has been summarised in the FIT (FIT 2004) report regarding design fire scenarios in tunnels. The key design fires are:

1. Design fire scenario for ventilation design and assessment
2. Design fire scenario for egress analysis
3. Design fire scenario for thermal action on structures
4. Design fire scenario for the safety of tunnel fire equipment
5. Design fires for work on tunnel construction, refurbishment, repair and maintenance

The design for structures and equipment are based on the temperature of the hot air versus time, i.e. temperature time curve (TT-curve). Whereas the ventilation and evacuation design are based on the HRR (or thermal power) in MW or the smoke release rate m^3/s. Therefore aspects affected by design fires size are the engineering of the ventilation system and the training of people dealing with fire in tunnels. Other aspects like engineering of the tunnel structure, fire testing of structural elements are based on prescriptive TT-curves which are explained in chapter 3. (Carvel March 2008) (PIARC 2004) (ITA 2004) It is possible to calculate an expected temperature for specific HRR's as design fires however these wary on the tunnel configuration, type and amount of fuel as well as ventilation conditions. Therefore maximum temperatures have been established for excepted fires in tunnel in the TT-curves presented in chapter 3. This correlates to the concept o building design where TT-curves are used for which derives from 'normal' compartment fires.

Since the initial effect of a suppression system in a tunnel is potentially to create tenable conditions and leverage of the design fire forming for ventilation design as well as significantly decreasing the temperature. The first three design fire scenarios above are considered here. Evidently all design fire scenarios may be more or less influenced by a suppression system, however the ventilation design with egress is considered to be the limiting factor. This is where the most of the focus will be, combined with general ventilation design and temperature issues.

It can be noted in the FIT report that assumptions and regulations, regarding design fires for ventilation systems, differed for different countries especially for large fires. Further it is stated that there are experimental evidence, for large fires, that the critical velocity becomes independent of fire size.

Later research shows a new aspect to consider, except for sole focus on the critical velocity, the fire growth. It has been shown in the Benelux and Runehammar test programs that ventilation and HRR are interacting, where velocity effects the fire growth. Ironically the critical velocity of 2.5-3m/s, often used to prevent back-layering, seems to give the most rapid fire growth. With early detection and activation of suppression a rapid fire growth may be avoided. (Carvel March 2008) This is discussed further in chapter 10.

Regarding egress analysis, time for hazardous conditions, which develop at particular locations, need to be compared with occupant egress times. The conclusion is that the concern is related to the issue of stratification of hot gases and smoke. Therefore tunnel designers should be careful and preferably avoid scenarios relying heavily on stratification.

In tunnel design it is necessary to choose the typical characteristics that correspond to the specific tunnel considered. To determine design fires and scenarios for tunnels both frequencies and intensities have to be considered. Some statistical evaluations and fire experiments can be found in the PIARC work (PIARC 2004). Recommending design fires used for ventilation capacity should consider the level of risk within the tunnel, and therefore the design fire size depending on the type of traffic allowed. The recommended relevant cases being:

- Passanger cars only
- Passanger cars and trucks; no dangerous goods
- Passanger cars and trucks including dangerous goods

There are two design parameters to determine the safety classification of a tunnel, tunnel length and traffic volume. Further the tunnel length and traffic volume are related to the probability of accidents and fires (Ingason, Haukur 2008).

Most tunnels allow passenger cars and trucks whereas dangerous goods often have restrictions to enter certain tunnels. Conditions under which dangerous goods is to be allowed in tunnels should be looked upon separately. Recommendations about this is can be found in material from PIARC:s joint research project with the Organisation for Economic Co-operation and Development (OECD), but does not form part of the scope of this thesis.

Examples of design fires taken from different guidelines have been summarised by H. Ingason, as shown in Table 3, where he refers to them as “magic numbers”. Magic numbers are defined as a technical design value obtained from a discussion group of experts without any physical validation or traceable origin. Mainly based on historical experience and tradition, different attitudes and perspectives as well as reasoning in conjunction with limited experimental data. (Ingason, Haukur 2008)

Table 3 – Examples of design fires taken from different guidelines, given in MW (Ingason, Haukur 2008)

Vehicle type / Guideline	PIARC	French	NFPA	New NFPA 2008 edition[10]
1 small passenger car	2.5			5-10
1 large passenger car	5		5	
2-3 passenger cars	8	8		10-20
Van	15	15		
Bus	20		20	20-30
HGV	20-30	30	20-30	70-200
Tanker	100	200	100	200-300

[10] This grey column has been added by the author to show the resent developing change in the view on design fire size for tunnels.

It is further shown by Ingason that these design values are based on rather limited data and that there is insufficient data for any type of statistical treatment. He explains further that there is reluctance in changing any levels once they are established, even though new research is available. The EUREKA 499 test in 1992, of a HGV fire, is a good example showing that HRR of 120 MW was considered an exception until the results was confirmed by the Runehammar tests, in 2003. The Runehammar tests resulted in HRR's of 67-202MW.

Even though there is a reluctance for change by authorities and regulators some changes are taking place. NFPA has been revised in the 2008 edition with a design fire size of 70-200MW in lieu of the previous 20-30MW.

In the tunnel guidelines of Australia (RTA 2006) the following fire sizes are the minimum to be considered for various fire scenarios considering occupant life safety:

- 1 MW
- 4 MW
- 20 MW
- 50 MW

It is expected that the fire scenarios should take the impact of suppression systems on occupant evacuation, fire size, fire growth rate and fire spread into account. I.e. it may be argued that a suppression system may limit a certain fire to a reasonable degree undertaking a fire engineering approach.

8.1 Ventilation influence in fire size

As mentioned previously ventilation velocities in tunnels change the HRR of fires, usually resulting in a higher HRR, than the same fuel in a free burning environment (Beard and Carvel 2005). It has been shown that an increase in tunnel ventilation velocity makes the HRR increase. This seems to be true for relatively small fires (0.45-2.4MW) (Aralt and Nilsen 2008) as well as for much larger fires (Carvel March 2008). For instance a relatively small pool fire free burning may in fact be more than doubled in size in a tunnel environment, under the influence of ventilation. Further there are infuses on efficiency in detection which may vary depending on type of detectors used and type of fuel burning. The ventilation influence on detection is discussed in chapter 5. Relevant research in ventilation and HRR interaction is presented and used in chapter 10 of this report in a design fire example.

8.2 Discussion

It was concluded above by Carvel that tunnel designers should be careful and preferably avoid scenarios relying heavily on stratification. This conclusion is strongly contradictive to the general strategy in Japan where activation of FFFS's is done after 3 minutes in tunnels with longitudinal ventilation and as long as 9 minutes in tunnels with transversal ventilation. Activation after 9 minutes is a design and fire strategy which is strongly dependent on stratification of hot gases and smoke. Further the general strategy in Australia is to activate a FFFS system as soon and safe as possible independent on type of ventilation system, however with various times depending on the configuration and specific environment and situation.

From an engineering point of view enabling the future work on potential trade-offs, it might be valuable to use performance requirements. Further considerations should be taken to investigate the possibility of identifying set HRRs. I.e. detection is required to further allow for a time lag for activation of suppression, resulting in an acceptable final HRR. This theory of working ourselves backwards may not only be beneficial in making the relevant assumptions for further work, but also highlight where more research, testing and/or product developments are required. Such an approach will detect many aspects that are somewhat uncertain, like detection times for instance verifying, depending the type of detection system, ventilation condition as well as the type of fuel burning. Further the suppression ability would differ between different suppression systems and their design parameters. Reasonable focus on a maximum HRR, assumed to be controlled by a suppression system and by calculation backwards, will identify the available amount of time required for detection and time lag to activate suppression system. This platform contributes with limitations showing what must be expected from detection and suppression to allow for potential trade-offs.

The question comes to mind; where is 'the point of no return'? How large may a fire be allowed to grow with kept confidence that any suppression system may still be effective? To confidently allow for trade-offs this question needs to be answered. Then the concept of calculating backwards can be applied, to investigate what scenarios may be possible to detect and suppress before 'the point of no return'.

A maximum HRR rate is not a number one may easily decide upon. As mentioned, before the design fire used for road tunnel design is typically between 30-50 MW and sets the smoke control requirements. However after resent research in the UPTUN and other research programs it is shown to be more in the range of 100-200 MW. It was stated at the New Jersey conference on suppression in tunnels (Johnson, Jönsson, et al. 2009) that the 50 MW normally used in Australia would appear to have never been properly researched. Where some argues that 50 MW takes into account the effectiveness of water based deluge system would never control a fire up to 50 MW. It was further stated that some argues for lower design fire size of 20-30 MW, based on the fire being suppressed by a deluge system.

Let's go back to Japan and their fire strategy, what happens with our design fire if we wait with activation of FFFS until 9 minutes after detection of the fire?

9. Fire brigade intervention

Short review on fire brigade intervention considering suppression systems.

The fire brigade has an important and critical role in decisions about installations and operation of fire protection facilities in tunnels (Vasilovska 2006).

For fires in tunnels the idea with automatic systems is to detect the fire and get the fire brigade into position to be able to fight the fire while it is still small and controllable. The time for intervention depend on factors like tunnel length i.e. travel distance in the tunnel. Fire services that are stationed in a tunnel may be able to hinder the fire growth however in most cases scrambling and travelling time may be up to 15 min. Buss- and lorry fires of magnitude of 10-30 WM may be easy to detect, however for this fire size and higher HRR, the risk of fire spread to nearby vehicles increase. For fires rising to a level of 100-200 MW it becomes difficult to do anything, except carrying out the dead after the fire is over. (Aralt and Nilsen 2008) Considering these large fire scenarios FFFS may be a safe and potentially beneficial option, depending on the tunnel configuration and use.

10. Design fire approach –Suppression with longitudinal ventilation

Analysis into design fires considering the influence of ventilation conditions and the presence of suppression.

There is the possibility of considering trade-offs for tunnels with FFFS's installed. This could result in, not only in benefits in safety, but also cost saving in design and construction. To use the design fire for relevant scenarios of potential trade-offs, when limited by a suppression system, it is crucial to investigate and fully understand all parameters involved forming the design fire. Important factors to look into is not only peak HRR and smoke production, but probably more importantly, the fire growth. Fire growth will affect time to detect a fire and activation of a suppression system, which further affect the expected peak HRR. Further the expected peak HRR could be used to determine if potential trade-offs, presented in chapter 11 are possible or not. To enable identification of such trade-offs the fundamentals of design fires and design fire scenarios needs to be investigated. The main aspects to consider for this analysis are summarised in Table 4.

Table 4 – Aspects considered for design fire analysis

Aspect	Affected parameter
Early detection	To enable early activation of a suppression system that further will limit expected peak HRR
Expected design fire growth	Will affect peak HRR after being limited by suppression system. Expected time for activation of suppression should be investigated, estimation of expected peak HRR.
Ventilation conditions	There is a possibility of detection time being affected by ventilation conditions. Changes in the design fire growth due to ventilation conditions, i.e. expected velocities in normal operation and in 'fire mode' will be considered.
Temperature conditions with and without activation of suppression	Will affect tenability for tunnel users, fire fighters and damage to tunnel structure in a fire incident.

One of the potential trade-offs that is of much interest is a possible reduction in ventilation capacity of the emergency ventilation system. The interesting part is that the ventilation capacity and the air velocity may strongly affect the peak HRR in itself. It's obvious that we are dealing with a complex process and therefore the factors will have to be assessed separately first, to be combined in a holistic view of an expected design fire limited by suppression. When doing so, focus will be made especially on the initial stages of the fire, i.e. the fire growth, detection and activation of active systems. The common FFFS's used in tunnel design, as mentioned earlier, are deluge water spray systems and most recently also mist systems. Since these systems vary in factors such as spray density, interaction with ventilation as well as applicable time for activation, it is necessary to look at them separately.

First of all it is important to investigate the time for detection and activation since this will influence the time for when a suppression system will start suppressing a fire. Time for activation will further decide how large the fire is able to grow. Obviously the expected peak HRR will also be dependent on the expected fire growth before activation and suppression.

For cars, time to reach maximum HRR may vary between 3-8 minutes. For HGV's and other fuel sources, like pool fires from leaking or ruptured tanks, have different time for maximum HRR and fire curve to consider. A fuel tank rupture or a pre started fire could only take some few minutes up to 10 minutes to reach peak HRR. (Aralt and Nilsen 2008)

10.1 Design fire analysis

The question discussed before, where is 'the point of no return' still stands? How large may a fire be allowed to grow with kept confidence that any suppression system may still be effective? To confidently allow for trade-offs this question probably needs to be answered.

Since there is no obvious answer to this question a good start would be to narrow it down to what would be an expected HRR needed to be held steady or suppressed, with a decreasing magnitude by the effectiveness of a suppression system? The expected HRR would rely upon the pre-burn time before activation of the suppression system and the fire growth rate. This leads back to expected detection time and time to activation.

This should be put together with the aspect that there has generally been two options in the approach in operation.

1. Activation as soon as possible
2. Activation after tunnels users have been evacuated

A common approach have been to activate as soon as possible for tunnels with longitudinal ventilation, compared to activation after tunnel users have been evacuated for tunnels with transversal ventilation. Some argue however suppression should always be activated as soon as possibly safe.

10.1.1 Fire detection and suppression activation

In order to make it possible to look into potential trade-offs when using suppression FFFS in tunnels, it is crucial to make sure that the detection and activation of the FFFS is reliable and effective. To be conservative the analysis will focus on large and fast growing fires. Therefore the fire may be considered to be detected within 2 - 3 minutes (Vasilovska 2006, Beard and Carvel 2005).

The strategy in activation adopted in Japan is interesting, since it to some extent take into account the time to alert tunnel users and evacuation conditions. Therefore 3 minutes activation for uni-directional tunnels, which may imply longitudinal ventilation, will be considered. 10 minutes activation time for bi-directional tunnels, which may imply transverse ventilation, require tests with transverse ventilation which is not the case for this analysis. However 10 minutes allowed as additional pre-burning time may be quite a long time for some fires, resulting i very high HRR's.

10.1.2 Fire growth

Fire growth in tunnel environment is not only affected by the type of fuel that is burning but is strongly affected by the ventilation conditions i.e. the amount of oxygen provided. There is useful work carried out in this field by Ricky Carvel (Carvel March 2008) where he summaries available tunnel tests with various ventilation conditions for comparison. This approach identifying a design fire based on fire limited by a suppression system only applies for longitudinal ventilation.

Figure 9 show a two step approximation of the fire growth, resulting from the tunnel fire tests in Benelux and Runehammar. The findings from Carvel presented a simplistic approach, adopting the two-step approximation of the fire growth and HRRs. The two-step linear curve approach where found a more adequate representation than the modeled t^2 fire curve.

Some of the conclusions made where that there was an apparent relationship between the rate of growth of a solid fuel fire in a tunnel and the tunnel ventilation velocity. The velocity of 3 m/s was considered the possible 'worst case' leading to the fastest fire growth. Evidently higher or lower ventilation velocities than 3 m/s may result a decreased fire growth.

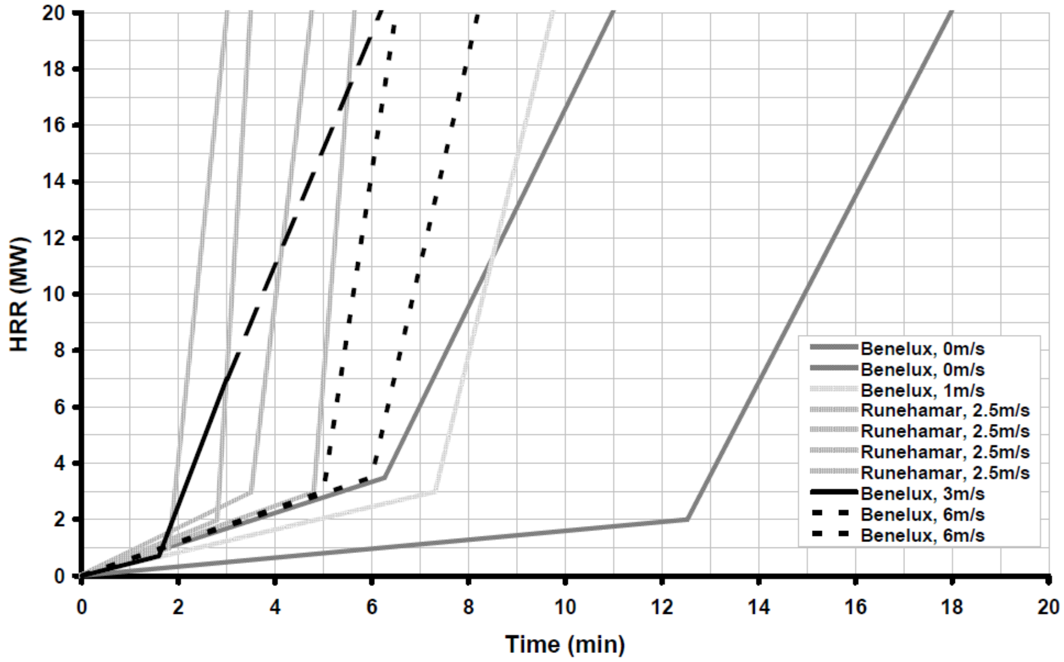

Figure 9 - Two-step approximation of the HRR data from the 2nd Benelux Tunnel fire test series and the Runehammar fire tests (Carvel March 2008)

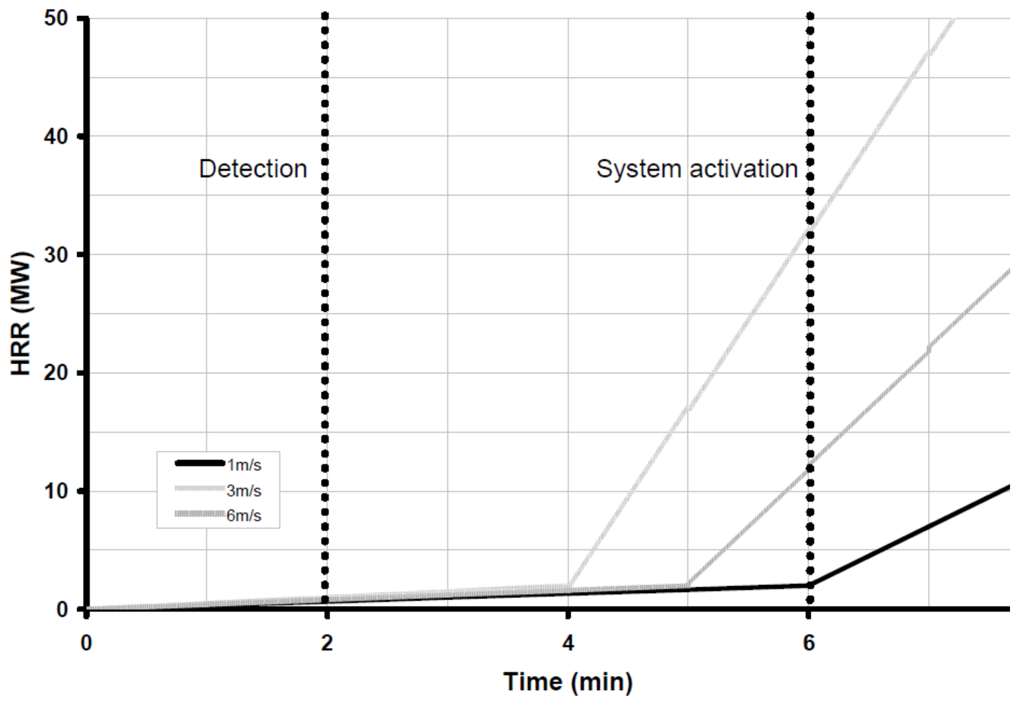

Figure 10 - Example design fire scenarios (Carvel March 2008)

The generalisation is based on an assumed detection time of 2 minutes followed by a system activation time (suppression) of 6 minutes. The uncertainties and complications with the assumption on detection is discussed further in chapter 10.1.1. Carvel describes the three example scenarios shown in Figure 10 in more detail as:

1. low unchanged ventilation leading to a delay phase of about six minutes – followed by a low growth phase of 5 MW/min
2. a **3m/s** unchanged traffic induced airflow leading to a delay phase of only 3 minutes followed by a high growth phase of **15 MW/min**
3. quickly activated emergency ventilation of 6m/s leading to an extended delay phase of 5 minutes followed by growth rate of 10 MW/min.

It should be noted, these are approximations and only rely upon a few tests. Therefore further research in this field is needed to confirm these findings.

10.2 Findings

The worst case is the 3 m/s velocity which would be the most common scenario in a normal tunnel. This corresponds to activation of the suppression system at the time of the fire being 30 MW. If a ventilation system where activated very rapidly then the growth rate might be lower than the expected 15 MW/min, on the basis that the velocity would be noticeable larger than 3 m/s. Lets proceed on the basis of a 15 MW/min growing fire. One important factor, except for the time of detection, is the time lag between detection and activation of the suppression system. By adopting a detection time of 2 minutes and a time lag of 4 minutes for activation of the suppression, this will result in a 35 MW fire. If for some reason, the detection time or the time lag would be longer than anticipated; this might result in a significantly larger fire growing with 15 MW/min. Potentially resulting in a fire size that might make the suppression ineffective.

10.3 Discussion

There is an uncertainty and difference in strategy for when to activate an FFFS depending on type of ventilations systems. An common approach have been to activate as soon as possible for tunnels with longitudinal ventilation, compared to activation after tunnel users have been evacuated for tunnels with transversal ventilation. The trend in Australia is, as mentioned in chapter 8, pointing towards activation as soon as possible independent on type of ventilation system. Australia use deluge sprinkler systems and the question is would the strategy of activation time look different if they were dealing with water mist systems? Mist systems contributing to less visibility than deluge sprinkler systems.

Based on resent research FFFS's may be capable of suppressing fires in the magnitude of up to 35MW. But what happens if a fire grows larger? For the purpose of adopting potential trade-offs reliability of detection, suppression as well as operating systems must be acceptable. Further a safety margin may be in place since fires may grow to be as large as 35MW for a scenario where everything is working perfectly. For instance if a safety margin of one minute each for detection and activation would lead to a final pre-burning time of 8 minutes, resulting in a possible HRR of approximately 60MW. In a design allowing for trade-offs, a safety margin similar to this seems reasonable. But would a suppression system be satisfactory on a 60 MW fire? It may be that the search for 'the point of no return' starts here?

The same design fire analysis should be carried out for a similar scenario considering transverse systems using for example an activation time of 10 minutes. However there is limited data on the ventilation affect on HRR under the influence of transverse ventilation. Further since there are several different applications of transverse systems this should be assessed specifically for every unique configuration.

In lack of information on the influence of transverse ventilation regarding fire growth, it is possible for guidance to assume that fire growth will be affected in a similar matter as for longitudinal ventilation. Based on this assumption and the conservative fire growth of 15 MW/min concluded by Carvel, a potential HRR of hypothetically 95 MW could be reached before activation of suppression. This requires information on if we are at the 'point of no return' or even beyond it? One should keep in mind that the 'point of no return' should be associated not only with the sufficiency of the suppression system but also if the ventilation capacity is high enough and if safe egress is and fire brigade intervention possible. Hence the answer is dependent on multiple parameters, type of fuel, design of the specific suppression system and ventilation capacity being the top three.

Design fires and peak HRR, associated with mist and deluge systems described above, is based on tests and research for longitudinal ventilation. There is a possibility that the outcome could vary for other types of ventilation. How big the difference would be is not possible to evaluate at this point. However more research is clearly needed for both longitudinal as well as for other types of ventilation configurations, to support the findings above.

Previously the main aim for research on the effectiveness of suppression systems in road tunnels has been the objectives from the manufacturer of the systems. I.e. the aim has been to show how effective their specific suppression system can be, without pushing the limits. There may be that 'the point of no return' has probably not been a financially suitable way to carry out their testing. 'The point of no return' should be subject to further investigated in an attempt of to give guidance of what maximum HHR are to be used for future testing of FFFS's. This to give guidance for research enabling new performance requirements for systems working together in a tunnel design, allowing smarter solutions with the potential of trade-offs. This is research that may contribute to safer tunnels, major cost savings for tunnel developers as well as new innovative designs.

There are parameters in technical designs in need more research. For instance ventilation systems (both longitudinal and transverse) way work in totally different matter with both high and low sufficiency depending on design parameters as ventilation strategy, capacity, type of nozzles used etc. Therefore set minimum performance requirements should be researched and used to allow for potential trade-offs. Further suppression systems should also have a set minimum performance requirements for suppressing a minimum design fire during certain ventilation conditions. Without such performance requirements the possibility of trade-offs comes with too many uncertainties to be acceptable in general design.

11. Potential trade-offs

Identified potential trade-offs are presented and explain.

As mentioned earlier there are still a need for more extensive research of FFFS's in road tunnels and this report will form a part of the work towards optimising the use of FFFS's in road tunnels considering fire safety in general, asset protection and business continuity as well as direct design and construction costs. By the identified benefits of FFFS's, potential trade-offs associated and further research to be considered in the future may be pin-pointed.

Trade-offs are generally not incorporated in the same manner in tunnel design codes and guidance document as for general building design. Design solutions for tunnels are done with a fire engineering approach often based on risk assessments. The risk based approach should be considered even for potential trade-offs in the design process, if chosen. Suggested trade-offs considered for tunnel design, incorporating suppression systems, are presented below. To identify benefits and concerns associated with them, the most promising trade-offs have further been selected and investigated in a qualitative risk analysis. Different tunnel configurations and ventilation systems may have an impact on suitable trade-offs (if suitable at all).

Suggested potential trade-offs are:

1. **Ventilation**: Lower design fire size and therefore less ventilation required than for solutions with no suppression. It has been concluded (Carvel R.) that the critical velocity for back-layering around 3m/s is in fact the velocity that results in the highest growth rate. It could be argued if early detection is provided, that potentially both back layering and fire growth, may be limited to an acceptable level, by combining ventilation (~3m/s) in conjunction with a suppression system. Since FFFS's would limit the fire growth, the potential increase in fire growth, due to ventilation may be less a concern, but should be accounted for in the growth phase until activation. This is relying on early detection and suitable time for activation of FFFS. The detection process and reliability of suppression system will have to be considered.
2. **Evacuation benefits:** Potential extended distances between exits way be argued for some cases due to lower levels of radiation, temperature and smoke production derived from a limited HRR. However visibility has to be considered and evaluated separately on a case by case basis.
3. **Passive fire protection:** Lower temperatures may be expected which could lead to a lower peak of the TT-curve used in the design of construction? The growth phase is still crucial and should be carefully evaluated since this will affect the expected design fire curve and further potentially also TT-curve. Alternatively there is a possibility to use an already existing but less severe TT-curve.

   The solution pp-fibres to concrete and cover to reinforcement could be assessed to expected temperatures of a limited TT-curve with a suppression system. –The applicability of 'new TT-curves' taking into account FFFS's should be investigated and further research. If such new TT-curves were to be used, caution has to be taken for passive fire protection with for example a set minimum. This to enable the tunnel structure to withstand a fire even though the suppression system would not activate or have extensively delayed activation. Here the potential of collapse (if failure of suppression system) will have to be considered an eliminated for tunnel constructions in locations where this would lead to a disaster with unacceptable consequences. Further thermal cladding and panelling may be reduced using the same concept in fire resistance requirement i.e. thickness.

4. Potentially changed criteria's of dangerous goods restrictions for specific tunnels? This specific topic does not form part of the scope of this report and will not undergo deeper investigation.

The mentioned trade-offs could result in cost savings which should be analysed separately on a project by project bases. Further improved conditions for self rescue and fire fighting personnel may be expected with the use of FFFS in tunnels. Trade-offs presented above will be depending on the reliability of the FFFS and therefore the maintenance and installation. It may be associated with higher requirements for reliability of detection and FFFS systems installed.

11.1 Discussion

As mentioned earlier the design fire size commonly used for tunnel ventilation, where HGV's are allowed, has been in the range of 30-50 MW. Based on resent research the fire size may however be much larger. It has been concluded that a design fire size of >70 – 200 MW would be more suitable. However it can be argued that a design fire size may be reduced with early activation of a suppression system to 30-50 MW. If the design fire sizes are higher than previously anticipated the potential of using trade-offs based on reduction in design fire size may become even more interesting than before. Figure 11 shows the logics behind the use of trade-off, associated with reduced design fire size, with the trade-off concept introduced in chapter 1.3.

1 and 2 shows the change in safety level after new findings in design fire with higher HRR. 3 and 4 shows an attempt on how to use trade-offs in both new and existing tunnels.

- New tunnel design involving trade-offs would go from a lower safety level of 2 through 3 to 4 with trade-offs.
- Existing tunnels way go from 2 to 3 by installing suppression solely to reach an acceptable safety level, using the concept of trade-off in a reversed manner (shown in red pattern in the figure).

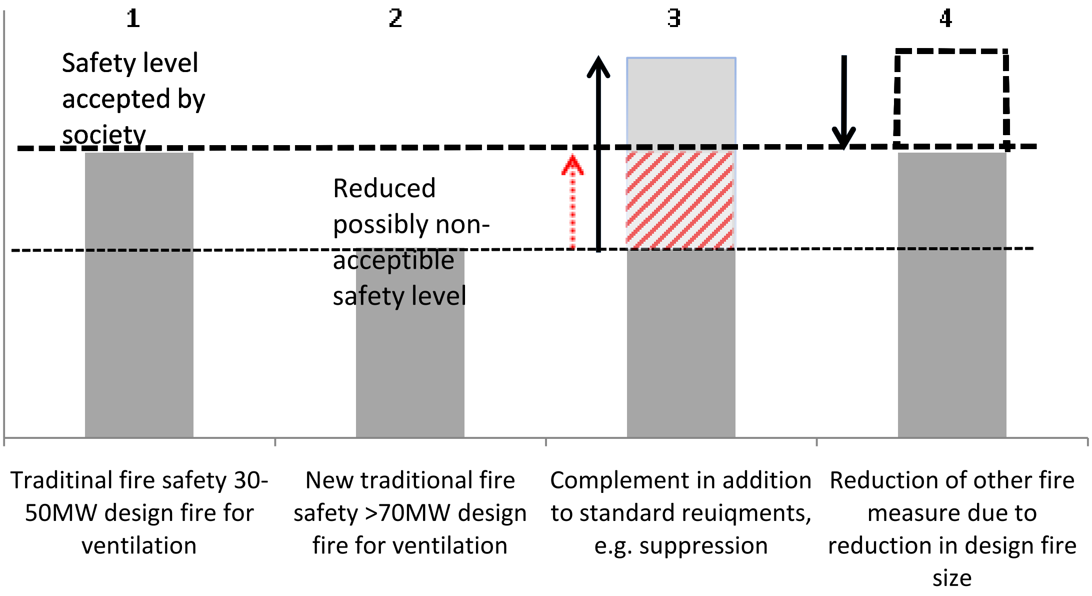

Figure 11 - Logics behind the use of trade-offs associated with reduced design fire size

Hence exciting tunnels may need to install suppression as an additional measure to reach an acceptable level of safety whereas new tunnel design may safe in other fire protection measures if incorporating suppression into the design.

Since the aim with Figure 11 is to explain the concept in safety level and trade-offs associated, with reduced design fire size, the concept may be applied in countries that regularly use FFFS in tunnel design as well as in other countries where it is not so common. No certain safety level is quantified but solely the feature of adding to or reducing the safety level.

Enabling evaluation of the identified potential trade-offs, it has been crucial to find out the approximate allowed pre-burning time for the suppression system, to limit the fire. I.e. the suitable activation time had to be identified. The expected fire load and type of fuel expected in tunnels was also investigated and the likely fire curves and activation time gave the possibility of an expected HRR. Design fires identified and suggested in this report may be suitable for use when considering potential trade-offs such as reduction in ventilation capacity, and evacuation benefits. There is still extensive research and testing required to support the findings and suggestions presented here.

The time requirement for passive fire protection, normally between 2-4h depending on performance requirement and location, should probably be the same as required for a tunnel without FFFS. Potentially designed to a less severe TT-curve? Making the trade-off related to temperature limitation, rather than a time limitation, is due to the possibility of covered fuels and the fact that a suppression system is only expected to limit the fire by suppressing it, rather than extinguish it. I.e. temperatures may be assumed to be decreased by the effects of a suppression system; however the duration is not necessarily affected. Local effects on the tunnel lining in the vicinity of a fire incident, needs to be considered. There might actually not be a big difference between 30, 50, 80MW fire in local damage, no doubt there will be a difference in temperature and damage along the tunnel, but the local damage may not vary too much. If FFFS is activated in time, there may be major benefits for the passive fire protection in general, local damage in the vicinity of the fire may be harder to prevent. In terms of possible reduction in fire resistance (trade-off), local damage may only be acceptable for certain tunnel constructions, but not to others.

12. Qualitative Risk Assessment – trade–offs

This chapter identifies the adopted and customised risk approach to select potential trade-offs for future tunnel design.

An event tree based methodology has been chosen. Rather than solely looking into a specific scenario, the general possible scenarios associated with the identified trade-offs, are presented in an event tree. This type of methodology is suitable for when a fire is to lead to a model, since several different scenarios are possible. The identification of scenarios is crucial to evaluate possible outcomes and consequences. Due to the nature of the event tree, being based on decisions and discussion rather than chance or probability, it will result in a qualitative assessment integrating best practice and judgement of the profession. An overview of factors involved and their dependability has been developed, working as guidance in discussions forming the qualitative assessment.

Quantitative risk analysis incorporating uncertainties, for example in technical systems, may be accounted for in a later stage for the specific trade-off chosen. These would be project specific and are therefore not further assessed here. Usually uncertainties of consequences are preferred not to be considered since they would make the analysis quite complex. Uncertainties and frequencies in the design factors considered are not known at this stage hence not assessed. Choosing an event tree methodology allows for dealing with more specific consequences, when all data are to be dealt with at a later stage. If a simple scenario analysis is used, the more detailed analysis including uncertainties, would be more difficult to identify and account for. Also a scenario analysis would solely cover a single chosen scenario and not the general conceptual design matters which are of interest.

Major safety objectives such as egress, tenability and structural fire safety, should be considered separately (Lundin, Delin and Johansson 2002). These objectives have been considered, as seen in Table 5, where tenability and structural fire safety are pin-pointed and egress strategies integrated with specific ventilation and traffic conditions. Further a third objective has been considered, where possible, fire brigade intervention.

This qualitative risk based approach, have been chosen to cover the majority of all outcomes, arising from the different trade-offs introduced in various kinds of tunnel designs.

12.1 Event tree analysis

For easy mapping and identification of scenarios an event tree analysis has been chosen. Safety objectives considered, as mentioned previously, are:

1. Tenability
2. Limit damage to tunnel structure and surroundings
3. Fire brigade intervention

Each safety objective has been considered separately, presented in the index Table 5, for evaluation of the different trade-offs suitable or not for various tunnel designs.

Egress is considered in fixed scenarios depending on ventilation and traffic conditions, as summarised:

- Longitudinal ventilation allowing for uni-directional traffic only and no queuing.
- Longitudinal ventilation allowing for bi-directional traffic or uni-directional traffic with queuing.

- Transverse or reversible semi-transverse ventilation with uni-directional traffic and no queuing.
- Transverse or reversible semi-transverse ventilation with bi-directional traffic or uni-directional traffic with queuing.

The strategy used in Japan, have to some extent been adopted, where activation of suppression will occur as quickly as possible for tunnels with uni-directional traffic, whereas activation of suppression in bi-directional traffic conditions will occur after evacuation of tunnel users. Potential queuing in uni-directional tunnels are considered if possible.

However one should consider the fact that a fire may grow to be too large for the suppression system installed to operate in the manner it is supposed to. Therefore activation may still have to be done before all tunnel users have been evacuated. It is possible that activation as soon as possible may be required for transverse ventilation as well.

An attempt to overview factors involved and their dependability are presented in Figure 12. Used as guidance in the discussions of the different scenarios to engage all factors present.

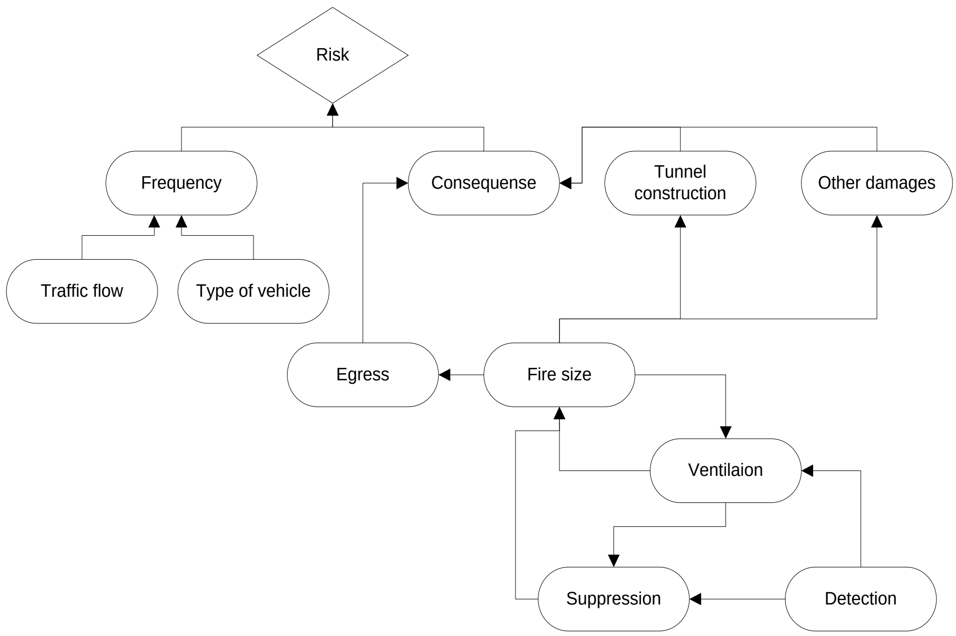

Figure 12 - Overview of factors involved and their dependability

An event tree presenting the identified scenarios, which have been used to evaluate possible trade-offs, is shown in Figure 13.

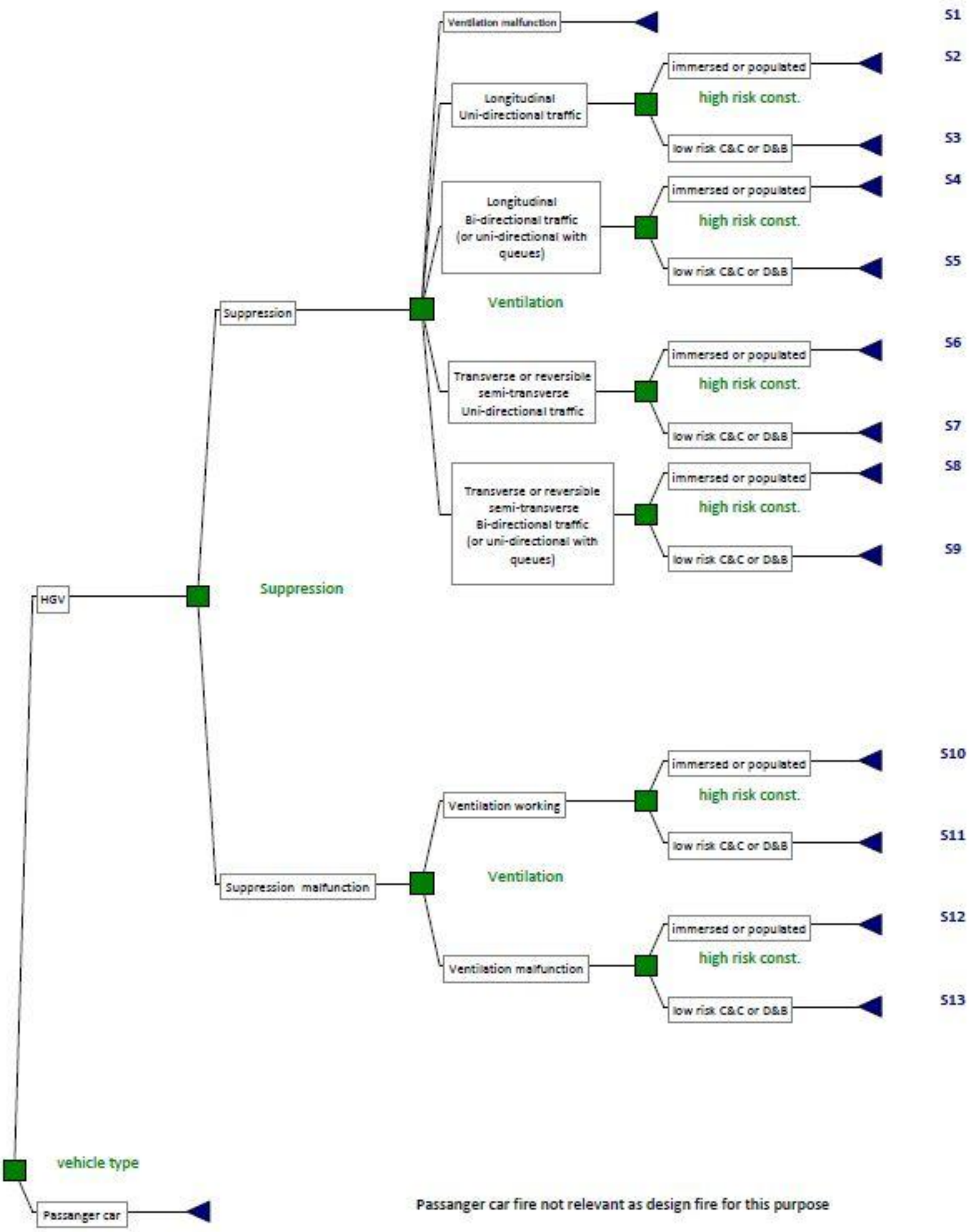

Figure 13 - Event tree presenting the identified scenarios used to evaluate possible trade-offs

Identified configurations (S1-S12) have been separately evaluated for each safety objective in Table 5.

Configurations S1 and S10-S13 in the event tree have been simplified and not evaluated for different ventilations and traffic conditions. S1, S12 and S13 is not dependent on type of ventilation system since they cover ventilation malfunctioning and will have the same affect on any traffic condition. S10 and S11 will result in similar matter for different types of ventilations systems and traffic conditions and all different configurations hare therefore not represented.

Table 5 – Outcomes and evaluation of identified configurations - cells marked in grey are not considered acceptable

(Not acceptable findings marked in grey)

Scenario	Conditions	Trade-off	Life safety	Limit damage to tunnel structure and surroundings	Fire brigade intervention	Possible trade-off?
S1	*HGV* *Suppression* *Ventilation malfunction*	*Ventilation reduction*	N/A	N/A	N/A	N/A
		Reduction in structural fire protection	Conditions are more beneficial than if no suppression was installed	Conditions are more beneficial than if no suppression was installed	Improved conditions for fire brigade intervention compared to if no suppression was installed	Yes
		Evacuation benefits	Conditions are more beneficial than if no suppression was installed	Conditions are more beneficial than if no suppression was installed	Improved conditions for fire brigade intervention compared to if no suppression was installed	Yes
S2	*HGV* *Suppression* *Longitudinal vent.* *Uni-directional traffic* *Immersed or populated*	*Ventilation reduction*	With early activation allowing for reduced ventilation, life safety of tunnel users may be significantly improved	Improved conditions and limited damage to tunnel structure expected	Improved conditions for fire brigade intervention	Yes (Based on no queuing)
		Reduction in structural fire protection	-	-	-	No See S9
		Evacuation benefits	Possibility for evacuation benefits, since no queuing is assumed and improved tenability is expected	N/A	N/A	Yes
S3	*HGV* *Suppression*	*Ventilation reduction*	With early activation allowing for reduced ventilation, life safety of tunnel users may be significantly improved	Improved conditions and limited damage to tunnel structure expected	Improved conditions for fire brigade intervention	Yes (Based on no queuing)

Scenario	Conditions	Trade-off	Life safety	Limit damage to tunnel structure and surroundings	Fire brigade intervention	Possible trade-off?
	Longitudinal vent. *Uni-directional traffic* *CC with no populated area above or DB*	*Reduction in structural fire protection*	Life safety or tunnel users will not be effected	Improved conditions and limited damage to tunnel structure expected	Improved conditions for fire brigade intervention	Yes
		Evacuation benefits	Possibility for evacuation benefits, since no queuing is assumed and improved tenability is expected	N/A	N/A	Yes
S4	*HGV* *Suppression* *Longitudinal vent.* *Bi-directional traffic (or uni-+queue)* *Immersed or populated*	*Ventilation reduction*	Not a preferred configuration, but suppression will contribute to improved tenability assuming early activation	Improved conditions and limited damage to tunnel structure expected	Improved conditions for fire brigade intervention	Yes, Even though bi-directional traffic in longitudinal ventilation conditions is not a preferred configuration
		Reduction in structural fire protection	-	-	-	No See S9
		Evacuation benefits	Tenability will be improved, but not to such a degree to allow for evacuation benefits	N/A	N/A	No
S5	*HGV* *Suppression* *Longitudinal vent.* *Bi-directional traffic (or uni-+queue)*	*Ventilation reduction*	Not a preferred configuration, but suppression will contribute to improved tenability assuming early activation	Improved conditions and limited damage to tunnel structure expected	Improved conditions for fire brigade intervention	Yes, Even though bi-directional traffic in longitudinal ventilation conditions is not a preferred configuration

Scenario	Conditions	Trade-off	Life safety	Limit damage to tunnel structure and surroundings	Fire brigade intervention	Possible trade-off?
	CC with no populated area above or DB	*Reduction in structural fire protection*	Life safety or tunnel users will not be effected	Improved conditions and limited damage to tunnel structure expected	Improved conditions for fire brigade intervention	Yes
		Evacuation benefits	Tenability will be improved, but not to such a degree to allow for evacuation benefits	N/A	N/A	No
S6	*HGV* *Suppression* *Transverse or reversible semi-transverse* *Uni-directional traffic* *Immersed or populated*	*Ventilation reduction*	With early activation allowing for reduced ventilation, life safety of tunnel users may be significantly improved	Improved conditions and limited damage to tunnel structure expected	Improved conditions for fire brigade intervention	Yes (Based on no queuing)
		Reduction in structural fire protection	-	-	-	No See S9
		Evacuation benefits	Possibility for evacuation benefits, since no queuing is assumed and improved tenability is expected	N/A	N/A	Yes (Based on no queuing)
S7	*HGV* *Suppression* *Transverse or reversible semi-transverse* *Uni-directional traffic* *CC with no populated area above or DB*	*Ventilation reduction*	With early activation allowing for reduced ventilation, life safety of tunnel users may be significantly improved	Improved conditions and limited damage to tunnel structure expected	Improved conditions for fire brigade intervention	Yes (Based on no queuing)
		Reduction in structural fire protection	Life safety or tunnel users will not be effected	Improved conditions and limited damage to tunnel structure expected	Improved conditions for fire brigade intervention	Yes
		Evacuation benefits	Possibility for evacuation benefits, since no queuing is assumed and improved tenability is expected	N/A	N/A	Yes (Based on no queuing)

Scenario	**Conditions**	**Trade-off**	**Life safety**	**Limit damage to tunnel structure and surroundings**	**Fire brigade intervention**	**Possible trade-off?**
S8	*HGV* *Suppression* *Transverse or reversible semi-transverse* *Bi-directional traffic (or uni-directional with queue)* *Immersed or populated*	*Ventilation reduction*	Since activation is assumed to occur after evacuation a ventilation reduction could affect life safety negatively	Since activation is assumed to occur after evacuation, a ventilation reduction may initially result in elevated temperatures compared to a 'normal' ventilation design. However limited after activation assuming 'point of no return' has not occurred	Limited negative effect on intervention assumed as long as 'point of no return' has not occurred before activation	No Possible yes with need for further investigations regarding: 1.) the possibility of activation as soon as possible in lieu of after evacuation 2.) time to 'point of no return'
		Reduction in structural fire protection	Is not assumed to affect life safety negatively	Since activation is assumed to occur after evacuation, initial elevated temperatures may occur however only for a short period of time. Catastrophic consequences if suppression malfunctioning or 'point of no return' is passed	Limited negative effect on intervention assumed as long as 'point of no return' has not occurred before activation. However possibly catastrophic consequences if suppression malfunctioning or 'point of no return' is passed	No
		Evacuation benefits	Since activation is assumed after evacuation any evacuation benefits would decrease life safety level	N/A	N/A	No

Scenario	Conditions	Trade-off	Life safety	Limit damage to tunnel structure and surroundings	Fire brigade intervention	Possible trade-off?
*S9 **	*HGV* *Suppression* *Transverse or reversible semi-transverse* *Bi-directional traffic (or uni-directional with queue)* *CC with no populated area above or DB*	*Ventilation reduction*	Since activation is assumed to occur after evacuation a ventilation reduction could affect life safety negatively	Since activation is assumed to occur after evacuation a ventilation reduction may initially result in elevated temperatures compared to a 'normal' ventilation design. However limited after activation assuming 'point of no return' has not occurred	Limited negative effect on intervention assumed as long as 'point of no return' has not occurred before activation	No Possible yes with need for further investigations regarding: 1.) the possibility of activation as soon as possible in lieu of after evacuation 2.) time to 'point of no return'
		Reduction in structural fire protection	Is not assumed to affect life safety negatively	Since activation is assumed to occur after evacuation, initial elevated temperatures may occur however only for a short period of time. Catastrophic consequences is not assumed to occur due to suppression malfunctioning or if 'point of no return' is passed	Limited negative effect on intervention assumed as long as 'point of no return' has not occurred before activation	Yes
		Evacuation benefits	Since activation is assumed after evacuation any evacuation benefits would decrease life safety level	N/A	N/A	No
*S10 **	*HGV* *Suppression malfunction* *Ventilation Working*	*Ventilation reduction*	Life safety jeopardized, however reduced means of ventilation still available	Possibly elevated temperatures and higher degree of damage to tunnel structure, however reduced means of ventilation still available. Assuming 'normal' structural integrity in place.	Intervention jeopardized to some extent, however reduced means of ventilation still available	Yes - If high level of reliability and redundancy of all active systems

Scenario	Conditions	Trade-off	Life safety	Limit damage to tunnel structure and surroundings	Fire brigade intervention	Possible trade-off?
	Immersed or populated	*Reduction in structural fire protection*	Not effecting life safety	Possible elevated temperature and extensive damage to tunnel structure or even collapse, in case of large fire	Intervention may be jeopardized due to spalling or structural collapse	No
		Evacuation benefits	Life safety jeopardized, however reduced means of ventilation still available	*N/A*	*N/A*	Yes - If high level of reliability and redundancy of all active systems
*S11 **	*HGV* *Suppression malfunction* *Ventilation Working* *CC with no populated area above or DB*	*Ventilation reduction*	Life safety jeopardized, however reduced means of ventilation still available	Possibly elevated temperatures and higher degree of damage to tunnel structure, however reduced means of ventilation still available	Intervention jeopardized to some extent, however reduced means of ventilation still available	Yes - If high level of reliability and redundancy of all active systems
		Reduction in structural fire protection	Not effecting life safety	Possible elevated temperature and damage to tunnel structure in case of large fire	Intervention may be jeopardized due to spalling	Yes - If hard rock conditions and/or CC construction with no populated area above
		Evacuation benefits	Life safety jeopardized, however reduced means of ventilation still available	*N/A*	*N/A*	Yes - If high level of reliability and redundancy of all active systems
*S12 **	*HGV* *Suppression working* *Ventilation*	*Ventilation reduction*	Life safety jeopardized, however improved conditions compared to the case of no suppression installed	Improved conditions compared to a ventilation malfunctioning with no suppression installed	Improved conditions compared to a ventilation malfunctioning with no suppression installed	Yes

Scenario	Conditions	Trade-off	Life safety	Limit damage to tunnel structure and surroundings	Fire brigade intervention	Possible trade-off?
	malfunctioning *Immersed or populated*	*Reduction in structural fire protection*	Not effecting life safety	Improved conditions compared to a ventilation malfunctioning with no suppression installed	Improved conditions compared to a ventilation malfunctioning with no suppression installed	yes
		Evacuation benefits	*N/A*	*N/A*	*N/A*	*N/A*
*S13 **	*HGV* *Suppression working* *Ventilation malfunctioning* *CC with no populated area above or DB*	*Ventilation reduction*	Life safety jeopardized, however improved conditions compared to the case of no mist installed	Improved conditions compared to a ventilation malfunctioning with no suppression installed	Improved conditions compared to a ventilation malfunctioning with no suppression installed	Yes
		Reduction in structural fire protection	Not effecting life safety	Improved conditions compared to a ventilation malfunctioning with no suppression installed	Improved conditions compared to a ventilation malfunctioning with no suppression installed	yes
		Evacuation benefits	*N/A*	*N/A*	*N/A*	*N/A*

*Assuming redundancy in design where, if a system failure occurs, only one system is malfunctioning. Either ventilation or suppression.

12.2 Discussion

It is not just only foreseen and calculated factors that may malfunction put furthermore unreasonable and irrational behaviour of tunnel users. Therefore one may argue that suppression systems should always be considered as a primary option in tunnel design. As additional benefit suppression systems offer the opportunity of potential trade-offs, opening a window of opportunity for more aggressive cost-benefit solutions.

The optimal branches above with uni-directional traffic with no queuing may not be a probable design for most tunnels designs. Therefore it may not be suitable with bi-directional traffic in tunnels with longitudinal ventilation without undertake further measures to deal with possible queuing. Further for tunnels with transverse ventilation in it is crucial to determine an activation time of suppression that is long enough to allow for kept stratification during evacuation as well as short enough to allow for activation before ‘point of no return’. The maximum time of 10 minutes used in Japan may not be the a suitable time, instead activation time may have to be shorter!? It is even possible that activation as soon as possible for all configurations of traffic and ventilation conditions is the best option.

A possible solution may be pseudo transverse ventilation systems where the area close to the fire extract and other areas supply to create a minimal zone around the fire smoke can be expected keeping the rest of the tunnel smoke free. This strategy would allow for early activation with minimal mixing and visibility issues i.e. independent of activation time of tunnel users.

Generally tunnel engineers may have to consider different strategies in activation time for deluge sprinkler systems compared to mist systems since mist tend to reduce visibility more than sprinkler systems.

12.2.1 Hidden risks - Arson, terrorism or sabotage

It is important that potential trade-offs does not offer an elevated opportunity for arson, terrorism or sabotage. For instance a trade-off is not to majority jeopardize the safety of tunnel users or the tunnel structure in case of a suppression failure. Here it is tempting only to see the probability for system failure assumed relatively low and use that solely for design purpose. Since it is common practice not to design fire safety for the event of arson or terrorism due to unrealistic cost, it is important to have this aspect in mind when developing a model for using trade-offs in tunnel design with suppression systems as a base. This may be done by using clear management procedures for security and safety purposes. For instance good practice would be for suppression systems not to be accessible from the public domain, to prevent arson. Complement with elevated of security classifications may be a possibly solution.

13. Design issues and Cost- Benefit

This chapter presents an interesting conceptual Cost-Benefit analysis carried out considering suppression in tunnels.

Incorporating suppression systems into tunnel design may be associated with the opportunity in cost savings. The benefits are not only in life safety and egress facilities, fire fighting, reduction in tunnel lining and/or ventilation but also in asset damage and operational continuity. A preliminary cost-benefit analysis considering asset protection and operational continuity carried out on a hypothetical typical tunnel with zoned deluge spray system installed in Australia (Johnson, Jönsson, et al. 2009), show an estimated total loss per year of AUD $16.5 million, compared to AUD $65 million for the same tunnel without suppression. The analysis was based on expected yearly frequencies of the fire types; car (6.11), truck-small (2.45), truck-damage to tunnel (0.31), truck-damage to structure(0.061), deluge system cost of AUD 25M and yearly maintenance cost of AUD $3 million as well as a 10% failure rate of the suppression system assumed.

Johnson and Jönsson further outlines the following design issues to be considered for design of ventilation and smoke control in the event of fire (considerations that form the base for a Cost-Benefit analysis):

- What is the length of the tunnel, the traffic flows, vehicle mix and traffic management arrangements?
- What type of ventilation is being provided for normal traffic operations, including for congested and stopped traffic?
- What are the tunnel grades, location of portals, and merging tunnels for entry and exit?
- To what peak fire size must the smoke control system be designed?
- What egress arrangements are provided in the tunnel, including exits and cross passages, and what are the tenability acceptance criteria?
- Is a suppression system to be provided?
- Will there be full-time skilled tunnel operators to manually activate suppression and ventilation systems?

The preliminary Cost-Benefit analysis conceptually showed the advantage of deluge system installation for asset damage and operational continuity. Also significant benefit was seen in the opportunity to reduce ventilation requirements as well as tunnel lining provisions.

13.1 Discussion

It seems as if the pay-off time for initial investments in a suppression system is less than a year. With an approximate pay-off time this short for solely considering asset damage and operational continuity, the potential trade-offs for reducing ventilation requirements as well as tunnel lining provisions must be of outmost interest of the tunnelling industry.

14. Conclusion

These final conclusions comprise conditions and performance equipments for identified trade-offs as well as the acceptable potential trade-offs identified resulting from the qualitative risk assessment, carried out in chapter 12.

A basic condition to allow for potential trade-offs, when incorporating suppression in tunnel design, is a high level of reliability and redundancy of both detection and suppression systems. This is not only dependent on the type of system and the installation but also reliable operational management.

A tunnel should to an acceptable extent withstand the credible fire scenarios chosen, without disastrous outcomes, if suppression system fails. Adopting trade-offs in areas of lower risks at first hand and be more cautious within areas of the design/construction that are associated with an elevated risk, is recommended.

The means of trade-offs is applicable to both new and existing tunnels. Existing tunnels may need to install suppression as an additional measure to reach an acceptable level of safety whereas new tunnel design may save in other fire protection by measures if incorporating suppression into the design.

14.1 Conditions and performance requirements – trade-offs

Conditions and performance requirements to form a base for safe tunnels in general as well as a base for potential trade-offs have been considered. Based on the authors view from the material used in this thesis the following conditions and performance requirement has been identified.

- Longitudinal ventilation is most suited for unidirectional traffic.
- Longitudinal ventilation is possibly the configuration most suitable for trade-offs except for state of the art pseudo transverse systems.
- It is crucial with early detection and warning signs and alarm, clearly telling drivers that there is a fire in the tunnel making them turn or park their car and use the planned escape route.
- Fire brigade intervention needs to be carefully considered in the tunnel design to incorporate where and when intervention may be possible and under what circumstances. Intervention should be evaluated in conjunction with design fire scenarios. When automatic detection and FFFS are used, alerting the fire brigade with established routines for the tunnel in question is vital.
- A short activation time of suppression is important to be able to limit a fire as much as possible and to avoid the scenario when ‘the point of no return’ is reached. However it’s important to avoid secondary collisions caused by low visibility in the smoke when the smoke layer and by water droplets mix. Therefore it should always be possible to evaluate the traffic condition after an before activating a suppression system. Bearing in mind that the shorter activation time the better. Activation time may be set at a fixed time with the possibility of an operator overriding it if a delayed activation is necessary.

  Generally tunnel engineers may have to consider different strategies in activation time for deluge sprinkler systems compared to mist systems since mist tend to reduce visibility to a larger degree than sprinkler systems.
- As discussed previously an important issue is the reliability of FFFS. If FFFS is associated with certain trade-offs this may be subject to even higher requirements on maintenance and installation, as well as at system itself, in order to assure an acceptable level of reliability. This should be accounted for in

a risk analysis for the specific tunnel project in question. Trade-offs will be dependent on the reliability of the FFFS. It may be associated with higher requirements for reliability of detection and FFFS systems installed compared to a design with no trade-offs.

- A safety margin can be in place of designs allowing trade-offs. For instance one minute each for detection and activation. This could lead to HRR of approximately 60 MW instead of 35 MW fire. In a design allowing for trade-offs, a safety margin similar to this seems reasonable.
- More extensive research is needed on whether suppression systems work satisfactory on fires larger than 30MW. Possibly tests should focus on HRR's that are allowed to grow to the magnitude of 40-70 MW prior to activation of suppression? To investigate 'the point of no return'.
- Clear management procedures for security and safety purposes are even more important when considering trade-offs subject to suppression systems. For instance good practice would be for the suppression system not to be accessible from the public domain, to prevent arson.
- There are parameters in technical designs in need more research. For instance ventilation systems (both longitudinal and transverse) way work in totally different matter with both high and low sufficiency depending on design parameters as ventilation strategy, capacity, type of nozzles used etc. Therefore set minimum performance requirements should be researched and used to allow for potential trade-offs. Further suppression systems should also have a set minimum performance requirements for suppressing a minimum design fire during certain ventilation conditions. Without such performance requirements the possibility of trade-offs is associated with too many uncertainties to be acceptable in general design.

14.2 Acceptable potential trade-offs identified

Potential trade-offs that have been identified and considered acceptable, summarised from qualitative risk assessment carried out in chapter 12, outlined below:

1. Ventilation reduction may be acceptable for the following tunnel configurations:
    a. Longitudinal ventilation with uni-directional (with no queuing) traffic for both high and low risk tunnel construction.
    b. Longitudinal ventilation with bi-directional traffic (or uni-directional traffic with queuing) for both high and low risk tunnel construction. Even though bi-directional traffic in longitudinal ventilation conditions is not a preferred configuration.
    c. Transverse or reversible semi-transverse ventilation with uni-directional traffic (with no queuing), for both high and low risk tunnel construction.
2. Reduction in structural fire protection may be acceptable for the following tunnel configurations:
    a. Longitudinal ventilation with uni-directional (with no queuing) for low risk tunnel construction only.
    b. Longitudinal ventilation with bi-directional traffic (or uni-directional traffic with queuing), for low risk tunnel construction only.
    c. Transverse or reversible semi-transverse ventilation with uni-directional traffic (with no queuing), for low risk tunnel construction only.

    d. Transverse or reversible semi-transverse with bi-directional traffic (or uni-directional with queue) for low risk tunnel construction only.

3. Evacuation benefits may be acceptable for the following tunnel configurations:
    a. Longitudinal ventilation with uni-directional traffic (with no queuing), for both high and low risk tunnel construction.
    b. Transverse or reversible semi-transverse ventilation with uni-directional traffic (with no queuing), or both high and low risk tunnel construction.

Introduced configurations found *not* to be subject to trade-offs are:

1. Ventilation reduction not acceptable for the following tunnel configurations:
    a. Transverse or reversible semi-transverse with bi-directional traffic (or uni-directional with queue), for neither high nor low risk tunnel construction, unless it is possible for activation as soon as possible in lieu of after evacuation, based on findings regarding 'point of no return'!
2. Reduction in structural fire protection not acceptable for the following tunnel configurations:
    a. High risk tunnel construction
3. Evacuation benefits not acceptable for the following tunnel configurations:
    a. bi-directional traffic (or uni-directional traffic with queuing)

Opportunities for combinations of trade-offs was also identified for:

- Longitudinal ventilation with uni-directional (with no queuing) traffic for both high and low risk tunnel construction.
    - Reduction in ventilation and structural fire protection as well as evacuation benefits, combined, can all be subject to trade-offs.
- Transverse or reversible semi-transverse ventilation with uni-directional traffic (with no queuing), for both high and low risk tunnel construction.
    - Reduction in ventilation and structural fire protection as well as evacuation benefits, combined.
- Transverse or reversible semi-transverse with bi-directional traffic (or uni-directional with queue) for low risk tunnel construction only.
    - Reduction in ventilation and structural fire protection combined, can all be subject to trade-offs on the bases that it is possible for activation as soon as possible in lieu of after evacuation, based on findings regarding 'point of no return'!

It should be noted that combinations off trade-offs always should be carefully considered in a risk assessment on a project by project basis.

There is a possibility with pseudo transverse systems since they use a strategy in between longitudinal and transverse systems. Pseudo transverse systems may provide possibilities in both early activation and a as well as visibility reduction due to smoke solely in minor section of a tunnel. There is however little research material identified in the literature search for this theses and a final conclusion is not possible for pseudo transverse systems.

For a conservative approach, the identified acceptable trade-offs outlined are consider not to result in catastrophic events like tunnel collapse or flooding due to suppression malfunctioning. Incorporating suppression increases the safety level in case of ventilation malfunctioning. High reliability and redundancy of active systems associated trade-offs considering suppression, should be mandatory, regardless.

15. Discussion

Final discussion and evaluation of methods used.

Discussed design fires and peak HRR associated with suppression, used in this report, has derived from fire growth rates from tests and research for longitudinal ventilation. There is a possibility that the outcome could vary for other types of ventilation and tunnel configurations as well as fuel sources. How big the difference could be is not possible to evaluate at this point. More research is clearly needed for both longitudinal as well as for other types of ventilation configurations to support the findings of this report.

15.1 Methods used

The subject in question was expected to be onerous and a holistic view was anticipated to be necessary. An attempt to deal with this was made in the initial stages of the literature search. In doing so the intent was to select only highly relevant research material, for the purpose of the thesis. More time than anticipated has been spent on literature search and selecting relevant literature, a better solution might have been to look into a narrower subject. However the subject chosen was out of interest and stipulated a general understanding of all systems and performance requirements associated with tunnel design as well as the view on suppression systems in tunnel designs worldwide. The thesis is relevant as a base with interim results for future research work, rather than a standalone document with final conclusions. Further it may well be that some relevant research and information not located or known by the author, has not been introduced in this report.

To identify if and for what tunnel designs trade-offs may be suitable, a risk approach with an event tree as a tool was used. Shown to be a helpful method in visualising various potential trade-offs. The initial mapping at first consumed some time, to explain and use the interdependency of systems, with the attempt to identify possible consequences of different trade-offs. Tunnel design systems regarding fire protection are not only dependent on each other, but also on other aspects; type of traffic, the surrounding environment, ground conditions as well as designers choice related to cost-effectiveness. An event tree presentation of the problem helped to visualise the options discussed to create a systematic identification of possible, acceptable and not so acceptable outcomes. A simplistic model of a complex problem may be useful; however there is always the risk of leaving out important aspects as well as making something look simpler than as it is.

The concept of using trade-offs in tunnel design needs extensive future research to justify the appropriateness. Either way it is crucial that decisions related to trade-offs, if made, always are incorporated into a risk and Cost-Benefit analysis, within a performance based approach, for the specific project in question.

16. Recommendations and suggestions for future work

The following chapter outlines recommendations and suggestion for future work.

Recommendations and the need of future research indentified, regarding tunnel fire safety and FFFS, are described as follows:

- Experimental data of dangerous goods fires in tunnels and potential effects of a suppression system is needed. It is possible that restrictions should be different for dangerous goods allowance in tunnels incorporating FFFS's and for those that don't, depending on the type of goods (if dangerous goods are allowed at all).
- More extensive research is needed on the reliability of suppression systems in tunnels, to allow for robust and cost-effective design solutions incorporating trade-offs.
- More extensive research is needed on whether suppression systems work satisfactory on fires larger than 30MW. Possibly tests should focus on HRR's that are allowed to grow to the magnitude of 40-70 MW prior to activation of suppression? This to investigate 'the point of no return'. One should keep in mind that the 'point of no return' should be associated not only with the sufficiency of the suppression system but also if the ventilation capacity is high enough as well as if safe egress is and fire brigade intervention is possible. The answer is dependent on multiple parameters, type of fuel, design of the specific suppression system and ventilation capacity being the top three.
- Fire growth rates approximations used in this report only rely upon a few tests. Therefore further research in fire growth rate due to ventilation influence is needed to support the findings.
- It may be possible to achieve reduced detection times by combining incident control with state of the art detections systems on the market. New state of the art systems should be tested and evaluated for tunnel environment. Further the combination with incident control systems should be refined.
- Research should be done investigating the possibility of developing a new TT-curve for the use in tunnel design with FFFS. Alternatively there is a possibility to use an already existing, but less severe TT-curve. This should only be applied on tunnels with low risk construction, considering the scenario of FFFS malfunction. As mentioned before this will be depending on the reliability of the FFFS and therefore the maintenance and installation. Therefore it may be associated with potentially higher requirements for reliability of detection and FFFS systems installed.
- Systems for evacuation and measures to enable tunnel users to make the right decisions should always be considered. If code requirement are non-existing they should be developed. Further there is a need for news in measures of safe evacuation to be implemented in relevant codes and standards internationally.
- A more unified design approach, for tunnel fire safety worldwide, regarding suppression systems is of great interest, since it would contribute to designing safe tunnels as well as the potential of major cost savings in tunnel projects.

A selection of questions for further work that has not been answered in this thesis are:

1. Do the benefits of suppression systems measure up to the cost of the design and construction face? How much does the benefits and costs related to the

whole life time of a tunnel such as maintenance costs and the possibility of increased business continuity benefits impact on the choice of using suppression in tunnels?

2. What is acceptable risk and who decides what is acceptable? Should the acceptable level of risk be reflective of a general number of fatalities acceptable internationally, or should it reflect the country or the state in question and its own adopted acceptable level of risk for public roads, potentially varying from country to country?
3. If and when Dangerous Goods are allowed in a road tunnel, under what circumstances should this be acceptable in tunnels with suppression systems? More research considering suppression systems (especially mist systems) in tunnels where Dangerous Goods are allowed is needed.

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Appendix A- Fire resistant construction and tunnel lining

Various fire resistance solutions and requirements exist for different tunnel configuration, location and their use. This section presents a summary of methods used for fire resistance in road tunnels.

A.1 Fire resistance

In general, fire protection of the tunnel structure is usually achieved by the inherent fire resistance built into the tunnel construction or the use of additional passive systems. Fire protection of the tunnel structure may also be provided by active FFFS's. This chapter will focus on passive fire protection only. FFFS's and their possible benefits are investigated in chapter 6.

Passive fire protection as known, is none or less flammable material for the tunnel lining. Such protection is included in the initial design. In addition it is however commonly used in after-care and repairs as retrofitting of older or damaged tunnels. The passive fire protection to the tunnel lining is there to maintain structural integrity. If this fails to be adequate for tunnels in for example soft ground conditions it may lead to leakage and/or collapse or other unwanted events. The purpose of providing structural fire resistance in tunnel construction is to prevent structural collapse and breach of compartmentation for the following reasons. (Beard and Carvel 2005) (PIARC 2004)

- To ensure life safety for tunnel users as allowing tunnel users to safely evacuate in case of a fire;
- Prevent significant damage and offer a level of property protection;
    - large direct repair and retrofitting costs
    - large indirect economic damage due to longer non-operational times etc.
- To allow fire fighters to safely carry out search and rescue operations;
- To prevent failure of ventilation and electrical systems critical for maintaining life safety and fire fighter operations;
- To minimise disruption to tunnel operations due to a fire and enable asset protection as well as business continuity as quickly as possible after a fire incident; and
- To limit insurance costs and meet insurers potential requirements.

These are major aspects to be considered when designing the tunnel lining. It should be noted that there are other implications related to the specific tunnel design and potential fire that may need to be considered.

The protection of the tunnel lining may depend on the type of construction in a tunnel design. There are various construction types commonly used and the chosen method may well vary within the tunnel itself, which makes the design process crucial and complex. Commonly used constructions of tunnels are:

1. Cut and Cover tunnels (CC-tunnels)
2. Immersed tunnels
3. Bored tunnels - commonly round profile
4. New Austria Tunnel Method (NATM) – commonly horseshoe profile

5. Drill and Blast tunnels (DB-tunnels)

A tunnel does not necessarily consist of only one construction type mentioned above. Various aspects as the ground and soil conditions, the planned use and the overall configuration of a tunnel among others will have affect on the preferred construction type or combination of types.

A.2 Fire resistance - code comparison

The general requirements and recommendations on fire resistance to tunnel linings and other constructions associated have been summarised. ITA has developed recommendations combining ITA and PIARC work which is shown in Table A 1.

Table A 1 - Joint recommendations of PIARC and ITA (ITA 2004)

Traffic Type	Main Structure				Secondary Structures[4]			
	Immersed or under/inside superstructure	Tunnel in unstable ground	Tunnel in stable ground	Cut & Cover	Air Ducts[5]	Emergency exits to open air	Emergency exits to other tube	Shelters[6]
Cars/ Vans	ISO 60 min	ISO 60 min	2	2	ISO 60 min	ISO 30 min	ISO 60 min	ISO 60 min
Trucks/ Tankers	RWS/ HC_{inc} 120 min[1]	RWS/ HC_{inc} 120 min[1]	RWS/ HC_{inc} 120 min[1]	RWS/ HC_{inc} 120 min[1]	ISO 120 min	ISO 30 min	RWS/ HC_{inc} 120 min	RWS/ HC_{inc} 120 min[7]

1 180 min may be required for very heavy traffic of trucks carrying combustible goods

2 Safety is not a criteria and does not require any fire resistance (other than avoiding progressive collapse). Taking into account other objectives may lead to the following requirements:

– ISO 60 min in most cases
– No protection at all if structural protection would be too expensive compared to cost and inconvenience of repair works after a fire (e.g. light cover for noise protection)

3 Safety is not a criteria and does not require any fire resistance (other than avoiding progressive collapse). Taking into account other objectives may lead to the following requirements:

– RWS/HC_{inc} 120 min if strong protection is required because of property (e.g. tunnel under a building) or large influence on road network
– ISO 120 min in most cases, when this provides a reasonably cheap protection to limit damage to property
– No protection at all if structural protection would be too expensive compared to cost and inconvenience of repair works after a fire (e.g. light cover for noise protection)

4 Other secondary structures should be defined on a project basis

5 In case of transverse ventilation

6 Shelters should be connected to the open air

7 A longer time may be used if there is a very heavy traffic of trucks carrying combustible goods and the evacuation from the shelters is not possible within 120 min

Further the requirements in NFPA 502 (NFPA 502 2008) are that the structure shall be capable of withstanding the Rijkswaterstaat (RWS) time–temperature curve. After a 120 minute period of fire exposure, the following failure criteria shall be satisfied:

1. Tunnels with cast in-situ concrete structural elements shall be protected such that:

   (a) The temperature of the concrete surface does not exceed 380ºC.

   (b) The temperature of the steel reinforcement within the concrete (assuming a minimum cover of 25 mm) does not exceed 250ºC.

2. Tunnels with pre-cast, high-strength concrete elements shall be protected such that explosive spalling is prevented.

3. Steel or cast iron tunnel linings shall be protected such that the lining temperature shall not exceed 300ºC.

The TT-curves referred to are presented in Figure 3 in chapter 3.

A.3 Spalling risk of different types of construction

The potential of high moisture content in constructions underground as well as the common use of high strength concrete are increasing the risk of spalling.

A.3.1 D&B tunnel construction

Tunnel lining may be high strength concrete and subject to high compressive axial loads which results in higher risks of spalling, alternatively sprayed tunnel lining subject to axial loads and/or ground movement.

A.3.2 TBM tunnel construction

Tunnel lining may be high strength concrete and subject to high compressive axial loads which results in higher risks of spalling.

A.3.3 C&C tunnel construction

A cut and cover type of construction is subject to both spalling due to elevated temperature but also sagging due to thermal deflection of the upper part of the construction. Therefore protection is needed to prevent leakage and the risk of collapse due to sagging as well as spalling. The top corners and soffit of the tunnel are crucial elements when applying fire protective measures.

A.4 Potential risk of spalling and protective measures

The feature of spalling referred to in this chapter is the breaking of layers or pieces of concrete from the surface of a structural element when it is exposed to high and rapidly rising temperatures experienced in fires. Generally there are 3 main types of concrete spalling. *Surface spalling* where concrete fragments typically up to 20 mm in diameter become detached*. Corner break-off* or sloughing off in the later stages of a fire and affecting more vulnerable concrete on wall corners where it is heated in two planes. *Explosive spalling* where early rapid temperature rise forcibly separates pieces of concrete at high pressure, with an 'explosive' effect. This is considered the most dangerous form of spalling and are often the one occurring in larger tunnel fires

Spalling may occur in some concrete already at surface temperatures around 200°C. At temperatures above 400°C the calcium hydroxid in concrete will dehydrate and produce water vapour which could lead to accelerated spalling as well as decreased strength of the concrete. Further elevated temperatures will lead to mineral transformation of quarts and decomposing of limestone.

Metal within concrete structures expand in high temperatures and will undergo reduction in its loading capacity. Common practice used is to protect the metal within the concrete from temperature higher than 250-300°C. One reason for this, except for reduction in loading capacity, is that metal and concrete expand in a similar manner in temperatures up to 400°C however above that the difference in behaviour might lead to damaging stresses within the mix.

In general higher strength concrete is used in bored tube tunnels which implies lower porosity and permeability whereas immersed tube tunnels and cut & cover generally usees a concrete with lower density and higher porosity. For drill and blast tunnels it may vary depending on what method of construction used for the tunnel lining. The differences of concrete properties greatly influence the performance of tunnel linings when exposed to fire and heat. (Beard and Carvel 2005) (Shuttleworth 2002)

As mentioned above low porosity high strength concrete commonly used in bored tunnels gives higher risks of spalling. Spalling occurs due to water vapour created, at temperatures higher than 100°C, from water contained in the concrete. The smaller porous within the concrete results in a decreased ability to allow for the expansion from water vapour and pressure build up. This may result in large pieces of concrete exploding off the tunnel lining i.e. explosive spalling.

Available fire resisting materials are presented in Table A 2.

Table A 2 - Typical fire resistant material for tunnels (ITA 2004)

MATERIAL	TYPE MATERIAL	TYPE CONSTRUCTION	ATTACHMENT
Calcium silicate board	Panel	Pre-manufactured panel	Anchor bolts
Light weight concrete	Light weight aggregate	Attached to surface	Spray applied
CIP Concrete	Cement	Cast-in-place	Integral with structure
CIP Concrete/fibers	Cement with Poly fibers	Cast-in-place	Integral with structure
Shotcrete	Cement/additives	Spray	Spray
Shotcrete /fibers	Cement/ additives/ poly fibers	Spray	Spray
Mineral wools	Mineral wool in cement matrix	Spray	Spray
Ceramic Refractory	Refractory cement/ceramic mix	Spray	Spray

To minimise the risk of spalling in high strength concrete Eurocode 2, Part 1-2 (Eurocode 2 2004) generally suggests several methods to prevent spalling which are summarised as follows (full details are found in Eurocode 2, Part 1-2):

1. Method A – A reinforcement mesh with a nominal cover of 15mm.
2. Method B – A type of concrete for which it can be demonstrated that no spalling of concrete occurs under fire exposure.
3. Method C – Protective layers for which it is demonstrated that no spalling of concrete occurs under fire exposure.
4. Method D – Include more than 2 kg/m^3 of monofilament propylene fibres, in the concrete mix.

It has been shown that the inclusion of 1 kg/m^3 of monofilament propylene fibres in high strength low permeability mixes significantly reduce the risk of explosive spalling (Shuttleworth 2002) see Figure A 1. The test was carried out on full scale segments with various additives and concrete mixes in conjunction with polypropylene fibres.

The 4 methods above cover the commonly used passive fire protection measures for concrete construction in general. A steel mesh in the concrete cover is working inherent to limit the depth of potential spalling and therefore prevent spalling to expose the concrete reinforcement. The protective layers are working as a shielding thermal boundary and may be specified with various fire resistance periods. Including polypropylene fibres is a relatively new method and is often referred as ‘fire-proof concrete’. The mechanism of preventing explosive spalling of durable concrete exposed to fire, by adding polypropylene micro fibres is not well understood however research has shown that the fibres will reduce the amount of spalling in the concrete panels.

The fibres melt at elevated temperatures and provides pathways for the passage of moisture in the concrete that evaporate and expand in fire conditions which otherwise would lead to explosive spalling. It should be noted that macro fibres such as steel fibre used as structural reinforcement to concrete does not provide the prevention of explosive spalling as polypropylene fibres (The Concrete Society 2007).

Although polypropylene fibres will prevent explosive spalling they cannot prevent heat the damage to concrete which still may lead to structural failure or the need for extensive structural repair and replacement. Therefore the polypropylene fibres on their own should only be seen as an additional fire safety measure to prevent spalling of the concrete structure, rather than to be used in exchange for any required fire resistance period to the tunnel lining or other fire separating constructions.

CONTROL WITH POLPROPYLENE FIBRES

Figure A 1– Full scale segment test with various additives in conjunction with polypropylene fibres (Shuttleworth 2002)

It should be noted that the polypropylene fibres can only work once as a fire protection system and have thus to be replaced after a fire incident (Kaundinya 2007). The inclusion of polypropylene fibres will however prevent spalling and thereby limit the amount of damage to the tunnel lining in a fire compared to if no or less effective measures are used to prevent spalling. Further polypropylene fibres will not limit the temperature of the exposed concrete and reinforcement bars which have to be taken under consideration in the design of a tunnel lining. Therefore the amount of polypropylene fibres added to a specific concrete mix or precast segment is to be assessed and tested case by case.

Research over the recent years and common practice for fire protection in road tunnels seems to point towards using either polypropylene fibres or thermal barriers for fire protection of tunnel lining.

For new tunnels it has been highly recommended to use concrete with an improved fire resistance rather than thermal barriers as additional cladding with steel mesh or boards. To improve concrete to an acceptable level of protection a specific mix has been suggested to get a quality of class C25/30 or higher for example:

> *Application of quarzite instead of chalky aggregates, addition of 3kg/m3 polypropylene fibres and in specific cases additionally the replacement of the maximum core group of aggregates by basaltic gravel* (A. Haak 2008).

The benefits with using a mix of concrete, as outlined above, with improved fire resistance are:

- No need for fire proof claddings or alike -no additional cubature -no additional construction step -sufficient fire protection already during the construction phase.
- Simple assembly techniques for all final installations -free access for inspection at any time without removing parts of cladding.
- Approximately the same life cycle as the tunnel itself, of about 100 years.
- Nearly no affect of spalling in a fire -only low damage given to the fire protection in case of a collision.
- The additional costs due to the special mix of the concrete are reasonable and generally low.

Therefore where applicable the use of polypropylene fibres is recommended.

As mentioned above research over the recent years and common practice point towards using either polypropylene fibres or thermal barriers for fire protection of road tunnel lining. With no polypropylene fibres or thermal barrier a steel mesh will limit the extent of damage when spalling takes place but not prevent it from occurring. (Khoury 2003) (Beard and Carvel 2005)

Mostly the required fire resistance in road tunnels is 4 hours however it may vary slightly with different design objectives and assessments. For concrete construction in general when providing 3 to 4 hours fire rating the thickness of concrete cover of the reinforcement bars is approximately 40-50 mm to achieve the fire rating. The amount of cover creates an increased risk of spalling, therefore the general code requirements (for example Eurocode 2) is to use a steel mesh approximately halfway into the cover.

The protection measures to prevent spalling in different tunnel constructions are similar for different tunnel configurations but may vary depending on different loadings and ground conditions.

A.5 Discussion

When designing fire resistance of for example 4h interpreted as the inherent structural integrity of the tunnel lining exposed to fire, if shown by structural analysis that no collapse will occur, it seems to be accepted in the past (and might still be) not to apply additional fire protection to the concrete lining, in itself providing sufficient structural integrity. In structural analysis application it is however most difficult to predict the amount of spalling that may occur. There are several attempts to develop calculation methods to take spalling into account and research in this field is still ongoing at several research facilities, universities and expert consultants. However the amount and effect of spalling is still not well predicted and it is recommendable that for reliably results, to test the specific construction specimen for the required design criteria’s (temp-time curve) on a case by case basis.

Recent research programs such as UPTUN and SafeT are pointing towards the need for using additional fire protective measure as thermal shield panelling, a sprayed fire resisting concrete cover or additives to make the concrete itself more fire resistant, rather than using the tunnel lining itself. Further the means of protective measures already included in a concrete mix as pp-fibres is being adopted as a good alternative for tunnel lining protection.

Appendix B – Automatic fire detection

The measures of detection is commonly automatic fire detection with linear heat detections devices. Also smoke detection systems or video monitoring (CCTV) for smoke and flame detection is used for early warning.

B.1 Detection time

Recent research has been done on automatic detection in tunnels in the Runehammar test tunnel in 2007 (Aralt and Nilsen 2008) to investigate the best suited principle for detecting a fire in an early stage. Smoke and heat detection was tested. For the purpose of the fire detection tests, small fires varying between 0.2 MW and 2.4 MW, with the argument that large fires starts small and it is of interest to see how fast the detection systems may detect small fires. Velocity conditions used was 1.2 m/s and 1.8 m/s. Temperature in the flames shall always be considered to reach 1000˚C. Most dangerous situations with small fires are for trapped people in their vehicles, or secondary collisions caused by low visibility in the smoke layer downstream of the fire. However the real danger is when a tunnel fire becomes catastrophic. Better detection to save some minutes or seconds may therefore be valuable to escaping tunnel users. A suggestion was made in the research for the Runehammar detection test, that heat detection may give fast response to larger fast growing fires while the dust or smoke systems may detect smaller fires and slow growing fires. It was also concluded that a major gasoline fire will be detected by heat detection due to its fast growth and radiated heat. Whereas smaller gasoline fires under a car would be harder to detect with heat detection due to reduced radiation reaching the detectors. The same concept applies for fires inside a car or in inside an engine room which will most likely not be detected before flashover occurs.

Linear heat detection

Linear heat detection is reliable for stationary sources and an alarm triggered by a linear heat detector activates automatically the alarm procedures. Alarm activation time may vary for different types of linear type heat detectors, 30-40 s, 30-60 s or 30-180 s depending on the type of system and type of detector (Beard and Carvel 2005).

Linear heat detection has good response to most fire scenarios based on rate of temperature rise, however longitudinal airflow may delay response times unless in some cases where the ventilation increases the size of the fire resulting in faster response times. A fibre optic based linear heat detection system may determine the fire location, within 10 m from the actual fire under a longitudinal airflow, shown in resent tunnel fire tests. (Liu, Kashef, et al., Symmary of International Road Tunnel Fire Detection Research Project - Phase II 2008)

Small fires in a one-way traffic tubes may however not be detected by heat sensors if the airflow velocity is as high as 3-5 m/s, which is quite normal. For ventilation velocities less than 1 m/s linear heat detection should operate quite well even for small fires. With this in mind it is important to note that a rapid rise in pollution will start the normal ventilation system which may increase the detection time for heat. This problem may be reduced by using longer integration times for ventilation together with a low integration time for the fire detection. The detection time and number of false alarms may vary with the normal conditions of the tunnel. Normally a heat detection system will have to be adjusted under a long term to optimise the contradictory demands of detection time and false alarms. (Aralt and Nilsen 2008)

Flame detection

Flame detection relay on a field view which makes it difficult to detect fires located under, behind or inside a vehicle, resulting in increased response times. Further devices, facing on-coming traffic, may become very dirty creating an optical fault condition and frequent nuisance alarms. To deal with this issue it has been found in full-scale testing that the sensitivity should be set to medium sensitivity rather than high sensitivity which provide a detection range of approximately 30 m. (Liu, Kashef, et al., Symmary of International Road Tunnel Fire Detection Research Project - Phase II 2008)

Smoke detection

Car fires, producing more smoke in comparison with liquid fires as heptane has been shown to be detected earlier by smoke detectors. Smoke detectors will detect a real car fire but will not detect smoke density under 3000 μm/m^3 [11] and may therefore have problems with detecting heptane fires fast enough. Since heptanes produces smaller amounts of smoke the detection time for smoke detectors may be longer than the transportation time. Integration time for reducing false alarms of 60s can be expected. F Car fire detection may be reached in less than 60s even for detectors with an integration time of 60s. (Aralt and Nilsen 2008)

Resent full-scale laboratory tests with sampling smoke detection placed in ceiling vents has shown to be performing well detecting most fires with few false alarms. However it was concluded that a detector placed in a main exhaust vent shaft was not practical, due to air blockage of the detector becoming excessively dirty, with the result of an air flow trouble signal. (Liu, Kashef, et al., Symmary of International Road Tunnel Fire Detection Research Project - Phase II 2008)

One problem is that smoke moves with the air and therefore the capturing of the source is not easy.

In most cases no automatic start of emergency procedures are done with smoke detection, manual confirmation by operator is required.

CCTV detection and traffic incident control

Smoke and flame detection with video-image processing tunnel where tunnel operators are enabled to detect dangerous situations very early, CCTV are used in countries like Australia, US and UK and some European countries among others. However mostly as a complimentary detection to a state-of-the-art system, that is in accordance with the international standards. (Beard and Carvel 2005, NFPA 502 2008)

CCTV systems have, in resent full scale testing, been shown to be able to detect small open fires within a detection range of 60 m. Systems that use both flame and smoke for detection have been shown to be unaffected by longitudinal airflow as well as better response to concealed fires. CCTV systems relying on field view for detection, as mentioned for flame detection, may not detect all fires and would therefore require multiple detectors to provide effective coverage. It has been found that systems with both flame and smoke detection may have large amounts of nuisance alarms compared to CCTV only using flame detection with effectively no nuisance alarms. (Liu, Kashef, et al., Symmary of International Road Tunnel Fire Detection Research Project - Phase II 2008)

Spot heat detection

Spot heat detection seems not to be preferable option for detection in road tunnels due to the inability to detect small fires under low ventilation conditions as well as delay in response times under longitudinal ventilation conditions. (Liu, Kashef, et al., Symmary of International Road Tunnel Fire Detection Research Project - Phase II 2008)

[11] Only few tunnels will ever have amounts of dust of more than 2000μm/m^3 therefore 3000μm/m^3 can be considered an adequate alarm level.

B.2 The work of PIARC

PIARC (PIARC 2004) have made statements in their Congress reports summarised as:

- 1979. Closed circuit television is particularly useful in detecting fire in combination with tunnel users, tunnel operational staff and appropriate equipment. For example by the removal of a fire extinguisher or automatic detection by maximum temperature or rate of rise.
- 1983. A sound alarm in the control room is further recommended. Early detection is required and temperature detectors are recommended with a set temperature and rate of rise. Smoke detection to detect small fires. Detection installation shall cover the whole tunnel. The criterias for fire detectors should be able to detect 20 l of burning petrol. Detectors should be installed in tunnels with much HGV traffic and where dangerous materials are allowed. Detectors and their effectiveness are not recognised by all operators, however they are usually placed in long and heavily-trafficked tunnels. Both types of detectors should be used in combination to avoid false alarms, and should be linked to the television installation.
- 1987. Fire detection should be provided in tunnels with significant risk (same requirements as from 1983 above). Detectors may consist of a metal tube with enclosed air or gas that expands when the temperature increases or of individual devisees not more than 25 m apart.
- 1995. Detection can be simplified to detect incidents by means of close circuit television (CCTV) monitoring. Development of automatic incident detection is ongoing. Fire detectors are also very helpful in unmanned tunnels with transverse or semi-transverse ventilation because if the fire is not detected the opacity sensors will otherwise start normal ventilation to maximum rather than stop and use smoke extraction mode.

New and more effective automatic fire detection has been developed over recent years which will detect most fires. These are mostly based on heat or rate of heat. These give few false alarms compared to detectors based on smoke. However smoke detectors give an earlier alarm. (Aralt and Nilsen 2008) (PIARC 2004)

Further due to differences in views about fire detection in tunnels and a common concern about false alarms, PIARC sent out a questionnaire that gave some guidance into how detection was being treated in their member countries. The results are summarised in Table B 1, showing that Austria, Germany, Italy, Japan, Switzerland and the United States generally use detection systems. Other countries that answered where more reluctant, however there seems to be a growing awareness and a more positive attitude towards detection developing in these countries. UK use CCTV combined with traffic incident control for detection of fires. This method was also used to some extent in the United States. The recommendations by PIARC are that linear heat detection is preferred. However there are concerns about false alarms and delayed alarms. Delayed alarm relate to the time required for a fire in the interior of a vehicle to have an impact on the tunnel environment. Further detection systems may be useful in tunnels that are long or complicated, that are carrying dangerous goods and/or are unmanned with transverse or semi-transverse ventilation. Also an automatic incident detection system detection system can be used as an alternative way to detect fires quickly.

Table B 1 – Summary of questionnaire done by PIARC on tunnel fire detection (PIARC 2004)

Country	Summary from questionnaire
Austria	All tunnels > 1500 m are equipped with a fire detection system, usually linear heat detection. A combination of fire detection and CCTV systems is very useful. In case of false alarms by the detection system it may be checked by the CCTV system.
Belgium	Two tunnels are equipped with fire detection which use point detectors that detect abnormal temperature variations. Only tunnels that carry dangerous goods have detection which is used to alert the police.
Denmark	The Guldborgsund tunnel has temperature-activated type detectors every 10m. Alarm will close tunnel and alert the fire department. Fire detectors are not considered as important as fire alarms which can be activated from emergency panels in the tunnels or emergency calls from tunnel users mobile phones.
France	No tunnel is equipped with fire detection system. Today fires are detected by CO and opacity meters that automatically switch on the highest ventilation regime. Fires are also detected by CCTV if any and by emergency telephones. France contemplates using fire detectors in semi-transverse tunnels that are not manned 24 hours a day. In a fire incident today in such tunnels the system will start blowing fresh air from the ceiling and delayering the smoke. They are also contemplated in tunnels with dangerous goods. The detectors would locate the fire so appropriate openings can be activated. Fire detection system should start the smoke control system immediately, if manned alert the personnel, further close the tunnel and alert the fire brigade.
Germany	Detectors in all tunnels > 350 m and must detect a fire of 20 litres of petrol.
Italy	Some tunnels (long-two way tunnels and shorter two-way tunnels with heavy traffic) are equipped with fire detectors with a

	cable with variable resistance.
Japan	Flame detectors are used and are required in all tunnels >1000 m and in shorter tunnels with heavy traffic. Upon detection the tunnel is closed, staff are alerted, fire department are alerted, ventilation system is set to fire mode and the evacuation route for people are designated.
Norway	No tunnel has fire detectors due to their high cost and the low traffic volume in tunnels. A fire detection system are being evaluated for the new 24 km long Laerdal tunnel.
Switzerland	Long tunnels are equipped with linear fire detectors. Table B 2 shows results from a test of six different types of fire detection systems. The test was made in the Mositunnel in Switzerland (1992).
United Kingdom / Netherlands	No fire detectors are used in tunnels in these countries. Due to unreliable and expensive nature of fire detection systems, a combination of CCTV, visibility monitoring equipment and traffic detectors are used to indicate when incidents have occurred.
United States	Fire detection in road tunnels utilises a number of systems including CCTV, traffic detectors and fire detectors. The traffic detectors identity the change in traffic flow; the CCTV is then used to verify an event. Where fire detectors are employed, linear type is used.

Table B 2 – Fire detector tests in the Mositunnel (Switzerland): Time (mn:s) before alarm from tests with alcohol and petrol fires (PIARC 2004)

TEST no	7	8	9	10	11	12	13	14
Fire source	Alc	Alc	Alc	Alc	Petrol	Petrol	Petrol	Petrol
Fire Area (m^2)	1	2	3	4	2	0.6	1	2
Temperature point detector -pre alarm -alarm	1:35 -	1:25 5:15	0.69 1:68	1:02 1:61	0:63 0:53	1:03 -	0:43 1:33	0:26 0:33
Coaxial heat detector	-	-	-	-	0:34	-	1:44	0:22

cable								
Linear temperature sensor	-	5:18	4:09	1:35	*	1:50	1:21	0:40
Linear smoke detector cable	-	4:51	-	4:52	0:02	0:03	0:02	0:03
Optic fibre sensor	3:34	4:50	1:10	1:08	0:42	1:05	0:52	0:33

It seems clear that if detection systems are used in tunnels a combination of two systems are preferable to minimize false alarms. Also two systems would provide redundancy in the detection process. Detection of a fire with no automatic detection system is then usually done by the CO or opacity sensor which would maximise the normal ventilation for most cases delayering the smoke and feeding a fire with more fresh air i.e. more oxygen.

Appendix C – Tunnel accident history

Table C 1 - Fire accident's in the world's road tunnels (ITA 2004)

Year	Tunnel Length	Location Country	Vehicle Where Fire Occurred	Most Possible Cause of Fire	Duration of Fire	CONSEQUENCES Consequences People	Damaged Vehicles	Structures and Installations
1949	Holland 2,550 m	New York USA	Lorry with 11 tons of carbondisulfide	Load falling off lorry explosion	4 h	66 Injured smoke inhalation	10 lorries 13 cars	Serious Damage Over 200 m
1974	Mont Blanc 11,600 m	France-Italy	Lorry	Motor	15 min	1 injured		
1976	Crossing BP-A6 430 m	Paris France	Lorry with drums of 16 tons polyester film	High Speed	1 h	12 light injuries (smoke)	1 lorry	Serious damage over 150 m
1978	Velsen 770 m	Velsen Nederland	4 lorries 2 cars	Front-rear Collision	1 h 20min	5 dead 5 injured	4 lorries 2 cars	Serious damage Over 30 m
1979	Nihonzaka 2,045 m	Shitzuoka Japan	4 lorries 2 cars	Front-rear collision	159 h	7 dead 1 injured	127 lorries 46 cars	Serious Damage Over1,100 m
1980	Kajiwara 740 m	Japan	1 truck with 3600 litres of paint in 200 cans	Collision with side wall and overturning	n/a	1 dead	1 truck, 4t 1 truck 10t	Serious Damage Over 280 m
1982	Caldecott 1,028 m	Oakland USA	1 car, 1 coach, 1 lorry with 33000 litres of petrol	Front-rear collision	2 h 40min	7 dead 2 injured	3 lorries 1 coach 4 cars	Serious Damage Over 580 m
1982	Salng 2,700 m	Mazar-e-Sharif-Kabul Afghanistan	Soviet Military column. At least one petrol truck	Unknown, probably mine explosion	n/a	>200 dead	n/a	n/a
1983	Pecorila Galleria 662 m	Gênes Savone Italy	Lorry with fish	Front-rear collision	n/a	9 dead 22 injuries	10 cars	Little Damage
1986	L'Arme 1,105 m	Nice France	Lorry with trailer	Braking after high speed	n/a	3 dead 5 injured	1 lorry 4 cars	Equipment destroyed
1987	Gumefens 343 m	Berne Switzerland	1 lorry	Front-rear collision	2 h	2 dead	2 lorries 1 van	Slight damage
1990	RØldal 4,656 m	Røldal Norway	VW transporter With trailer	n/a	50 min	1 injured	n/a	Little damage
1990	Mont Blanc 11,600 m	France-Italy	Lorry with 20 tons of cotton	Motor	n/a	2 injured	1 lorry	Equipment destroyed
1993	Serra Ripoli 442 m	Bologne-Florence Italy	1 car+lorry with rolls of paper	Collision	2 h 30min	4 dead 4 injured	5 lorries 11 cars	Little damage
1993	Hovden 1,290 m	HØyanger Norvay	Motor cycle 2 cars	Front-rear collision	1 h	5 injured in the collision	1 motor-cycle 2 cars	111 m insulation material destroyed
1994	Huguenot 3,914 m	South-Afrika	Bus with 45 passengers	Electrical fault	1 h	1 dead 28 injured	1 coach	Serious damage
1995	Pfander 6,719 m	Austria	Lorry with trailer	Collision	1 h	3 dead in the collision 4 injured	1 lorry 1 van 1 car	Serious damage
1996	Isola Delle Femmine 148 m	Palermo Italy	1 tanker with liquid gas + 1 little bus	Front-rear collision	n/a	5 dead 20 injured	1 tanker 1 bus 18 cars	Serious damage, tunnel closed for 2.5 days
1999 14 July	Mont Blanc 11,600 m	France-Italy	Lorry with flour and margarine	Oil leakage Motor	n/a	39 dead	23 lorries 10 cars 1 motorcycle 2 fire engines	Serious damage, tunnel reopens 22.12.2001
1999	Tauern 6,401 m	A10 Salzburg-Spittal	Lorry with paint	Front-rear collision 4 cars and 2	n/a	12 dead 49 injured	14 lorries 26 cars	Serious damage

Year	Tunnel Length	Location Country	Vehicle Where Fire Occurred	Most Possible Cause of Fire	Duration of Fire	CONSEQUENCES		
						Consequences People	Damaged Vehicles	Structures and Installations
		Austria		lorries				
2000	Seljestad 1,272 m	E134 Drammen-Haugesund Norway	The trailer truck that caused the multiple collision had a diesel fire in the engine room before collision	Front-rear collision A trailer- truck pushed a car into 4 cars that had stopped behind another truck	45 min	6 injured	1 lorry 6 cars 1 motorcycle	Serious damage. NOK 1 mill. Tunnel closed for 1 ½ days
2001 28 May	Prapontin 4,409 m	A 32 Torino-Bardonecchia Italy	Romanian truck, loaded with beets	Mechanical problem	n/a	19 injured by smoke	n/a	Closed until 6 June in westerly direction
2001	Gleinalm 8,320 m	A 9 near Graz Austria	Car	Front collision Lorry-car	n/a	5 dead 4 injured	n/a	n/a
2001	St. Gotthard 16,918 m	A 2 Switzerland	Lorry	Front collision 2 lorries	2 days	11 dead	13 lorries 4 vans 6 cars	Serious damage Closed for 2 months

Other incidents have occurred since ITA published their report such as:

The Santa Clarita, I-5 Tunnel fire in California 2007. Investigators determined that 31 vehicles including big rigs and one passenger vehicle were involved in the crash, which killed two men and an infant and injured at least 10 people. The fire spread from vehicle to vehicle, sent flames shooting nearly 100 feet in the air outside the tunnel and reached temperatures as high as 1,400 degrees (BNET 2007). The fire shut down California's central artery for more than two days at a cost of US $17 million in cleanup and repairs (Popular mechanics 2008).

A major fire incident with a suppression system present is the Burnley Tunnel Fire in 2007, where the deluge system and the ducted semi-transverse smoke controls system were activated rapidly, together controlling smoke volumes to a zone of about 100m downstream of the fire, as designed. (Johnson and Barber 2007)

For more details and short summaries of some of the major road tunnel incidents mentioned above the reader is referred to The Handbook of Tunnel Fire Safety (Beard and Carvel 2005) and the FIT report Design Fire Scenarios report (FIT 2004) as well as the UPTUN report, Fire Scenarios and accidents in the past (UPTUN WP2 Report 2008).

Appendix D - Research and upgrade programs for tunnel safety

This chapter briefly outlines the available research projects and thematic networks regarding road tunnels.

There are several European research projects / thematic networks as presented by Lacroix (Lacroix 2008):

DRATS (Durable And Reliable Tunnel Structures - www.dartsproject.net) with the aim to minimise cost increases during construction.

SafeTunnel (Innovative Systems and Frameworks for Enhancing of Traffic –safety in Road Tunnels – www.crfproject-eu.org) looked at benefits of communication between vehicles and the infrastructure.

Sirtaki (Safe Improvement in Road & Rail Tunnels using Advanced Information Technologies and Knowledge Intensive Desicion Support models – www.sirtakiproject.com) aimed to enhance operational management of emergencies.

VirtualFires (Virtual Real Time Emergency Simulator – www.virtualfires.org) developed a prototype simulator for training emergency teams.

UPTUN (Cost-effective, sustainable and innovative Upgrading Methods for Fire Safety in existing Tunnels – www.uptun.net) with a budget of 12 million euro's and 41 partners from 16 countries, developing technologies and as assessment method for improving fire safety in existing tunnels during the period of 2002 to 2006.

FIT – thematic network (Fires In Tunnels www.etnfit.net) ran from 2001 to 2005 and produced shared databases on various aspects of fire safety in tunnels and a report relating to design fires, fire-safe design and emergency response.

SafeT thematic network (Safety in Tunnels – www.safetunnel.net) started 2003 and finished 2006 and proposed recommendations covering all aspects of tunnel safety.

SOLIT - Safety Of Life In Tunnels with the objective to improve evacuation conditions and to create effective facilities for a speedy fire fighting. The 'SOLIT' Research Project was sponsored by the Federal Ministry of Economics and Technology (Germany) and initiated by FOGTEC with the ending in 2007-2008.

L-surf (Large Scale Underground Research Facility – www.l-surf.org) feasibility study on safety and security of enclosed underground spaces, with the aim of full scale testing, training as well education. This is the only project funded under the 6th EU framework programme.

The programs which has been found most relevant of the ones identified above, for investigations considering potential trade-offs are: UPTUN, FIT and SOLIT. Therefore these are the ones considered for use in this report.

Appendix E – Efficiency of suppression system

Available research and testing of various suppression systems are summarised in Table E 1.

It does not seem appropriate to compare the tests presented in Table E 1 in a diagram or alike since the test facilities, fires used and mitigation measures differ, compared to each other. However the results may give some guidance in to what extent suppression systems have the ability to mitigate a tunnel fire.

17.1 Other findings

One overstatement of the benefit of water mist is that a water spray curtain makes smoke conditions more "breathable" in a tunnel fire scenario. The claim of smoke scrubbing by water mist is frequently overstated; however, it has a general benefit that comes by default with all water mist systems. Water mist can be expected to do a better job of mixing with smoke than spray water systems due to difference in drop size. However the scrubbing efficiency is not consistent, especially not for large spaces. Scrubbing work to some extent for soot particles, but mist cannot remove insoluble toxic gases such as carbon monoxide from smoke. There is no question that installation of such a system in a road tunnel would greatly improve conditions for evacuation in most cases, of the public and fire-fighter access, particularly compared to the present situation in which there are no suppression/cooling systems. The main benefit would be the cooling and suppressing effect rather than a scrubbing effect. Cooling of the smoke causes loss of stratification, which somewhat reduces visibility at floor level, compared to un-cooled smoke. That is an acceptable trade-off considering the alternative, which has sadly been demonstrated in recent years with the large number of deaths in highway tunnel fires in Europe. However considering that the water mist cannot remove insoluble toxic gases such as carbon monoxide, the claim of improved breathability is a dangerous overstatement. Also one should not forget that general mixing of mist with smoke containing HCl from burning plastic, without collection of the mist in a closed chamber, creates a dangerous and corrosive humidity that burns the eyes and lungs. (J. R. Mawhinney April 2002)

Table E 1 - Summary of research on suppression

Type of system and setup	Discharge rates or spray density and pressure litre/(m^2min) or mm/min	Pressure	HRR	Type of fuel	Activation time of suppression after ignition	Ventilation condition	Geometry	Visibility and toxicity	Temperature	Results	Comment	Reference
Water spray	19	Not reported	Not reported	Aircraft petrol fuel: 100 L - 6.6 m^2 pool 500 L - 47.5 m^2 pool 1000 L - 95 m^2 pool	Not reported	Not reported	W = 4 m H = 6 m	Visibility significantly reduced due to hot steam and cooling of smoke layer.	Temperatures of 1200-1400 ˚C after 1-2 min after ignition, before activation	Fire extinguished within a short time. Large amount of steam production Vapour was re-ignited after being extinguished in the vicinity of the fire resulting a deflagration that significant damaged the setup and ventilation of the tunnel.	Tests were carried out in a narrow old one track rail tunnel, which may not be suitable to compare to road tunnels.	Ofenegg tunnel Switzerland 1965 (Liu, Kashef, et al. 2007)
Water spray	12.5	Not reported	15-40	Simulated stationary vehicle fires: Van loaded with wood cribs, HGV with wood pallets and aluminum truck loaded with wood cribs	6-22 min after ignition	Longitudinal 0-1m/s (three tests) 3 in (one test)	W = 9 m H = 5.1 m	Visibility almost entirely obstructed, with 5-15 min time to improve.	Temperature upstream and downstream decreased from approx. 250-350 to 20-30 ˚C shortly after activation, which prevented fire spread.	No significant steam-formation and no deflagration observed.		Benelux tunnel Netherlands 2001 (Liu, Kashef, et al. 2007, Vasilovska 2006)

Type of system and setup	**Discharge rates or spray density and pressure litre/(m²min) or mm/min**	**Pressure**	**HRR**	**Type of fuel**	**Activation time of suppression after ignition**	**Ventilation condition**	**Geometry**	**Visibility and toxicity**	**Temperature**	**Results**	**Comment**	**Reference**
Water spray	6	Not reported however lowest requirement in Japan is 0.34 Pa	5 MW	4 9 Gasoline pool and a bus fire	Not reported but probably 3 min	Not reported	Ø = 115 m²	Not reported	Temperatures quickly decreased to ambient after suppression activation.	No report of smoke disruption and steam generation during fire suppression.	-	Test series by Japanese authorities (Liu, Kashef, et al. 2007)
Foam Water Spray (AFFF protect against possible flammable liquid fuel or chemical fires).	2.4 - 3.8 3 % AFFF (Aqueous Film Forming Foam)	Not reported	10, 20, 50, 100 MW	Diesel pool fires	Not reported	4.2 m/s Longitudinal	Not reported	Not reported	Not reported	Fires extinguished in less than 30 s in all four tests. Suppression effectiveness was not affected by	It would be interesting to know how big the fires were allowed to grow before activation.	Memorial tunnel (Liu, Kashef, et al. 2007)
Compressed air foam (CAF)	5.6		200 MW 300 MW	100 m² diesel pool 100 m³ wood pallets	2 – 3 min 5 – 10 min	2 – 3 m/s	W = 9 m H = 6 m L = 1600 m	Visibility was completely lost before the discharge of the CAF-system due to large fire size and long pre-burn time.	Temperature upstream of the fire was cooled down to 50 ˚C and to 100 ˚C downstream, preventing fire spread.	Successful in extinguishing the diesel fire. Controlled the solid fuel but did not extinguish. No significant steam or deflagration were generated.	-	European NTO project, Runehammar tunnel, Norway 2005 (Liu, Kashef, et al. 2007)

Type of system and setup	Discharge rates or spray density and pressure litre/(m^{2}min) or mm/min	Pressure	HRR	Type of fuel	Activation time of suppression after ignition	Ventilation condition	Geometry	Visibility and toxicity	Temperature	Results	Comment	Reference
Low pressure water mist	0.6-2.3		2-5 MW*	One pool fire	2-3	1 - 2.5 m/s Longitudinal	Ø = 40 m^2 L = 100 W = 8.0 road	Toxicity with respect to CO and O_2 acceptable. Visibility reduced to 0.5-1m during the first minutes and downstream of the fire. As the fires size and HRR reduced visibility generally increased. Backlayering and visibility improved upstream for largest fires >10 MW	Not reported	0-60 % HRR reduction	Effect of mitigation systems strongly depended on type and location of nozzle and water discharge rate.	UPTUN test program (Opstad and Stensaas 2006)
			5-13 MW*	Two pool fires	2-3					0-80 % HRR reduction		
			17 MW*	Three pool fire	2-3					80 % HRR reduction		
			22-24 MW*	Four pool fires	2-3					70-80 % HRR reduction		
			17-25 MW*	Wood pallets	>> 3					40 % HRR reduction		
High pressure water mist	0.6-2.3		4-5 MW*	One pool fire		1 - 2.5 m/s Longitudinal	Ø =40 m^2 L=100 W=8.07 (road)	Toxicity with respect to CO and O_2 acceptable. Visibility reduced to 0.5-1 m during the first minutes and downstream of the fire. As the fires size	Not reported	10-70	Effect of mitigation system strongly depended on type and location of nozzle and water discharge rate.	UPTUN test program (Opstad and Stensaas 2006)
			10-11 MW*	Two pool fires						Minor		
			15-20 MW*	Three pool fires						10-70		
			18-25 MW*	Four pool fires						10-70		
			18 MW*	Four pools with AFFF						50		

Type of system and setup	Discharge rates or spray density and pressure litre/(m^2min) or mm/min	Pressure	HRR	Type of fuel	Activation time of suppression after ignition	Ventilation condition	Geometry	Visibility and toxicity	Temperature	Results	Comment	Reference
			17-20 MW*	Wood pallets				and HRR reduced visibility generally increased. Backlayering and visibility improved upstream for largest fires >10 MW		50-80		
	0.5 – 1.5	Not reported	20 MW	Vehicle fire	8 min	Not reported	W = 9.3 m H = 2.55	Visibility upstream was reduced after activation and improved downstream. Outside: CO = 775 ppm CO_2 = 2 % Inside vehicle: CO = 210 ppm CO_2 = 0.64 %	Temperature 75 m downstream of the fire was reduced to 40˚C and inside temperature was 25˚C	Fire was controlled by the mist system and no fire spread occurred. Combustion gases was cooled the radiative heat flux reduced. Tenability conditions inside vehicles was improved.		A86 East tunnel, Switzerland

* HRR at the activation time of suppression.

Ad interim.