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Tunnel Safety and Ventilation

Sicherheit und Belüftung von Tunnelanlagen

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Institute for Internal Combustion Engines and Thermodynamics

Technische Universität Graz
Graz University of Technology

PREFACE

Ladies and Gentlemen, Dear Participants,

In 2002, the Institute of Internal Combustion Engines and Thermodynamics organised an International Conference on Tunnel Safety and Ventilation. The aim of that conference was to provide a forum for information exchange among operators, users, technicians, scientists and companies involved in the design, construction and equipping of road and rail tunnels. The success of the 2002 conference led to the organization of biennial follow up meetings.

Each conference has been accompanied by an exhibition, and each year, like the conference itself, the exhibition has grown. The success of the exhibitions has forced us to leave the confines of our University campus and to move to the roomier facilities of the trade fair centre.

Our interests and focus have also changed and this is reflected in our topics. Our first conferences were strongly influenced by the tunnel incidents of the late 1990's and related safety issues. Nowadays road tunnel operation, and the conflict between tunnel design and environmental concerns are of major interest.

Traffic is increasing, at both a national as well as an international level. Thus, while in densely populated areas there is much greater demand for sub-surface transportation, in rural areas there is an increasing need to upgrade the road infrastructure. The implementation of the EU Directive on the minimum safety requirements for tunnels in the trans-European road network (2004/54/EC) forced many of the tunnel operators to upgrade the existing tunnels.
Many of the existing tunnels (i.e. those 20 to 30 years old), are currently being refurbished and upgraded by the addition of a second tunnel tube. The construction of second tubes constitutes a big challenge in practice, as – in contrast to new tunnel construction – several prevailing structures and systems act as constraints and have to be taken into consideration in planning. There is also the additional need to ensure that traffic flow can be maintained throughout the construction period. Many of the underlying concepts in tunnel design and safety, equipment standards etc. have changed dramatically over the last decade. This often means that many of the existing tunnel structures prove to be more of a hindrance than a help in second tube construction.
The question of tunnel safety is a highly controversial field. It is often claimed that several new techniques are now on the market and that these can help improve safety due to quicker and more reliable detection, more efficient installations and/or additional equipment. However, such 'improvements' often result in significant increases in complexity, as well as in the cost of operation and maintenance of the new safety equipment. The time is now right for us to discuss what safety standards are required in our tunnels and at what price. We hope that the present conference will be of some value in such a discussion.

Risk assessment provides a valuable tool when attempting to deal with questions of safety. During the last couple of years many applications have been found for such tools. One aim of this conference is to highlight the pros and cons, as well as the limitations, of such applications.

This conference wouldn't be the "Graz" conference without the related exhibition. Many companies have put a lot of effort into presenting their latest developments and technologies. Conference participants now have the chance to get into contact with leading companies in the electro-mechanical tunnel business, to establish new contacts, and also to strengthen existing ones.

Another exciting and distinguishing aspect of the "Graz" conference is its live fire test. This final highlight of the conference will be performed in the Himmelreich Tunnel close to the city of Graz. Many thanks to the road department of the federal government of Styria in general, and to Mr. Göbl specifically, for organising this test and for providing such practical insight into the final commissioning tests used for road tunnels.

We wish to extend a special thank you to our scientific committee for its valuable work in defining the objectives of this conference, and in selecting the presentations.

We also extend our professional thanks to the authors for their hard work in preparing abstracts, papers, and of course their presentations.

And finally, we wish to offer our sincere thanks to all the people in the background who have been working to ensure that this will be a smooth, enjoyable and effective conference for us all.

It is our pleasure to welcome you all on behalf of the conference scientific committee and to wish you all a successful meeting and a sound basis for fertile networking in the future.

Peter J. Sturm Helmut Eichlseder

Graz, April 2012

NEW SEMMERING BASE TUNNEL, PROJECT DESCRIPTION AND VENTILATION CONCEPT

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ABSTRACT

The New Semmering Base Tunnel is one of the most important infrastructural projects in the heart of Europe. The 27.3-kilometer-long, twin-bore tunnel, with an emergency stop in the middle, connects Gloggnitz in Lower Austria with Mürzzuschlag in Styria. The emergency ventilation includes air extraction and supply through a 400-meter-long shaft situated at the emergency station. This article gives an overview of the tunnel project including a description of the ventilation concept.

Keywords: rail tunnel, ventilation requirements

1. INTRODUCTION

The New Semmering Base Tunnel is one of the most important infrastructural projects in the heart of Europe. This twin-bore railway tunnel stands as a long-term investment in Austrian business, creating substantial value and a positive influence on the Austrian employment market for years to come.

The Südbahn southern railway line is the central connecting section of the trans-European, high-speed line from the Baltic to the Adriatic. As a result of the extension and modernization of this Baltic-Adriatic corridor via Warsaw and Vienna, Austria is gaining access to new markets and economic areas. Together with Vienna’s new main railway station, the redevelopment of Graz main railway station and the Koralmbahn section, the New Semmering Base Tunnel ensures that the Südbahn line will remain attractive with a secure future, both for goods and passenger transportation.

The 27.3-kilometer-long tunnel connects Gloggnitz in Lower Austria with Mürzzuschlag in Styria. The route implemented was selected as the best of a total of 13 variations. This involved investigation and consideration of aspects relating to the areas of transport and technology, location and environment along with economic criteria.

In addition to the twin bores, the tunnel construction also comprises:

- architecturally sophisticated entrance designs in Gloggnitz and Mürzzuschlag
- the intermediate construction sites at Göstritz, Fröschnitzgraben and Grautschenhof, which play an important role in the construction phase
- the Longsgraben spoil dump with a capacity of up to 5 million cubic meters for the disposal of excavated material
- temporary roads for construction site access and to reduce the load on public transport during the construction phase
- comprehensive hydro-engineering measures for flood prevention

- an emergency stop around the midpoint of the tunnel
- construction-phase ventilation shafts in Trattenbach and Sommerau, which are necessary for the supply of fresh air during the day
- an auxiliary bore
- and railway power supply lines and substations in Gloggnitz and Langenwang for supplying electricity to the trains in the tunnel

The New Semmering Base Tunnel consists of twin parallel bores each of around 10 meters diameter. The twin bores have a separation of between 40 and 70 meters and are connected at maximum intervals of 500 meters by cross-passages (see **Figure 1**).

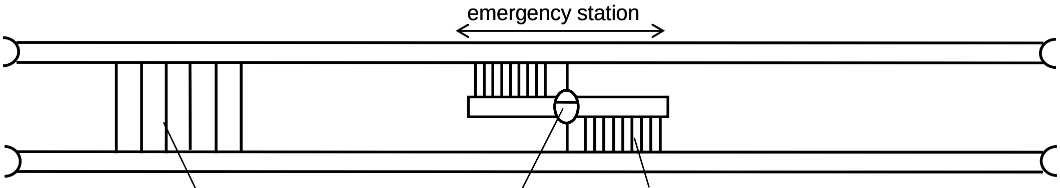

Figure 1: Schematic of the New Semmering Base Tunnel

Thus the tunnel fulfills the latest requirements for tunnel safety. In the event of a train breakdown, passengers can be evacuated via the cross-passages. In addition, around the midpoint of the tunnel and between the main bores is an emergency stop. Here, in an emergency, passengers can move to a safety area via escape tunnels and be brought out of the tunnel from there (see section 3).

From the point of view of transportation engineering, the New Semmering Base Tunnel constitutes the necessary complementary development of the historical Semmering mountain section.

In contrast with the 42-kilometer-long mountain section, the 27.3-kilometer-long tunnel has a very small gradient of only 0.84%. This means that even the heavy goods trains of up to 1600 tons, which negotiate the southern route daily, can be pulled by a single locomotive. The Base Tunnel allows speeds of up to 250 km/h along the Semmering section. It therefore merges seamlessly with the high speed network for trans-European passenger and goods transportation and offers a modern level of comfort with substantially reduced journey times. The tunnel is a robustly forward-looking complementary development of the UNESCO-World-Heritage Semmering mountain section, which will also continue to operate. Work will begin on building the New Semmering Base Tunnel in 2012 (tunneling will begin in 2014), with completion planned for 2024.

Initially there will be hydro-engineering work for flood prevention on the Schwarza in the area of Gloggnitz. This phase of construction also includes two new railway bridges, a new road bridge and underpass construction for the B27 trunk road. Site clearing and preparation of a construction area in Gloggnitz form the preparatory work for actual tunnel construction.

Depending on geological and hydro-geological conditions over three principal phases of construction, a variety of tunneling methods will be applied. In **Figure 2** excavation using tunnel boring machines and conventional excavation by diggers and blasting are shown.

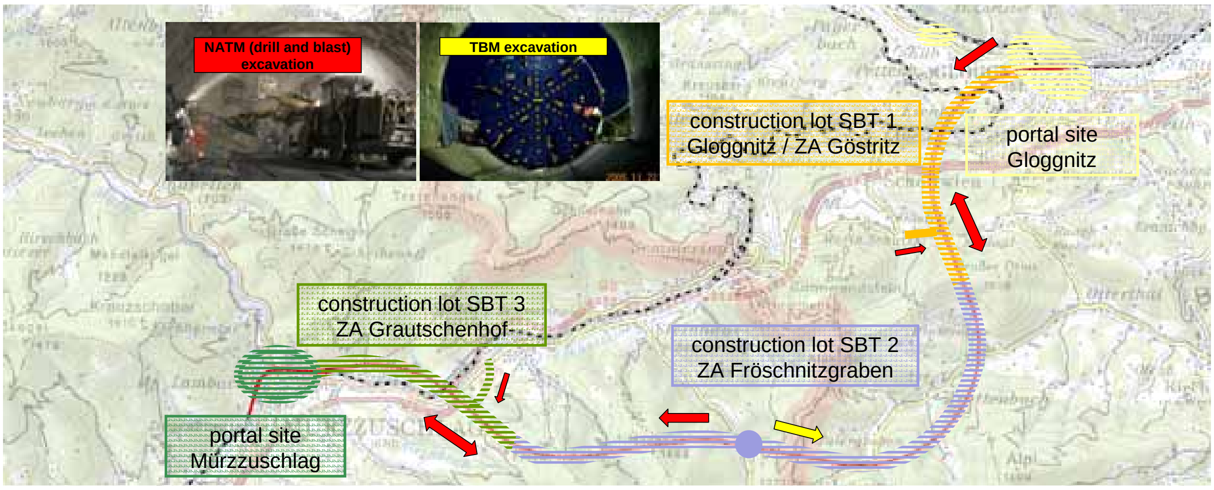

Figure 2: Tunneling methods

In the case of tunneling by boring machine, the cutter head of an approximately 200-meter-long boring machine digs through the rock. The tunnel bore is secured by pre-cast concrete sections, the liner segments. Once installed, they serve to react to the load from the boring machine for the next section of excavation. Very high excavation rates are possible using this tunneling method.

In the case of conventional excavation, also known as the “New Austrian Tunneling Method (NÖT)”, the material is extracted by blasting or by diggers and then dumped, meaning it is brought out of the tunnel by dump trucks. After each stage of blasting, the vault of the tunnel is secured using sprayed concrete, steel reinforcement and tie bars, and in this way, the tunnel grows bit by bit.

Several intermediate construction sites are foreseen in order to comply with the planning to finish work in 2014 (cf. **Figure 3**).

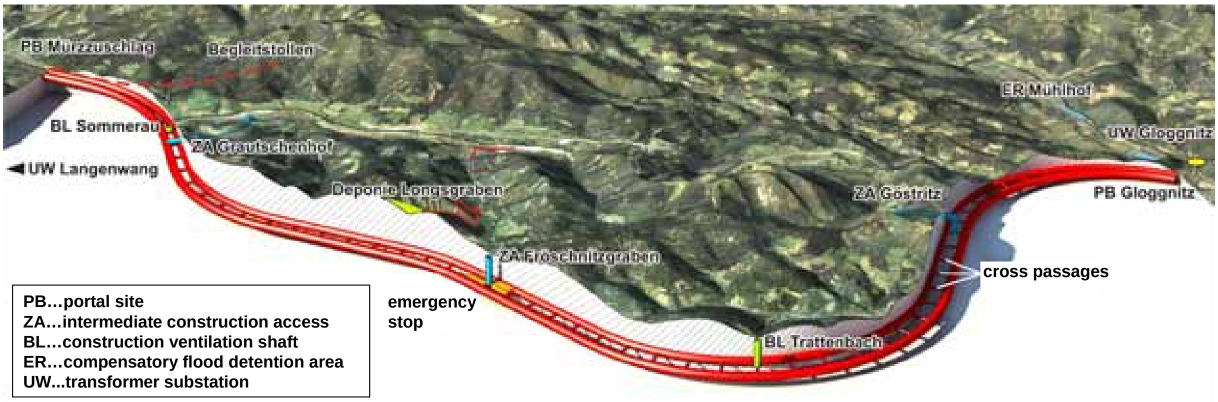

Figure 3: Tunnel overview with intermediate sites

At the Göstritz intermediate site, in a particularly challenging zone for tunneling, excavation will be conventional, employing a combination of 1000 meters of gallery and around 250-meter-deep shafts in the mountain down to tunnel level.

At the Fröschnitzgraben intermediate site, first of all two shafts will be sunk more than 400 meters deep and up to 22 meters in diameter. The emergency stop will be built at the foot of these shafts. It is then from here that the tunnel boring machines will start work in the direction of Gloggnitz.

At the third intermediate site, Grautschenhof, tunneling will take place via an approximately 1300-meter-long access gallery towards the Fröschnitzgraben intermediate site and Mürzzuschlag.

All shafts and galleries will be closed off after construction of the tunnel, except for one shaft at Fröschnitzgraben, which will be used for ventilation when the tunnel comes into operation.

The Semmering area constitutes a valuable ecological system and its protection has the highest priority. Particular attention was therefore paid to all relevant aspects of the environment during planning for the environmental impact statement, above all the topics of ground, mountain and surface water in this water-rich area.

The following aspects were also investigated:

- climatic and air pollutants
- noise and shocks
- regional development and local land-use planning
- animals and plants and their habitats
- agriculture and forestry and many more

Ahead to the year 2019; construction work on the New Semmering Base Tunnel is progressing according to plan. The heavy machines are still boring, digging and blasting their way through the mountain where, in a few years, goods and passenger trains will pass through Semmering via a state-of-the-art tunnel.

Once tunneling is concluded, the structure will be equipped for forthcoming rail traffic:

The tunnel outer shell is necessary to support and secure the overlying rock. The water-collecting drains lie within the subsequently installed invert concrete.

The next activities are to construct the supports for the tunnel arch concrete, install the longitudinal drainage which collects the water, and line the tunnel bores with arch concrete.

With its various layers, the track superstructure must withstand axle loads of up to 22.5 tons.

Cable ducts in both peripheries carry cables whose total length exceeds a million meters. A total of 54 kilometers of illuminated handrail ensure a sense of orientation. The equally long overhead cables supply the trains with power at 15,000 Volts.

A milestone for construction of the New Semmering Base Tunnel was set in May 2010 when over 10,000 pages of reports and 700 m^2 of plans were submitted to the relevant authorities. Once the official notifications are issued by the authorities, work will begin on preparatory construction in 2012 and actual tunneling will start in 2014.

Thus, in 2024, the future of rail transport on the southern railway line (Südbahn) will become reality, matched to the requirements of the Baltic-Adriatic axis.

2. SAFETY CONCEPT AND VENTILATION REQUIREMENTS

The Tunnel Safety Concept of the New Semmering Base Tunnel is based on the regulations for Austrian rail tunnels, which are being designed at the moment or have been established in recent years; for more information (cf. [1]). Within the safety concept of the New Semmering Base Tunnel a range of specific protection goals were defined. The protection goals which concern the ventilation concept include:

- The creation of a safe area in the middle of the tunnel system (emergency station).
- Emergency station, non-incident tube and portals are safe areas (cf. [2]) and should remain free of smoke for at least 180 minutes.
- Avoiding further danger to following trains in the incident tube.
- The prevention of the simultaneous entry of smoke into both tubes as a result of a fire in a technical room.

The following main ventilation objectives have been derived based on the protection goals:

- In order to prevent smoke propagation through open cross-passages (tunnel) and escape passages (emergency station) into the safe areas, there must be a sufficiently high over pressure in the non-incident tube and in the refuge room of the emergency station with respect to the incident tube. For hot incidents in the tunnel this objective is implemented by the requirement of a minimum flow velocity through open cross-passages.
- In order to prevent smoke propagation into the non-incident tube at the portal regions, the exit of smoke from the incident tube must be avoided or the outflow velocity from the non-incident tube must be high enough to prevent smoke entry. This objective is implemented by the requirement on the flow velocities in the tunnel tubes.

Further ventilation criteria / requirements include:

- not to exceed the maximum allowable flow velocity through open cross-passages (v_{max} = 10 m/s) to prevent a negative impact on the escape procedure,
- low air flow in the incident tube (to prevent a rapid smoke propagation and an impairment of the smoke layering),
- high reliability by low complexity of the ventilation system and its control.

3. VENTILATION CONCEPT

During normal operation, ventilation is achieved by the train-induced piston effect. Hence, no active ventilation is foreseen.

During maintenance work, one tunnel tube will be completely closed. Pollutants produced by working machines, e.g. exhaust emissions from engines, will be sufficiently diluted and transported out of the tunnel system by the extraction fans (250 m^3/s).

In the event of a hot train incident, the two design scenarios "Incident in the emergency station" and "Incident outside the emergency station" have to be considered.

Incident in the emergency station

When a fire is suspected due to a report from the driver or irregularities in operation, the emergency station will be prepared for train evacuation (cf. **Figure 4**):

- doors in the emergency station from the incident tube into the escape area are opened automatically,
- fresh air is fed into the escape area (150 m^3/s) and
- air is extracted at the emergency station (250 m^3/s).

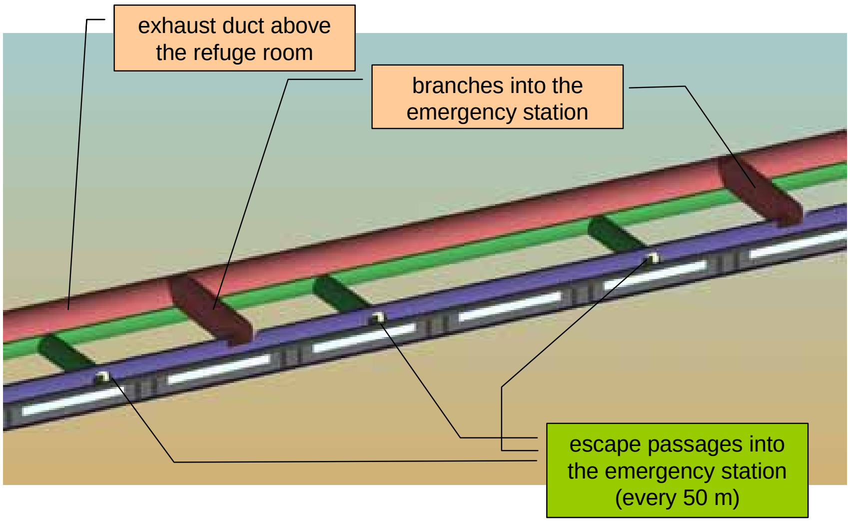

Figure 4: Duct system for the ventilation in the event of an incident with a train stopping at the emergency station

Three supply- and three extraction fans are foreseen. The actual planning status of the smoke extraction in the emergency station is described in section 4.

Incident outside the emergency station

If the incident train stops outside the emergency station:

- the open doors in the emergency station (prepared for the event of an incident in the emergency station) from the incident tube into the escape area are closed,
- fresh air is reduced (100 m^3/s) and fed into the non-incident bore and
- air is still extracted at the emergency station (250 m^3/s).

Simultaneous air extraction from the incident bore and air supply into the non-incident bore leads to a pressure difference between both tunnel bores (**Figure 5**). Hence, air flow from the non-incident bore into the incident bore through open cross-passages prevents smoke propagation into the safe area.

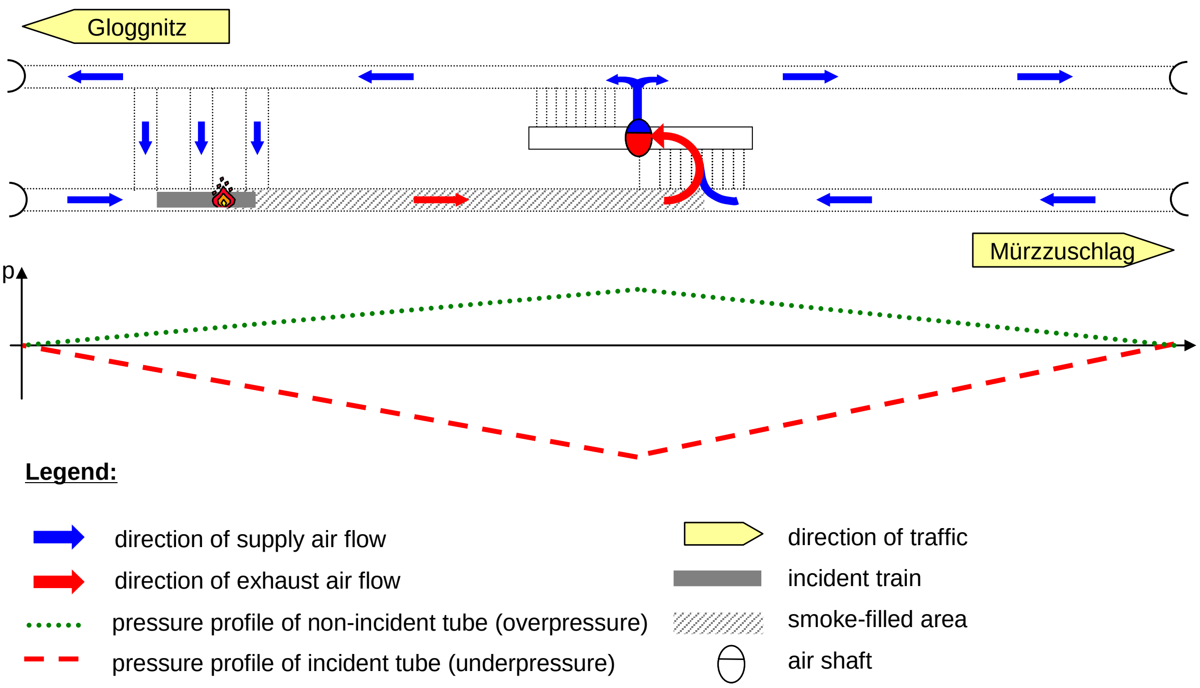

Figure 5: Ventilation scheme and pressure profile for an incident with a train stopping outside the emergency station (dashed line = incident tube, dotted line = non-incident tube)

4. CURRENT STATUS OF THE PROJECT PLANNING

4.1. Smoke extraction in the emergency station

The design of the extraction system was chosen based on project-specific protection goals and ventilation criteria. Two possible smoke extraction systems were investigated with the help of 1D simulations based on a variant study:

- Extraction at the ends of the platform: Two extraction locations at each end of the emergency station,
- Distributed extraction: Five extract locations along the emergency station.

3D simulations showed that the conditions for self- and third-party rescue are much better with a distributed smoke extraction with 5 extraction locations along the emergency station. The main advantages are (cf. **Figure 6**):

- Much better smoke and temperature stratification on the emergency platform.
- Shorter retention time of the smoke in the emergency station.
- Shorter smoke-filled sections along the emergency station.

Distributed smoke extraction along the emergency station (five extraction points) is applied for the long tunnels crossing the Alps (Lötschberg Base Tunnel, Gotthard Base Tunnel, Brenner Base Tunnel). Hence, this is a state of the art solution.

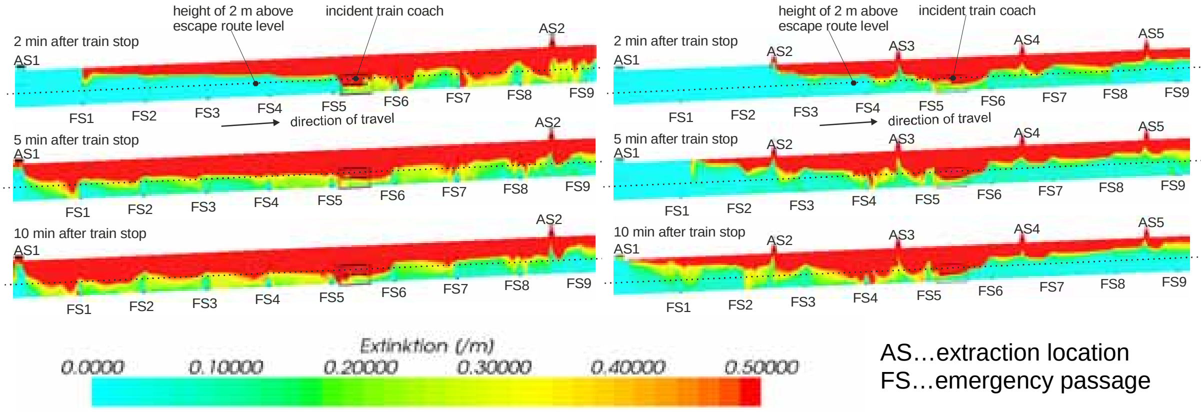

Figure 6: Extinction coefficient in a longitudinal section in the emergency station for different times
(left figure: 2 extraction locations, right figure: 5 extraction locations).

4.2. Air quantities

There must be a sufficient positive pressure in the safe area in comparison to the incident tube to ensure that smoke cannot cross over when the cross-passages and escape passages are open. The air supply and extraction quantities are designed as follows:

Extraction quantity (250 m^3/s)

Various aspects had to be taken into account for the determination of the extraction quantity. In case of an incident where a train stops at the emergency station, there should be no airflow back out of the emergency station, even if the portal pressure difference is high or if a fan stops. The extraction quantity is also to be designed to ensure a sufficiently high flow velocity through open cross-passages, even near the outermost cross-passages, so that smoke propagation can be prevented, even under unfavorable conditions. With the help of an event tree analysis it has been shown that the extraction quantity of (250 m^3/s) is adequate (cf. [3]).

Air supply quantity (150 m^3/s)

The main function of the air supply is to prevent smoke entering the safe area in the emergency station. 3D simulations showed that for the distributed extraction along the emergency station (cf. section 4.1) an air quantity of 100 m^3/s is close to the lower limit. Either additional structural or ventilation measurements are required for the distributed extraction. To reduce the danger of smoke entering the escape area the air supply quantity was increased compared to the submission project. It could be shown with the help of 3D simulations that the higher sideways flow does not impair the smoke layering in the emergency station when increasing the distance of the escape doors to the emergency platform.

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REFURBISHMENT, RISK AND RESPONSIBILITY – DECISIONS WHEN UPGRADING TUNNEL FIRE PROVISIONS

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Stacey Agnew Pty Ltd

ABSTRACT

This is a paper as much about the governance and contractual management approach to refurbishing tunnels as it is about the treatment of risk.

In new road, rail or bus tunnels in Australasia, a variety of factors has caused a ratcheting-up of fire safety provisions, often leading to every conceivable measure being included at the project conception stage and not critically questioned at later stages. The 'FEB Process' is then often a charade in which we (the project) pretend, via the "process", that we don't know by inspection that the tunnel is safe enough and we (fire engineers) spend a lot of time on sometimes questionable analysis to 'test the trial design' before concluding it is OK.

If there is wasted expenditure in any over-provisioning, it is hidden by the massive civil costs of tunnelling. In a refurbishment, the mechanical and electrical plant is closer to 100% of the project cost, and so there is more focus on justifying the fire safety design and its cost. There is also generally a contractual framework which facilitates such questioning. Consequently, the decisions for tunnel refurbishment projects can be very different, particular in tunnels which have a very high access cost because they are already in heavy use.

We also know that, for most modern tunnels, the absolute risk cannot justify half the gear we put into them, yet the community has a heightened perception of the risk and an understandable aversion to major incidents or entrapment, however low the probability. Those responsible for the judgments on risk and expenditure have a difficult task. This paper discusses the flaws inherent in the common fire engineering approaches to tunnel fire safety and seeks to offer a new simpler perspective for the governance and project decision making around the provisions to be included in a refurbishment design. The thoughts offered may be useful in getting to the right answer for project teams, giving context for a clear justifiable decision basis in the project's format.

Keywords: tunnel refurbishment, decision, fire, safety, risk

1. THE CONTEXT

There are a number of points to be made about the risk from fire in road tunnels which set the context for the fire safety design.

1.1. Very low relative risk

The first point is that the fire risk to occupants in modern unidirectional road tunnels is in fact very low. A study for the 4.7 km Clem Jones Tunnel in Brisbane indicated a risk due to fire which is at least three orders of magnitude lower than the risk from all causes on open roads. (It is noted that the Clem Jones Tunnel has a smoke duct which most Australasian tunnels don't have). There will be other differences between the Clem Jones Tunnel and any other project, however the order of magnitude estimate is considered relevant. Similar results have been seen for other tunnels.

1.2. Economic rationalist approach

At such risk levels, and with competing demands for funds to reduce risk or provide benefit elsewhere, it is not justifiable to spend noticeable sums to further reduce the risk. Indeed, at that level of risk, on an 'economic rationalist' value for money basis, the reduction of risk has probably absorbed too much investment already. Government (or private) funds would better be spent on 'black spot' road programs, hospitals or perhaps more tunnels.

1.3. Community perception of risk

Counter to the economic rationalist approach, the community generally, the media, and political leaders have a heightened sensitivity to fire incidents in tunnels. The community is generally more sensitive to risks in tunnels than say open roads. We saw an example of this heightened sensitivity after the 2007 Burnley Tunnel incident. In that incident, three people died and Melbourne had extraordinary congestion during the three days for which the tunnel was closed. The loss of three lives is tragic, but, seen in the context of the 333 road deaths that year in Victoria, and 1616 road deaths for 2007 Australia-wide, it is peripheral to the overall road safety statistics. And yet, the incident was the subject of a coronial inquest lasting many years.

Other parts of community expectation include the attitudes to catastrophic events and the need to facilitate response. The community generally expects strong measures to be taken to avoid catastrophic events, regardless of how unlikely they may be. That is; the focus is more on consequences than on risk (which is the product of consequences and probability). Measures directed at avoiding catastrophes, and which have a community cost out of proportion with the risk reduction, may well still receive community support. That is; a rapidly growing fire event in a tunnel full of stopped traffic, which might have more severe outcomes than the 38 fatalities in the Mont Blanc fire, should perhaps be 'prevented' at any cost.

The prospect of an event proceeding with no ability for emergency services to effectively intervene is also seen as unacceptable, again without particular reference to likelihood or real risk. The community expect that, if people or critical assets are threatened, the intervention of the fire brigades to effect rescue or preserve the tunnel will be facilitated in reasonable ways. The prospect of being helpless in a developing emergency may be more frightening than the final consequences and evokes an emotional response which supports enhanced provisions being made, again with diminished regard to the probability of the situation.

There is also the question of informed risk acceptance. Risk acceptability varies with the level of prior knowledge about the risk, and with the person's own level of control of the risk. On the open road, there are considerable risks. Some are 'random' and some are related to the skill of the driver. All of them are well known to all in the community. When driving out onto the road, we do so in full knowledge of the risks, both those in our control and those visited upon us. If there were additional risks unknown to us, but known to an authority or designer, we might reasonably expect those risks to be controlled to a level below the risks we had knowingly accepted. It could be argued that fire risk in tunnels is a risk that the community is aware of; however it still seems reasonable that the risk level be brought below that on roads generally.

That the individual's control of risk factors, knowledge of the risks and acceptance of the risks has an impact on acceptability can be demonstrated by a comparison at Mont Blanc. In 1999, 38 people died in a fire in the Mont Blanc road tunnel. It made world news for weeks. In 2008 on Mont Blanc, there were 58 deaths, with 10 missing presumed dead. The difference was that the 2008 deaths were all people who thought they knew of the risks, that they were in control of them, and had accepted them. They were climbing the mountain. The people who died in the road tunnel perhaps did not make such a conscious decision to accept a risk.

If we are to design tunnels in response to community perceptions and not as economic rationalists, and the Burnley and Mont Blanc responses are indicative of community perceptions, then a risk from tunnel fire three orders of magnitude lower than other driving risks might not be inappropriate.

There are also reputational, operational and service continuity risks which may change the perception of value and hence alter the above conclusion. Whatever risk is considered, it is recognised that reduction of risk comes at a cost and that the community acceptability of risk must ultimately be related to the costs, either financial or otherwise, of further reducing risk.

1.4. Fire Engineering prior practice

In Australasia, the assessment of tunnel fire safety had fallen into a fairly narrow approach, driven by building code “performance-based design” practitioners. Analysis is often done in a deterministic way to show that the ‘available safe egress time’ (ASET) exceeds the ‘required safe egress time’ (RSET) by some margin, for a range of ‘worst credible’ parameters. However, the nature of tunnel fire risk, in that very rare but very severe scenarios contribute the majority of the remnant risk, leads to problems in 'proving' tunnel safety by applying such deterministic approaches which are commonly applied in less complex situations. Comparing RSET against ASET falls down for a couple of reasons. The first is in selecting the "design fire".

The huge range in possible fire sizes and growth rates in road tunnels means that it is possible to argue for adoption of design fires which either don't threaten anyone, or which will almost certainly cause fatalities when applied in parallel with conservative egress models. Selecting a design fire which makes the method work for tunnel configurations believed to be "safe" is then only making the method suit the answer and not really proving an answer.

The second way in which the ASET vs. RSET approach falls down is in the statistical nature of the input parameters. If there are only two or three parameters (time to respond, walking speed etc) in a simple case, then taking conservative or limiting values for each gives a highly unlikely scenario. If there are a dozen or so parameters, the chance that all of them will be at their worst value is so low that an already very rare major fire case will be taken to extremes of probability where a much lower level of overall system performance is acceptable.

That is; combinations of Normally distributed parameters taken at their 3σ value do not give a scenario which is at the 3σ value in overall severity. In fact the case is so improbable that it should not be considered as a design case for pass/fail judgement of the systems. It does not take all parameters to be at their extreme values to make an already improbable situation extreme. Choosing more central estimates is also not particularly informative as, for example, the 50 percentile fire might be around 1 MW and not a threat to anyone. Such analysis may be carried out in order to understand likely response limits and inform response planning, however it is not appropriate that it form the central part of the design acceptance criteria.

The ways to handle such variability in parameters are via an event tree style assessment, or better still, through Monte Carlo simulation. In the author’s experience, the answers, for all modern, reasonably well-equipped tunnels, will show that risk is so low that no further expenditure should be considered. That is where the discussion in this context section started.

1.5. ‘Ratchetting-up’ of safety measures

As it seems that the economic rationalist optimum expenditure on risk cannot, on its own, guide the design, we are left to work with the less defined 'community expectation'. However, there is a danger that in relying only on community expectation, provisions and costs increase with each project, without proper assessment of need or value. Whether or not the measures implemented on earlier projects were justified at the time, their very existence creates a community expectation that they are more than justified, and are in fact the minimum essential measures for a new project.

Community expectation can also have a politico-legal amplification. It is often politically difficult to say that a new project does not need as many risk reducing measures as an earlier project. In the continuous spectrum of community attitude to risk, there will always be some who are close to the high expenditure end, calling for every conceivable measure to be in place. There are many issues to be addressed politically for a new tunnel project. If the extra fire safety provisions only add a few percent to the cost of a new tunnel, it is easy politically to put them all in, effectively removing risk from the project debate. While the few percent cost change is swamped by other issues in the public eye, it could still be tens of millions or even a hundred million dollars on a major project.

The legal amplification comes about from the fear of a claim. In adding a design feature, an employee or a consultant will be aware that they are spending the owner's money. They will also be aware that, should there be an incident with the feature in place, they cannot be criticised (or sued) for leaving the feature out. There might be considerable work involved in documenting and arguing the case that the feature has minimal benefit and is not justified. Going down that path may cause them to run over the design budget, which causes immediate pain. It is not common for employees, consultants or contractors to be given grief for going too far (spending too much client money) on public safety. The path of least resistance is then to put the particular feature in and complete the documentation quickly.

The contracting framework often contributes to a monotonic increase in provisions and cost with each new project. At project inception, an owner’s consultant can prepare conservative documentation, leaving the ‘optimisation’ to bidding Design & Construct teams. Those D&C teams then have short tender periods, difficult change approval processes, and client perceptions to manage, so are very unlikely to ‘optimise’ far from the established path. The last contracting issue is drawn in by contractual phrases such as: “to the satisfaction of the fire brigade”. The fire brigade will be equally nervous about criticism for leaving a feature out, they have no responsibility for expenditure by any other party, and, even if they were responsible for cost-risk trade-off, not all fire brigades have the expertise to make the risk judgements which we are grappling with here. Without the benefit of constraining guidance from the government parties, such contract clauses push the design in only one direction; decreasing an already low risk, and increasing cost.

The alliance project delivery method, properly run, can assist in promoting rational and holistic decision making and the author has seen good examples.

1.6. Brownfield sites

Refurbishments are generally severely constrained in the changes that can be made. Engaging in any civil or structural work would typically increase the project cost several-fold, and so typically the tunnel internal cross section is fixed and any new drainage, equipment or egress provision must fit within the available envelope. Even where the envelope is altered, there will be geometric and logistical constraints which would not be present were the refurbished tunnel being designed from scratch as a new tunnel.

The refurbishment of an operating tunnel is also more expensive than a new build as the work must be done with the traffic operation in mind. If that does not restrict the work to shifts late at night and over weekends, then there may also be an economic cost attached to the tunnel unavailability.

These factors increase costs and change the cost-benefit in favour of doing less work, and making fewer provisions. Whereas the civil costs may mask the fire safety costs in a new build, in a refurbishment, the fire safety costs are clear. For these reasons, in refurbishments, there tends to be a sharper focus on what level of provisions are really required.

1.7. Traffic operations

Significant tunnels in Australasia are generally monitored and controlled 24 hours a day. The diligent operation and supervision of tunnels, particularly the traffic control and incident response, is probably the most significant feature in ensuring the safety of tunnel users in a fire incident. Besides ensuring that incidents are noticed and responded to intelligently, traffic control can almost completely eliminate stopped traffic in unidirectional tunnels, taking the probability of people being downstream of a fire to almost zero. A key element of refurbishments is often modernising the communications, supervision and control systems, perhaps involving a control room for the first time in the tunnel's operation. Thus the planning for the refurbishment and the overall safety case needs to be operator focussed.

1.8. Safety in Design

Addressing fire safety in tunnels often results in more equipment being installed. That introduces additional risks for workers during construction and also through maintenance. Such risks need to be weighed up against fire risk reduction. For example; are the construction safety risks from smoke duct construction actually greater than the corresponding reduction in fire safety risk?

1.9. Context Summary

The absolute risk, given by a quantitative risk analysis, of tunnels resulting from conventional design practice is generally so low that it cannot guide the design decisions.

Prior project provisions are not sufficient justification for any design approach, as the reference project(s) may have been over-provisioned and may have a different cost structure and opportunities. However prior projects may give useful reference points.

Community expectation is a complex thing, and one which most of the project participants are not equipped to, or empowered to, make judgements on. (Note though that it is our profession's responsibility to advise the project leaders of our view on such matters.)

Tunnel fire risk can be very strongly influenced by traffic management and there will be a strong interface between the developing fire safety design and the separately detailed traffic management and incident response plans.

2. THE PROBLEM

The problem is how to decide what goes into the refurbished tunnel. How safe does it need to be? How do we justify costs? Or alternatively, how do we justify omitting features to give a lower expenditure? In the absence of a unified field theory type of resolution to tunnel fire safety, how do we organise the governance framework and technical assessment to arrive at an answer, particularly for the less clear-cut case of refurbishment?

3. THE ANSWER

The following approaches have worked for the author on tunnel refurbishment projects.

3.1. Risk - keeping it simple

In explaining the approach within projects, I have sometimes found it helpful to borrow and adapt the 'fire triangle', which has been used in public education to explain fire risk minimisation through noting that fires must have three components; air (oxygen), fuel, and heat and that loss of any one will eliminate the fire. In tunnels, given a fire occurrence, life safety risk is created by having people on both sides of the fire (bidirectional or stopped traffic), having smoke descend to roadway level, and having no apparent escape. Thus the three sides of the tunnel smoke risk triangle are traffic state, smoke logging and entrapment. Eliminating any one of these nominally gives zero risk to all occupants not intimately involved with the fire. Eliminating two triangle sides is clearly a preferable approach, giving some redundancy to cover for any failure to successfully or completely eliminate one or the other. By seeking to eliminate all three with sufficient vigour to ensure a reasonable probability of success at each, the risk from an already rare event (major fire) falls to levels that comfortably meet community expectations and are orders of magnitude lower than our benchmark open road risk.

3.2. Responsibility

From the above, the first part of the answer is that the project must make reasonable efforts to:

- prevent stopped traffic (by design and by operational management);
- appropriately manage and, if possible, remove or blow away smoke, and;
- provide opportunity through egress paths, lighting and signage for people to rescue themselves.

What constitutes 'reasonable efforts' will be addressed later. Outside the efforts to dismantle the triangle of smoke risk, there are two other design responsibilities related to community expectations. The project must also make reasonable efforts to:

- facilitate the intervention of emergency services (firemen), and;
- protect the structure and fittings to provide for rapid resumption of traffic operations after the fire.

These last two points are the real drivers for installing fire suppression in tunnels. Water-based suppression may have life safety benefits when the smoke risk triangle remains intact (traffic on both sides, no smoke control and no egress) and also for any people trapped in the incident vehicle(s). If there has been any success in dismantling the smoke risk triangle, the benefits of water-based suppression are no longer related significantly to life safety.

3.3. Refurbishment

The brownfield nature and the geometric constraints of refurbishment sites may prevent the effective achievement of some of the above five points in Section 3.2. Here 'prevent' means that the cost is such that the funds are not realistically going to be made available. This places more emphasis on addressing the other points well.

For most tunnels, there will be a number of refurbishment options, consisting of combinations of different approaches to addressing the five points to various extents. The exception is bidirectional single-tube tunnels over say 300 m long. Of course older tunnels needing refurbishment are more likely to be in this class. In such tunnels, the traffic case cannot be effectively addressed, with vehicles almost guaranteed to be on both sides of the fire for any significant traffic flows. If the smoke control can only be longitudinal, and there is also no cross section available to build a separate egress passage, the smoke risk triangle is intact. This situation then requires emphasis both on the reliable operation of equipment to suppress the fire, and on the systems to monitor the tunnel and facilitate rapid evacuation of motorists out to the portals. The author is involved in the refurbishment of two tunnels with these characteristics; one a 460 m long tunnel with large, high cross section, and one a 610 m long tunnel with a smaller cross section. It is the author's opinion that the 460 m long tunnel is about at the length limit where suppression, egress planning and vigilance can be seen as sufficient compensation to allow long term operation. For the more restricted 610 m tunnel, those measures are seen as only interim, with either effective smoke capture or additional egress, or both, to be planned as part of a subsequent upgrade. Additional egress provisions would necessarily involve mining works.

3.4. Design and decision methodology

Experience in cost-constrained tunnel refurbishments has given rise to a detailed decision approach, with a number of elements that can be included to varying extents depending on the owner's needs. As they will vary for each project, and this paper is specifically about the discharge of responsibility in managing risk, it is sufficient here to note steps in an overview form, with some elaboration on key risk-related steps.

1. Natural opportunities

   The very first step is to creatively explore opportunities and possible synergies that may allow the five critical points to be addressed economically. For example;
   - Is the duplication likely to be in time to provide better egress? or;
   - Can the local swimming pool be the suppression reservoir (the level might only drop seriously every hundred years or so)?, or;
   - What can the existing water system deliver and is that useful?

   This is a creative activity, requiring that all contributing disciplines have not only good senior level insight (as opposed to journeyman capability) but also enthusiasm for jointly seeking good ideas.

   Since the blank sheet of a new design is not available, and we know that the absolute risk justifies almost nothing, we must look hard for natural opportunities for addressing the key five points.

2. Chase down and verify inputs and requirements

   It is surprising how often the assumed immutable client or third party requirements morph or dissolve when the ultimate authority is checked in the context of the likely consequences of the stated requirement. This step is often missed.

3. Identify scheme options

   There may be combinations offering different strengths, for example excellent egress and nominal smoke control, or full smoke extraction and lower standard egress.

4. Eliminate schemes not seen as making reasonable effort on the five points

   Here the test of reasonableness comes up again. The only real arbiter of this is the government as representatives of the community. Generally this responsibility will be borne by executive staff of a government agency charged with delivering the project. The project fire engineers can advise and argue the case, but final decisions can only be made by the government officers who act for the community both in accepting outcomes and in laying down cash.

   The biggest mistake is in confusing the responsibility and authority of the project's government 'owner' with the comments and input from other third parties, and assigning each similar weight. There is a trend in Australia, supported by a document interestingly called "International Fire Engineering Guidelines", to append: "...as agreed by stakeholders" to decision approaches. With the exception of some legislative fire service responsibilities (or Authority Having Jurisdiction in the USA), this is of course a nonsense, as all other third parties need only be accommodated to the satisfaction of the sponsoring government agency. Generally these other parties ('stakeholders') will be new to tunnels and should comment and question, but will not understand the issues in sufficient depth to make determinations. They certainly are not in a position to assess cost-risk trade-offs.

   Occasionally, if third parties seek to exert influence beyond their authority or expertise, the sponsoring agency might need to bring the decision process back on track, and the project should not be backward in requesting such involvement.

   The judgement of reasonableness of the response to the five points can now be clarified. With the decision authority structure clearly understood, the sponsoring agency receives advice on which refurbishment options are reasonable in terms of the effort made against the five key points. The agency then makes a determination after asking whatever questions and making any other enquiries they see fit. Options where the effort is not reasonable are eliminated from consideration. It can be that straightforward.

5. Compare and score options.

   One option may have a slightly different risk profile to another, and that could be bundled-in and assessed, scored and weighted as part of the options comparison. However, if the risk difference is such that it has a materially different monetary value, then the risk is really too high and would not meet community expectations. The higher risk option should be discarded. The project team is then left only with options which have acceptable (and quite low) fire safety risk. The options assessment can proceed without risk as a parameter.

3.5. Governance

Sensible decisions require good project governance. Some well intentioned projects lose direction through having 'mediocrats' in the leadership structure. Mediocrats are those who preside over a mediocracy and for whom any decision is OK as long as there is one and the timesheets are in order. Matters of technical principle are then negotiable and may be buried for political purposes. Obviously, the outputs of a mediocracy are mediocre.

4. SUMMARY

Based on the arguments above, it is the author's contention that:

Quantitative Risk Analysis (QRA) will not get to the answer on how a refurbishment should provision a tunnel. While time consuming and hence lucrative for an hourly rates consultant, the fact that it gives such low risk outcomes and points to a level of provisions much lower than the owners and regulators would accept means that it is excluded from meaningful contribution. Further, as QRA will necessarily be accurate to an order of magnitude at best, it is difficult to realistically compare options which involve different types of risk calculation inputs.

Asking third parties, including fire brigades, what level of risk they would accept (eg: expected fire fatalities for the 100 year life) is not productive. Despite most fire service legislation giving some role to advise on fire risk reduction, fire brigades are not generally equipped to nominate such a figure, despite their government's treasury departments generally maintaining figures with names such as 'the economic value of avoiding a fatality' (not 'value of life'). Only the sponsoring government agency can decide that. Given the point above, the decision will be made on assessed "reasonableness" and not on an absolute risk figure.

Responsibility can be discharged by making reasonable efforts to:

- prevent stopped traffic (by design and by operational management);
- appropriately manage and, if possible, remove or blow away smoke;
- provide opportunity through egress paths, lighting and signage for people to rescue themselves;
- facilitate the intervention of emergency services (firemen), and;
- protect the structure and fittings to provide for rapid resumption of traffic operations after the fire.

While the project must offer advice, the decision as to whether efforts to address fire safety are 'reasonable' can only be made on behalf of the community by the government agency sponsoring the project, as only they answer to the community for both safety and cost.

RISK ANALYSIS AS DECISIONMAKING TOOL FOR TUNNEL DESIGN AND OPERATION

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ABSTRACT

The EC-Directive 2004/54/EC established risk analysis as performance based approach for the assessment of road tunnel safety. The paper presents a survey of typical applications for risk analysis, focussing on its application as decision making tool. 3 case studies provide insight in typical problems addressed by risk analysis: For the existing Učka Tunnel in Croatia, the decision on the ventilation system of the planed second tube was taken on the basis of a risk analysis, for the Markovec tunnel in Slovenia, the influence of specific wind conditions on tunnel risk and its consequences on the layout of the ventilation were studied with a scenario-based method and for the Heidkopf tunnel in Germany the decision on the acceptability of the transport of dangerous goods was taken on the basis of a risk-based approach.

Furthermore the case studies demonstrate that different risk analysis methods and risk evaluation strategies are required to be able to specifically address different kinds of problems.

Keywords: Risk analysis, risk based decision making, system-based risk analysis, scenario-based risk analysis

1. WHY APPLYING RISK ANALYSIS

Since the EC-Directive 2004/54/EC [1] introduced risk analysis as a performance based approach for the assessment of safety standards, it has been established as complementary element to the traditional prescriptive based approach to tunnel safety. The application of this tool has become more and more common for various purposes [2]:

- To check the general consistency of safety planning
- To choose between alternatives – in design as well as in operation
- To evaluate (additional) risk mitigation measures
- To optimize safety planning in terms of cost effectiveness
- To demonstrate safety in case of deviations from prescriptions

In the past few years a dynamic development took place in terms of evolution of quanitative risk models, which enable the user to draw conclusions on the basis of quantitative results reflecting the influence on safety of specific features of tunnel design or operation. The improvement of risk models – more and more based on simulations – made the evaluation of even complex situations possible, thus providing a better basis for an informed decision for the people responsible for tunnel safety - including aspects of financial implications of their decision.

5 typical fields of application can be defined for the use of risk analysis as a support tool for decisions in tunnel design and tunnel operation:

- Upgrading of existing tunnels: older tunnels often do not fulfil modern tunnel safety standards. In an upgrading process the safety standard has to be improved. In existing tunnels however – other than in new ones - often severe technical, operational and financial restraints have to be taken into account, so that it may not be possible (or not adequate) to just adopt it to new standards. In such situations, typically different design solutions are developed which have to be evaluated in terms of their consequences on safety, operation and cost – a typical application of risk analysis as evaluation tool for tunnel safety. In this context, reference is made to the new PIARC report "Assessing and Improving Safety of Existing Road Tunnels" which defines a clear procedure for the implementation of safety in the upgrading process. This report was presented at the World Road Congress in Mexico City in November 2011 and will be published in near future in the PIARC virtual library.
- Safety relevant design decisions for new tunnels: also for new tunnels, sometimes different options are available to fulfil a given safety standard or additional safety measures are required to compensate a special characteristic; in both cases risk analysis may contribute to decision making, by providing information on the effects on safety of the different design options, which can be used as input data for a cost-effectiveness assessment. The most common application in practice are decisions on the design of the ventilation system.
- Safety relevant design decisions for tunnel operation: operational regulations influencing safety are an option for additional safety measures for existing as well as for new tunnels. For the transport of dangerous goods this type of measure has been established on a regulative basis: every tunnel has to be allocated to one of five ADR tunnel categories (category A: all dangerous goods allowed – category E: all dangerous goods forbidden). The decision, which classes of dangerous products are allowed to be transported along the tunnel route or are to be diverted on alternative routes is typically taken on the basis of the results of a risk analysis
- Investigation of specific non standard situations, with lack of information or unclear situations in tunnel regulations; risk based studies on such topics may provide results and conclusions of general interest, giving input to tunnel design for comparable situations.
- Giving input to modifications of tunnel design guidelines: regulations on tunnel design were developed based on experience and expert judgement; the experience of the increasing application of quantitative risk analysis models indicate, that specific definitions may require modifications if seen from a mere safety point of view. Research activities on such topics are under way aiming to provide a proper basis for the discussion of such adaptions – for instance the project "Procedure for the definition of the ventilation system of road tunnels" for the German Federal Highway Research Institute or the research activities of the upgrading of the Austrian Tunnel Risk Model TuRisMo

This paper is focussing on three case studies presenting three different practical situations which require the application of a risk-based approach as a basis for decision making.

2. REGULATIVE BACKGROUND FOR DECISION MAKING ON THE BASIS OF A RISK ANALYSIS

Although the EC Directive 200/54/EC defines "minimum safety requirements" (limited) derogations of the requirements in Annex I are allowed under specific conditions. The basic principle for the acceptability of such exceptions is always the compensation by alternative safety measures, resulting in an equivalent or higher safety level, which has to be demonstrated by a risk analysis. This principle is addressed in several chapters in the Directive, e.g. in article 3 (for existing tunnels) or in chapter 1.2.1 of Annex I, and it is always linked to specific conditions like missing feasibility or disproportionate cost.

National tunnel safety regulations also refer to risk analysis as a basis for decision making. The Austrian Tunnel Safety Law [3], for instance, implements the minimum safety requirements defined in the EC Directive as minimum standard for all tunnels of the Austrian highway network; at the same time it establishes the principle for limited derogations defined above as general principle for exceptions for all prescriptive requirements layed down in Annex I (however, for tunnels on the transeuropean road network the specific definitions of the Directive are applied). In the German tunnel guideline RABT [4] risk based decision making is established as well: for instance, for tunnels with bidirectional or congested traffic with a length between 600m and 1.200m the decision on the ventilation system has to be taken on the basis of a risk analysis [5].

3. CASE STUDIES

3.1. Učka Tunnel (Croatia)

The problem

The Učka Tunnel is a 5,062 km long tunnel in Istria with one tube and bidirectional traffic, built in 1981. In the next years, a second tube will be built. The risk assessment study covers the new tunnel configuration. The focus of the study is on the decision on the ventilation system of the future tunnel configuration; furthermore it is intended to define safety requirements for the tunnel design.

Usually, the selection of the ventilation system is based on definitions in regulations. In Croatia, at the time being there are no specific national tunnel regulations; in practice the Austrian regulations RVS are applied. In RVS 09.02.31 [5] a limit of 3 km for the tunnel length is defined for the application of longitudinal ventilation systems. For tunnels longer than 3 km a transversal ventilation system is required. In practice, there are several examples for unidirectional tunnels longer than 3km equipped with a longitudinal ventilation system, for example, the 5,8 km long Strenger tunnel located in Austria at the S16.

The existing Učka Tunnel is equipped with a longitudinal ventilation system. The implementation of a transversal ventilation system in the existing tunnel tube would cause big technical problems (the tunnel cross section would have to be enlarged) and major costs; for the new tunnel tube a transversal ventilation system would be a major cost parameter as well.

From the safety point of view, a ventilation system with smoke extraction in principle shows advantages (because in fire scenarios, smoke can be sucked off), however in tunnels with two tubes and unidirectional traffic and low probability of congested traffic, the benefit is only minor and highly disproportionate to the resulting costs. Furthermore, the Učka Tunnel is a tunnel with very specific conditions and a series of non-standard safety measures already installed.

The approach

As the Austrian tunnel design guidelines RVS are applied in Croatia, as method for the risk assessment study the Austrian tunnel risk model TuRisMo (defined in RVS 09.03.11) was chosen. TuRisMo is a system-based risk model, expressing tunnel risk as expected risk value, distinguishing between risk due to mechanical accidents, fire risk and risk involving effects of dangerous goods. However, for this specific application an extended version of the model was applied: additionally to the 5MW and 30MW fire scenarios a 100MW fire scenario was implemented in the event tree and the consequences of tunnel fires were specifically calculated for the Učka tunnel, thus replacing the standardized RVS damage values, which were not applicable for this specific situation. For the simulation of smoke propagation in Učka tunel a 3D CFD model (FDS Fire Dynamic Simulator [6]) was applied and the results were transferred into an evacuation simulation model (bulidingExodus [7]) to calculate the consequences on people in the tunnel

For the evaluation of the results of the risk analysis, a relative approach is applied: the risk of the real future tunnel is compared to the risk of reference tunnels, representing the admissible safety level. In this specific case, several comparisons to different reference tunnels are made:

- Comparison **Učka tunnel - Reference tunnel EC-Directive**
  to demonstrate an adequate safety level or highlight requirements for additional safety measures with respect to minimum safety requirements according to EC-Directive

- Comparison **Učka tunnel – Reference Tunnel RVS (transversal ventilation)**
  to demonstrate, that the benefit of transversal ventilation can be compensated by existing safety measures or to highlight requirements for further compensation, in case a longitudinal ventilation is chosen

The results

Consequence values for fires

On the basis of the smoke propagation simulations combined with the evacuation simulations the following damage values (model values per event) were obtained:

Table 1: Characteristic damage values for fires (fatalities per event) – Longitudinal ventilation (LV) / Transversal ventilation (TV)

	5 MW		30 MW		100 MW	
	LV	TV	LV	TV	LV	TV
Tube 1 – direction Istria	2,0	0,2	4,4	4,3	29,0	5,8
Tube 2 – direction Kvarner	1,7	0,6	4,8	4,4	35,5	6,2

The model values depicted in the tables above do not take the probabilities of the individual scenarios into account and are only valid for congested traffic situations; in normal traffic situations the value is 0 in all cases. The comparison of the values for longitudinal and transversal ventilation respectively shows the generally positive effect of smoke extraction in fires with congested traffic. In this specific case, the effect is rather low for the 5 MW and 30 MW fires, but significant in cases with bigger fire scenarios.

These values were calculated on the basis of the standard model assumptions (referring to the standard safety level without taking risk mitigation measures into account). However, in the Učka tunnel efficient additional safety measures are already in place:

- Early detection of accidents, incidents and fires by an optimised automatic video detection system and well trained and highly motivated staff in the tunnel control center as well as at the toll stations at both tunnel portals; The efficiency of this measure is documented in detail by statistical data and accident and incident reports.

- Fast and efficient tunnel closure – by means of barriers at the toll stations at both tunnel portals; as a consequence the number of vehicles entering a tunnel after an incident is limited, thus reducing the number of people possibly being effected by a fire in the tunnel.

Taking these already implemented measures into account, the model values for a 5 MW and a 30 MW fire are reduced below the respective values of the reference cases shown above, only the values for the 100 MW scenario still exceed the respective value of the transversally ventilated tunnel (see table below). However, the influence of this scenario on risk is very low - due to a very low probability.

Table 2: Characteristic damage values for fires (fatalities per event) – including effects of additional safety measures

Učka Tunnel – real conditions,			
	5 MW	30 MW	100 MW
Tube 1 – direction Istria	0,2	0,8	12,4
Tube 2 – direction Kvarner	0,4	0,8	13,3

Overall risk

Based on these specific fire damage values the overall risk of Učka Tunnel was calculated in TuRisMo. The results are compared to the two reference cases defined above (see table 3). Although the relative differences are quite small (because the fire risk is small), they are reliable – due to the relative approach, which eliminates the inevitable fuzziness and uncertainties of a risk analysis.

Table 3: Overall risk – expected value (fatalities per year)

	Real conditions	**Reference tunnel EC-Directive**	**Reference tunnel - RVS transversal v.**
Mechanical risk	0,1009	0,1031	0,1017
Fire risk	0,0022	0,0025	0,0024
DG Risk	0,0021	0,0023	0,0034
Overall risk	0,1051	0,1079	0,1075

These results can be commented as follows:

- The fire risk in the new Učka Tunnel is very low (approximately 2,0 – 2,5 %);
- Hence also the influence of all measures influencing the fire risk is very low (including ventilation, length of escape routes). This is characteristic for a tunnel with unidirectional traffic and a low congestion risk.
- With respect to the reference tunnel “EC-Directive”: the overall risk as well as the relevant partial risk of the real tunnel are well below the respective values of the reference tunnel; hence the future tunnel will be sufficiently safe with respect to the minimum safety requirements defined in the EC-directive 1004/54/EC.
- With respect to the reference tunnel “RVS – transversal ventilation”: the overall risk as well as the fire risk of the real tunnel are well below the respective values of the reference tunnel; hence the future tunnel (with a longitudinal ventilation system) will be sufficiently safe with respect to the requirements of RVS 09.02.31 in terms of selection of the ventilation system.
- The already implemented (operational) risk mitigation measures of the real tunnel are able to compensate the risk reducing effect of a transversal ventilation system in terms of fire risk; hence no further safety measure are required.

3.2. Tunnel Markovec (Slovenia)

The problem

Markovec tunnel is an approximately 2,150 km long bidirectional motorway tunnel under construction at the Adriatic coast near Koper in Slovenia; In this region a specific wind situation may occur – the so called “Bora”. Bora is characterized by unsteady heavy wind with gusts with very high velocities which regularily causes problems in traffic operation. There was a concern that Bora winds may influence tunnel safety as well, resulting in a discussion to what extent Bora should be considered at the definition of the design criteria for tunnel ventilation. Therefore – in addition to a standard risk analysis – a specific scenario analysis was carried out for Markovec tunnel to investigate the influence of Bora on the risk of tunnel users

The approach

The concern was focussing on the fact, that in Bora situations much higher wind velocities can occur than normally taken as basis for ventilation design, which would lead to considerable backlayering of smoke or even spread of smoke in the wrong direction – i.e. against the direction of traffic. If this were true, this could cause harm to people in situations, when vehicles queuing behind a fire normally are protected by the ventilation system.

As basis for this investigation wind measurements of a wind measuring station in the vicinity of the Koper portal of Markovec tunnel were provided by the client. This data showed a highest recorded velocity of 15,5 m/s as absolute top value (i.e. not yet normalized on tunnel portal).

Based on the considerations outlined above a total number of 32 numerical simulations of smoke propagation was performed in order to cover a representative set of scenario developments.

The first series of simulations was based on the assumption of a 200pa wind gust for a duration of 40s on top of a basic pressure difference created by an average wind speed of approximately 4.8 m/s (15pa). This corresponds to a total velocity of approximately 18 m/s over a long period of time. This is higher than the measured velocities and the duration has more the characteristics of static wind than a short gust and can be therefore considered as very unfavourable case. Additionally a short gust of 15s has been simulated with the same velocities. For both cases 2 incident locations and 2 fire scenarios (5MW and 30 MW) have been simulated in order to assess the influence of altering longitudinal gradient and influence of moving vehicles in the early phase.

The results

As a representative example the effects of such a gust (18 m/s for 40 sec., 4,8 m/s basic wind) on smoke propagation in a 30 MW fire scenario in the self rescue phase (300 sec. after start of event) are shown in the figure below.

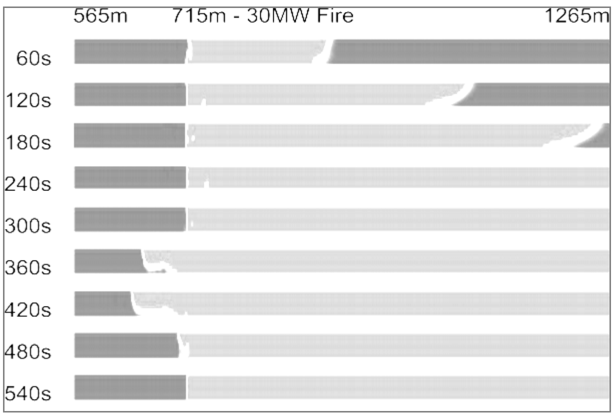

Figure 1: Smoke propagation in a 30MW fire at 715m, 40s Bora gust at 300s

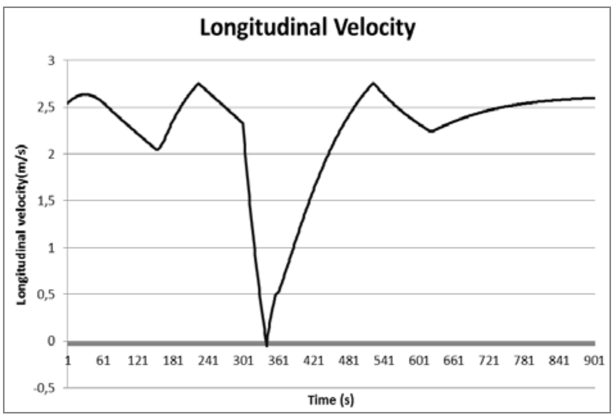

Figure 2: Evaluation of longitudinal air velocity, 30MW fire at 715m, 40s Bora gust at 300s

The gust hits the tunnel portal between 300s and 340s after the start of the fire. At this time the fire is fully developed but fire ventilation is already activated and can restore the longitudinal flow a short time after the gust has ended. The strong and long gust causes a reduction of longitudinal velocity to almost 0 m/s and which results in a temporarily concentration of smoke and flue gases at the fire location. During this phase the hot gases of the 30MW fire begin to cause some backlayering. The furthest point which is affected by smoke in the ceiling layer is about 70 m behind the fire location. However, only a very short area behind the fire location (about 20m) is affected over the entire cross section (including walking level). As soon as the longitudinal velocity reaches the target value of 2.5 m/s backlayering stops and the smoke is cleared from the upwind side of the tunnel. The time of exposure is relatively short even for persons, which are sitting still in their vehicles.

Even though the most unfavorable assumptions have been made for the investigation no relevant effects on the endangerment of people in the tunnel do result. Calculation with more realistic assumptions show no non negligible effects at all. A rough estimation of probabilities of such scenarios which may increase consequences showed that the effect in terms of a quantifiable influence on risk is negligible. Hence it can be concluded that a layout of the ventilation system according to RVS standards in this particular case would be sufficiently safe also for Bora situations.

3.3. Heidkopftunnel (Germany)

The problem

The Heidkopftunnel is a 1.7km long twin bore tunnel for unidirectional traffic in the Lower Saxony Motorway network. Since its opening in 2006 the tunnel was closed for carriers of dangerous goods (DG). Transportation of DG was routed via the highways B27 and B80 which are the assigned alternative routes.

In 2010, the new ADR tunnel regulations became effective and the Heidkopftunnel had to be classified to one of five ADR tunnel categories according to these recently established rules (category A: all dangerous goods allowed – category E: all dangerous goods forbidden). This decision should be taken on the basis of the results of a risk analysis.

In Germany a harmonised procedure for risk assessment of DG transports through is established since 2009. This methodology is outlined in the report “Procedure for the road tunnels categorisation of road tunnels according to ADR” [8]. The method consists of a multistage procedure with a rough assessment in stage 1 followed by an in-depth analysis in stage 2, if required. As on the basis at the results of stage 1 no decision could be taken, the Heidkopftunnel had to be examined in more detail with a complex, quantitative risk analysis model (stage 2a). This thorough analysis should allow a statement whether the tunnel could totally be opened for DG traffic or had to be kept closed for certain groups of DG (explosives, flammable fluids, toxic substances).

The risk analysis had to be performed for the current traffic volume (year 2010) as well as for the traffic prediction for the year 2015. Additionally a maximum traffic volume was calculated up to that the tunnel could remain open to transportation of dangerous goods.

The approach

The eight main scenarios defined in the methodology [8] represent four different types of DG in two sizes of exposure each. These types of events are:

- **Pool fire** resulting of the spill of flammable liquids
- Release of **Toxic Gases**

- Release of combustible gases (**Torch Fire**, **VCE**, **BLEVE**)
- Detonation of **Explosives**

The structure and most of the required data for the risk calculations is defined in the methodology [8]. However, in order to increase the resolution of the risk analysis the calculation of consequences was specified in 2 ways:

- Variation of **traffic** load
  Instead of computing the number of casualties for the AADT the calculation was performed for every hour of the average day curve of traffic in Heidkopftunnel. This allows to cover hours with low traffic (night) as well as peak hours with elevated risk potential. The representative numbers are then calculated as weighted average over the incident frequency (proportional to traffic volume)

- Variation of **incident location**
  Instead of computing the casualty numbers at a location in the middle of the tunnel immediately in front of an emergency exit or alternatively exactly in between two exits the incident location was moved in 10m steps along the tunnel. This means the exact location of the nearest emergency exits is taken into consideration when performing the evacuation simulation at a given incident location.

These variations of traffic volume and incident location result in a different appearance of the curves in the FN diagram. Instead of a rather small number of steps (the step size represents the frequency of a single event) the edges are smoothened out giving an almost continuous graph.

The results

The results of the risk analysis were evaluated by comparing the F/N-curves of all scenarios and also the cumulated F/N-curve (summed scenarios 1 - 8) to the reference line in the F/N diagram (see Figure 3).

The risk analysis for the current traffic volume showed that the overall risk resulting from the transportation of DG is still below the reference line which is defined as absolute risk acceptance criterion in the German methodology [8].

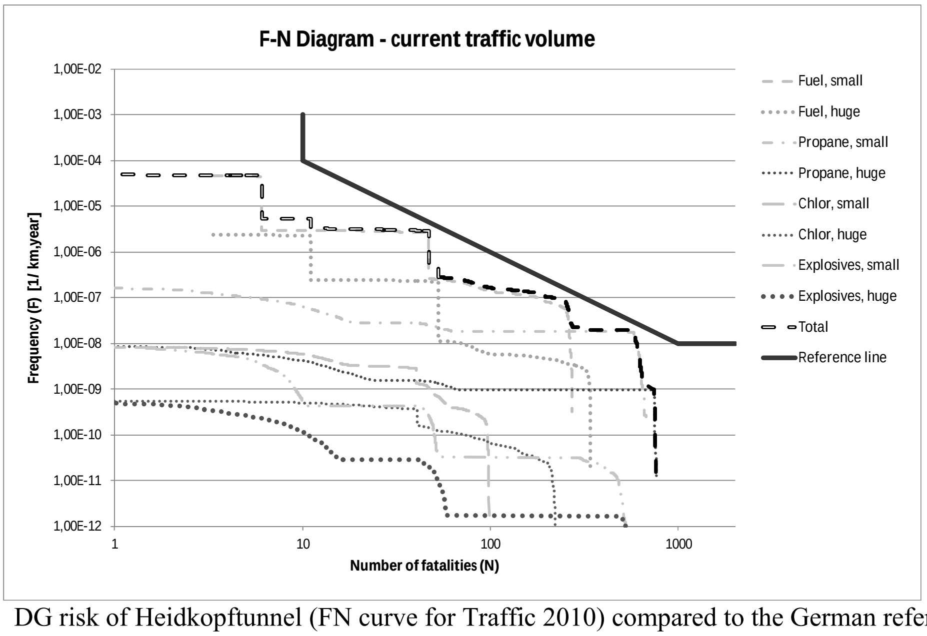

Figure 3: DG risk of Heidkopftunnel (FN curve for Traffic 2010) compared to the German reference line

However, the predicted traffic for 2015 would slightly exceed the acceptable risk level. For this reason an approximation was made in order to calculate the maximum AADT for which the tunnel still fulfils the criterion. It was found that the maximum AADT is only slightly lower than the predicted traffic for 2015.

As result of the risk analysis the tunnel could be opened to transportation of DG in January 2012 and can remain open until the calculated maximum AADT is reached.

4. CONCLUSION

The three case studies demonstrate that the use of risk analysis can provide a better basis for safety relevant decisions in tunnel design and operation, by assessing the effects on risk of the investigated alternatives in a traceable, mostly quantified manner. However the influence on risk is only one relevant parameter for such decisions, other important factors may be operational or financial aspects or influence on assisted rescue. The three examples also show, that for different problems different risk analysis methods as well as different approaches for the evaluation of the results are required. Hence, the choice of the methods should be done by considering the respective advantages / disadvantages in the context of a specific situation. The selection of the appropriate method to investigate given issues has to match the specific problem, the required depth of assessment and the available resources [2].

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RISK EVALUATION FOR ROAD TUNNELS: CURRENT DEVELOPMENTS

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ABSTRACT

Besides the implementation of prescribed safety measures according to guidelines and standards, the application of risk based approaches in the process of tunnel safety management is nowadays an accepted widely used procedure in several countries. Within the risk assessment process, risk evaluation is a very important and sensitive element. It is intended to answer the question of whether a tunnel is safe enough; i.e. whether the risks identified/quantified in the risk analysis are acceptable or whether additional safety measures are needed to fulfil the safety targets. Based on the basic principles of risk-based approaches the specific aspects of risk evaluation strategies are discussed.

Keywords: risk assessment, risk analysis, risk evaluation, risk acceptance criteria, safety level, safety targets, expected value, FN diagram, cost-effectiveness

1. INTRODUCTION

Besides the implementation of prescribed safety measures according to guidelines and standards, the application of risk based approaches in the process of tunnel safety management is nowadays an accepted and widely used procedure in several countries.

Risk assessment is a systematic approach to analyse sequences and interrelations in potential incidents or accidents, hereby identifying weak points of the system and recognising possible improvement measures. Three steps characterise the risk assessment process:

- *Risk analysis:* Risk analysis is concerned with the fundamental question: “What might happen and what are the consequences?”. Therefore a set of “typical” scenarios, which can occur in road tunnels, has to be defined and analysed. Risk analysis can be carried out in a qualitative or in a quantitative way or in as a combination of both. For system-based risk assessments quantitative methods are common practice. Thus probabilities of accidents and their consequences for different damage indicators (e.g. in terms of fatalities, injuries, property damage, interruption of services) – considering relevant factors of the system and their interaction – and the resulting risk are assessed.
- *Risk evaluation:* Risk evaluation is directed towards the question of acceptability and the explicit discussion of safety criteria. For a systematic and operable risk evaluation one has to define safety criteria and to determine whether a given risk level is acceptable or not. In other words risk evaluation has to give an answer to the question “Is the estimated risk acceptable?”
- *Planning of safety measures (Safety management):* If the estimated risk is considered as not acceptable, additional safety measures have to be proposed. Therefore the effectiveness and also cost-effectiveness of different safety measures can be determined by using the initial frequency and consequence analysis of the scenarios which will be positively or negatively affected under the assumption that the investigated safety measure has been implemented. Planning of safety has to answer the question “Which measures are necessary to get a safe (and cost-efficient) system?

The risk assessment process allows a structured, harmonised and transparent assessment of risks for a specific tunnel including the consideration of the relevant influence factors and their interactions. However it should always be kept in mind that every kind of risk analysis – whatever method is used - is a more or less simplified model relying on preconditions and assumptions and is not a copy of reality. Nevertheless assessment models provide a much better understanding of risk-related processes than merely experience-based concepts may ever achieve. Moreover, they allow coming up with the best additional safety measures in terms of risk mitigation and enables a comparison of different alternatives.

2. RISK EVALUATION AS A BASIS FOR DECISION-MAKING

Risk evaluation is a very important and sensitive element of the whole risk assessment process. It is intended to answer the question of whether a tunnel is safe enough; i.e. whether the risks identified/quantified in the risk analysis are acceptable or whether additional safety measures are needed to fulfil the safety targets.

Whereas the first step of the risk assessment process (risk analysis) is a rather scientific process including the assessment frequencies and potential consequences of incidents, risk evaluation goes beyond the domain of technical and engineering experts. The question of risk evaluation concerns decision-makers, responsible authorities, politicians but also laypeople or even society as a whole. Furthermore risk acceptance criteria or acceptable safety levels respectively cannot be defined in an absolute sense. They need to be related to society's means and ends. Therefore the definition of risk acceptance criteria is a demanding task because it is embedded in a specific legal, social and cultural environment. It is important to realise that decision-making about risks is complex. Not only are technical and mathematical aspects important, but ethical, political, societal and other factors have an important role as well.

3. BACKGROUND TO RISK EVALUATION

3.1. Factors influencing risk perception

The discussion about the acceptability of risks is strongly influenced by risk perception. It is important to know that human behaviour is primarily driven by perception and not by facts or by what is understood as facts by risk analysts and scientists. Most cognitive psychologists believe that perceptions are formed by common sense reasoning, personal experience, social communication and cultural traditions. Perceptions of risk can therefore vary significantly between technical experts, decision-makers, stakeholders and others. For this reason, the need to effectively communicate the level of risk involved in an activity is essential if an informed, valid decision is to be made. Technical experts tend to emphasise factors in terms of the probability of an occurrence or its likelihood and consequences, while a layperson tends to emphasise factors such as the following:

- *Perceived Benefits:* It's easier for people to accept risks when the expected benefit is clear (nobody questions the use of cars although road traffic causes a risk that would never be accepted with other technical systems).
- *Voluntariness:* People are more concerned about risks that are imposed (accident in chemical industry) rather than voluntarily accepted (mountain climbing)
- *Controllability:* People are more concerned about risks not under personal control (e.g. flying in an aeroplane) than those under personal control (e.g. driving a car)
- *Familiarity:* People are more concerned about unfamiliar risks than familiar risks

- *Understanding:* People are more concerned about poorly understood activities than those that may be understood
- *Natural / man-made:* People are more concerned about man-made risk than about natural risk
- *Scientific uncertainty:* People are more concerned about risks that are scientifically unknown or uncertain than risks well known to science
- *Reversibility:* Risks which have potentially irreversible adverse effects are perceived to be greater than risks constituting no long-term threats.
- *Dreadfulness:* The worse (more suffering) the possible consequences from a risk, the more concerns are evoked.
- *Catastrophic potential:* People are more concerned about fatalities and injuries that are grouped in time and space (e.g. aeroplane crashes) than about fatalities and injuries that are scattered or random in time and space (e.g. car accidents)
- *Media attention:* Media attention is a key factor for the influence of risk perception on public opinion; fires in tunnels are reported widely in the international press for their nature, rareness and maybe the exceptional dimension of the impact. By contrast, information about road accidents with many more annual casualties is often reported only briefly, if at all.

Some of the above mentioned factors can be considered rationally and objectively (e.g. voluntariness), others are more the result of subjective awareness. Risk analysts, recognising the legitimacy and importance of public values, have begun to incorporate such factors into risk-based decision making in terms of specific concepts.

3.2. Risk aversion

Regarding the practical application of risk evaluation criteria, one aspect plays an important role, the so called risk aversion. Risk aversion refers to the fact that some accidents are perceived to be much worse than their inherent risk would indicate. For example an accident with a hundred fatalities and a frequency once every one hundred years may be judged much worse than a series of accidents, each with one fatality and a frequency of one per year, although the risk in terms of expected value is the same in both cases. It has to be noted that there is no generally accepted definition for the term risk aversion. Depending on the field and/or scope, different definitions are used. Risk aversion can also depend on the activity considered (e.g. risk aversion for road tunnels is not the same as for nuclear plants) and all the other risk perception factors mentioned above. The (public) reaction to certain accidents strongly affects the actions of those responsible for a system (e.g. the authorities). A number of examples are known where the indirect effects of such large accidents have directly led to the collapse of companies or to the implementation of more stringent (and often costly) regulations. Therefore the aspect of risk aversion is often included in strategies for risk evaluation by intentionally overvaluing the risk of accidents/scenarios causing large consequences in the risk evaluation process. Setting quantitative values for a risk aversion function is a subjective process and reflects also value judgement. It should be noted that including risk aversion or setting a risk aversion function is not an arbitrary process and depends on the activity considered.

4. PRINCIPLES FOR RISK EVALUATION

4.1. Risk evaluation strategies

Even though risk evaluation always includes aspects of weighting and judgments on acceptability, strategies for risk evaluation can be developed in a structured way considering the different aspects of risk perception. Therefore, for the determination of risk evaluation criteria there is no generally applicable "right" or "wrong" safety target. The definition of criteria for risk evaluation takes account of risk perception in various forms, depending on the chosen methodological approach and consequence indicators. Risk-based criteria include an evaluation of both the frequency/probability and the resulting consequences of accidents. Establishing evaluation criteria can be done in different ways with different levels of complexity. From a practical point of view it should be noted that there are several approaches to the implementation of risk evaluation strategies. In practice, combinations of such strategies are often applied. An illustrating overview of different risk evaluation approaches is given in the following.

4.2. Qualitative risk evaluation strategies

Regarding qualitative risk evaluation there is a wide range of different approaches. The most common approach is the application of prescriptive based criteria such as regulations, standards and guidelines. Other common approaches include:

- Safety audits
- Checklists
- Expert evaluation (e.g. judgement by experts on the basis of scenario analyses)
- Risk matrix / Points schemes

In some cases, qualitative approaches may be used as a first step in the overall risk assessment process, to act as a screening tool whereby the lower risk elements are filtered out and attention for more detailed quantitative and/or deterministic analysis is focussed on the higher risk elements.

4.3. Quantitative risk evaluation strategies: Societal risk

Societal risk is defined as the relationship between frequency and number of people suffering from a specified level of harm to a given population and a number from the realization of specified hazards. In other words it is the resulting risk to a group of people due to all hazards arising from an operation (e.g. operation of a road tunnel). The level and nature of consequences is often measured in terms of loss of life (fatalities). The most common approaches of societal risk evaluation are presented in the following.

4.3.1. Expected value (EV)

A typical measure of societal risk is the EV. It is the long-term average number of statistically expected fatalities per year due to a particular hazard and for a particular system, e.g. a tunnel.

- *Application of EV as absolute criteria:* The results of a risk analysis - expressed as expected risk value (e.g. (statistically) expected number of fatalities/year for the tunnel investigated) are compared to a predefined target value. If the risk of the tunnel investigated is equal or below this target value, it is acceptable, if it is exceeded, then further action has to be taken. This approach is easy to apply because it delivers unambiguous results.
- *Application of EV as relative criteria:* The results of a risk analysis expressed as expected risk values for two or more alternatives are compared to each other in order to select an alternative which represents a lower level of risk. This concept can be used for different applications, such as evaluation of additional safety measures or risk evaluation by means of a “reference tunnel” (e.g. fulfilling all regulative requirements). The “reference tunnel” is typically defined as a tunnel which assures that the safety objectives are fulfilled in an equivalent way, taking into account all prescriptions of safety-relevant regulations.

4.3.2. FN diagram

FN diagrams are frequency-consequence graphs – usually plotted on a double logarithmic scale – showing the cumulative frequencies (F) of incidents involving N or more units of damage. FN diagrams provide information on the magnitude of consequences in relationship to the (cumulated) frequency of the type of hazard investigated.

Application of absolute criteria: A typical representation of a practical application of acceptability criteria in the FN diagram is shown by the criterion lines in the following Figure **1**. For practical applications, there are often two lines defined in the FN diagram. For the area that lies between the acceptable and unacceptable risk lines, in general the philosophy is to implement risk reduction measures on the basis of cost-effectiveness considerations. A commonly used principle for this is the ALARP principle where risks are to be reduced to As Low As Reasonably Practicable. It implies that risk reduction in this area should be implemented as long as the costs of risk reduction are not disproportional to their risk reduction effects.

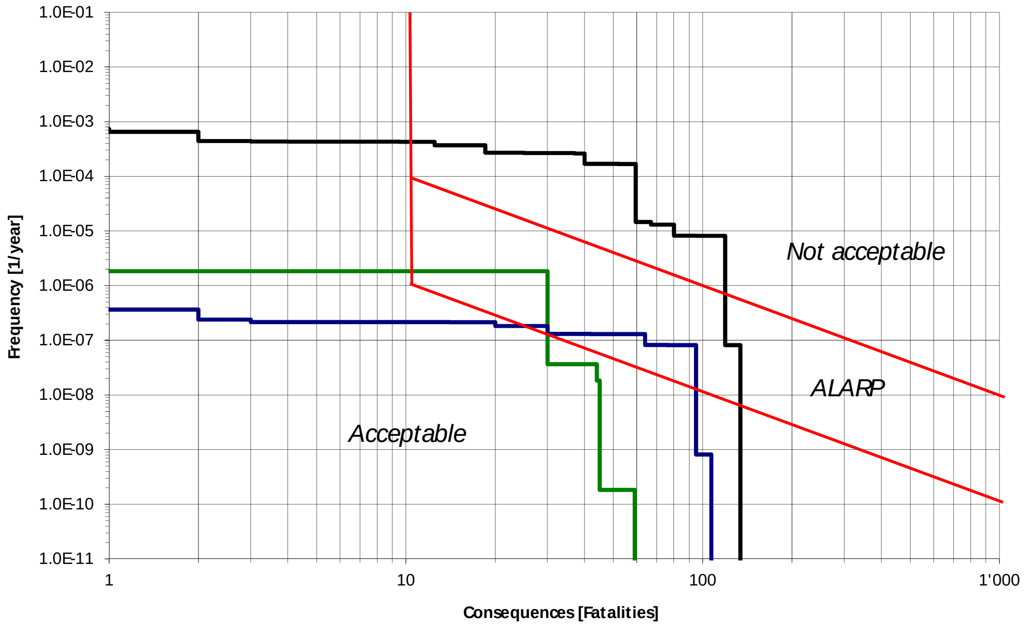

Figure 1: FN diagram with absolute risk acceptance criteria (fictitious example)

- *Application as relative criteria:* Similarly to the relative criteria using the EV, the approach with FN curves also relies on the reference tunnel concept. The same risk analysis methodology as used for the tunnel under consideration is applied for the “reference tunnel”, resulting in a second FN curve. Evaluation is by relative comparison of the two curves where the curve of the “real” tunnel should be sufficiently below or close to the curve of the “reference tunnel”. In practice it is often difficult to evaluate risks by comparing two FN curves, especially when they intersect. In such cases, the results of the comparison of two curves may be ambiguous and the interpretation may be difficult.

4.3.3. Cost-effectiveness

The cost-effectiveness approach considers the efficiency of safety measures compared to their potential for risk reduction. As well as proving the efficiency of safety measures from an economical point of view, this approach can be applied as acceptability criteria. Thus it ensures that the resources spent to reduce risk are spent in such a way that an optimised level of safety is obtained. Furthermore it can be applied for the comparison and evaluation of different safety measures.

The application of cost-effectiveness approaches is a possible way to bring tunnel safety towards an optimum from an economic point of view. It helps achieve the maximum efficiency in terms of risk prevention and resources spent. The definition of the risk acceptability criteria is included in the determination of marginal costs. Marginal costs are the price one is willing to pay for a marginal increase in safety or – in other words – the willingness-to-pay for saving one unit of damage (e.g. a fatality).

4.4. Quantitative risk evaluation strategies: Individual risk

Individual risk is the risk experienced by a single individual (e.g. tunnel user) which is expected to sustain a given level of harm from realisation of specified hazards in a given time period. The number of people exposed to the hazard does not have any impact on the value of the individual risk. As experience shows, it is more common to evaluate risk in terms of societal risk and there are only a few applications of risk evaluation based on individual risks for road tunnels (e.g. in the Netherlands).

5. PRACTICAL EXAMPLES

5.1. Application of risk evaluation criteria based on expected values (EV)

A typical application of EV as absolute criteria is the evaluation of the risk of transport of dangerous goods (DG) through tunnels. Various countries have developed different evaluation procedures; one common characteristic of these procedures is the use of a step-by step process, with the first step focussing on the separation of critical and non-critical tunnels. For this purpose, absolute target values for the expected value are used as 'relevance criteria'. If the calculated expected values fall below that limit it is ensured that other risk acceptance criteria are not violated; hence the risk is acceptable and no further investigations and no measures are required. Such an approach is for example applied in Austria, France, Germany and Greece (strictly linked to the DG-QRAM method):

Table 1: Target values (EV) for transport of DG through tunnels

Country	Target value (EV, [fatalities/ year])		Application
Austria, France, Greece	All scenarios:	$1.0 \cdot 10^{-3}$	per tunnel
Germany	Fire: Fire and Explosion; Explosion: Toxic effects:	$5.0 \cdot 10^{-3}$ $2.2 \cdot 10^{-3}$ $1.0 \cdot 10^{-6}$ $4.0 \cdot 10^{-4}$	per tunnel-km

This approach is easy to apply because it delivers unambiguous results. However it has to be noted however that risk evaluation based upon an absolute EV is a rather general approach and - without specific precautions – does not take into account specific aspects such as:

- Information on accident consequences (accidents with very low probability/very high consequences only contribute to a minor extent to the expected value)
- Information on different damage effects (e.g. fires, explosion etc.)

These deficiencies may be overcome by including risk aversion, defining separate target values for specific scenario groups, depicting the share of different damage effects in the expected value and/or strictly limiting the use of this approach to clearly defined applications.

5.2. Application of risk evaluation criteria based on FN diagrams

The application of acceptability curves in the FN diagram as a basis for evaluation of risk in road tunnels is used in a number of different countries. It has to be noted that some of the reference criteria are valid for the risk of the overall traffic whereas some criteria are only valid for the risk of transport of DG through road tunnels. Criteria for transport of DG may be more restrictive than those for the overall traffic. Additionally it shall be stressed that some reference lines are strictly linked to a specific method or risk model.

One of the practical applications of such criteria can be found in Germany. In the course of the implementation of the ADR tunnel regulation a specific methodology for the analysis and evaluation of risk of transport of dangerous goods was developed within a research project. The developed procedure for a risk-based classification of road tunnels in categories according to ADR consists of two stages. In a rough evaluation a tunnel will be checked in two steps to determine whether it can allow all DG transports or not. When the DG risks – represented as EV – are evaluated as being too high by means of the simple models of stage 1 (see also chapter 5.1), the tunnel has to be examined in-depth. The resulting risk has to be represented as an FN curve (normalised for 1 km) for the analysed scenarios and the overall risk. If the determined risk is below a comparative curve based on empirical values, the tunnel can allow all DG transports. If the risk curve is above the comparative curve, the tunnel will be classified according to requirements, i.e. it will be blocked for DG transport with the appropriate tunnel restriction code and/or constructional, technical or organisational measures will be taken respectively to reduce the risk. The reference criteria for the FN diagram are in Figure 2:

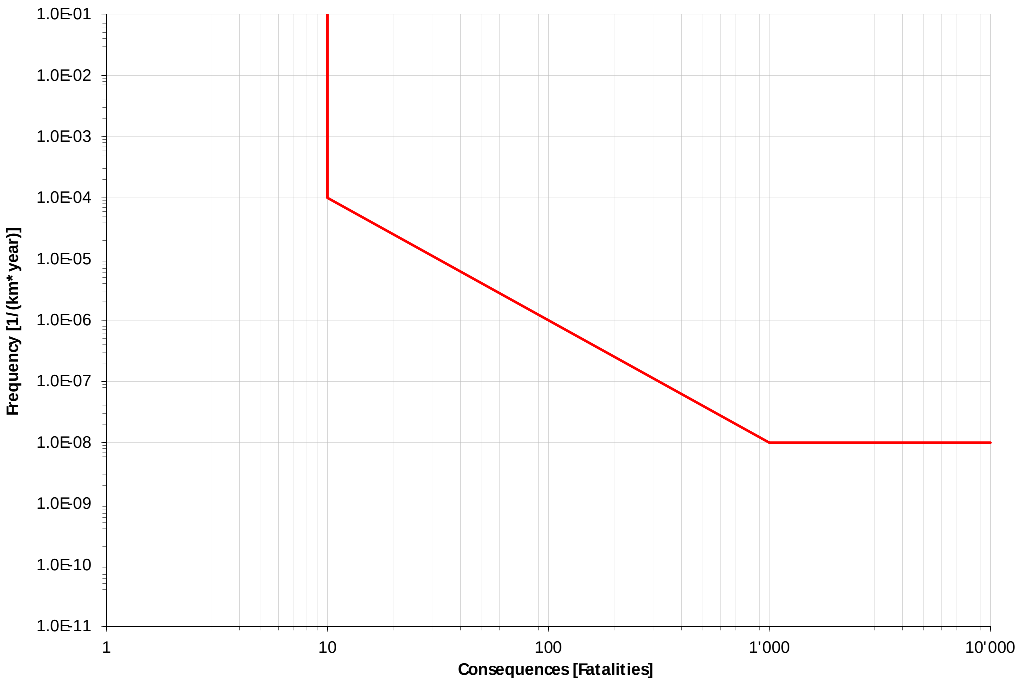

Figure 2: German risk criteria for DG Transports through road tunnels

- $F = 0.1 \cdot N^{-2}$ per kilometre per year, for 10 fatalities $\leq N <$ 1’000 fatalities
- $F = 10^{-8}$ per kilometre per year, for $N \geq$ 1’000 fatalities

Generally the evaluation based on acceptability curves in an FN diagram applied as absolute risk criteria delivers unambiguous results. Furthermore it provides more detailed information about the risk profile and the relevance of specific scenarios. It should be noted that for practical reasons, uncertainties in the risk assessment are normally not taken into account in terms of acceptability curves. Therefore the discussion of sensitivities of the resulting risk – especially if the cumulative frequency curve is near the acceptability curve – is important.

Concerning the deficiencies of this approach it should be noted that for the evaluation based on absolute criteria for FN curves, the definition of the acceptability curves/boundaries can be a long-term process in which all stakeholders should be involved (as for all absolute criteria). Furthermore, as experience shows, the evaluation of risks for which the cumulative FN curve is in the ALARP area is often not clear and the interpretation of appropriateness of additional safety measures is not always treated in a consistent way as experience shows.

6. CONCLUSIONS AND RECOMMENDATIONS

The following recommendations can be given for the practical use of risk evaluation criteria:

- Risk analysis and evaluation is usually just one of a number of bases for decision-making in tunnel safety management
- When determining risk evaluation criteria it is important to consider that the strategy for risk evaluation is strongly dependent on the method of risk analysis chosen and the specific scope and circumstances of the risk assessment
- Although risk models try to be as close to reality as possible and try to implement realistic base data, it is important to consider that the models can never predict real events and that there is a degree of uncertainty and fuzziness in the results
- Considering the uncertainty, the results of quantitative risk analysis should be considered accurate only to an order of magnitude and should be supported by sensitivity studies or similar.
- Risk evaluation by relative comparison (e.g. of an existing state to a reference state of a tunnel) may improve the robustness of conclusions drawn

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RISK ANALYSES OF THE SAFETY LEVEL OF GALLERIES

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ABSTRACT

Today the German tunnel directives (RABT) are not only applied to tunnels but also to open overhead noise barriers, such as galleries and partly covered troughs. Therefore, galleries have to be equipped with the same operational and safety equipment as tunnels.

Existing project-specific studies indicate that even if single predefined operational equipment elements are abandoned, a safety level can be reached that meets the requirements of a comparable tunnel with full operational and safety equipment.

Thus, a research project was initiated by the Federal Highway Research Institute (BASt) on behalf of the German Federal Ministry of Transport, Building and Urban Development to determine possible adapted requirements concerning the equipment of open overhead noise barriers by means of a risk-based analysis. It aimed at defining constructional and operational minimum standards for different types of open overhead noise barriers. The procedure was broken down into three steps:

- Comparative hazard analysis for tunnels and galleries
- Definition of representative construction types of galleries
- Risk-based, comparative analysis of representative scenarios and determination of the corresponding safety level for different types of galleries and reference tunnels.

The results of the project have revealed that for galleries with specific constructive conditions minor requirements regarding operational and safety equipment could be admissible.

Keywords: overhead noise barriers, galleries, tunnel safety, comparative risk analysis

1. INTRODUCTION

At present the German „Directive for the Equipment and Operation of Road Tunnels (RABT)“ is fully applied to open overhead noise barriers, such as galleries and partly covered troughs. This means that galleries have to be equipped completely with the same operational and safety equipment as tunnels. An analysis of relevant guidelines in many European countries and the US showed that in most cases no or comparatively few concrete specifications have been defined at regulatory level concerning lower requirements for (open) overhead noise barriers, which may differ from the requirements for tunnels.

However, existing project-specific studies indicate that even if single predefined operational equipment elements are abandoned, a safety level can be reached that meets the requirements of a comparable tunnel with complete operational and safety equipment.

Therefore, a research project by the Federal Highway Research Institute (BASt) on behalf of the German Federal Ministry of Transport, Building and Urban Development [FE 15.492, 2010], [4] was initiated to determine possible adapted requirements concerning the equipment of open overhead noise barriers by means of a risk-based analysis. It aimed at defining constructional and operational minimum standards for different types of open overhead noise barriers. Its results can be incorporated as recommendations when updating the regulations or respectively in specific project work to ensure a more efficient construction and operation of open overhead noise barriers.

2. METHODOLOGY

The objective of the project was to derive constructional and operational minimum requirements to be met by the different types of overhead noise barriers on the basis of comparative risk-based studies.

In the first step the aspects to be considered in the analysis were substantiated and existing risk-based examinations were analysed in view of the question. In addition, a scheme was developed regarding the handling of the issue abroad on the basis of a comparison of different international regulatory provisions as regards the safety equipment of noise barrier structures.

Since - due to the varying equipment options - there is no clearly defined safety level neither for tunnels nor for galleries which are equipped according to the relevant guidelines, a typification was undertaken in the second step which defined characteristic open overhead noise barriers in terms of design features and possible significant influencing factors regarding user risks.

The focus was especially on provisions which contribute significantly to the risk reduction in relevant partial scenarios and/or which require considerable efforts (investment and maintenance costs). For simplification, in the following examinations a distinction was made between two types of overhead noise barriers as depicted in Fig. 1:

- Noise barriers with lateral openings: Galleries with lateral openings on one side, like noise barrier galleries or protective galleries (against rock fall etc.), for example
- Noise barriers with ceiling openings: Overhead noise barriers with openings in the ceiling, e.g. designed with light grids or longitudinal openings (for example partly covered troughs).

One examined sub-type was “partly open”, which means the combination of open sections with closed tunnel sections.

Noise barrier with lateral opening		**Noise barrier with ceiling opening**	
			
open	*partly open*	*open*	*partly open*

Fig. 1: Schematic depiction of different types of overhead noise barriers

In the third step the safety levels of open overhead noise barriers and of related reference tunnels were determined by a risk analysis. The risk-based studies and comparative calculations allowed determining the wide range of possible results for the respective safety levels. In view of the definition of future requirements for open overhead noise barriers those regulatory safety requirements which are necessary for tunnels and which have great savings potential concerning investment and maintenance costs were examined. Based on the comparison of the safety levels of variably equipped open overhead noise barriers the influence of infrastructural and technical characteristics of the respective constructions was investigated and the effectiveness of safety measures derived.

Methodically, the safety level was quantified by risks which were calculated using an event tree analysis. To assess the individual degree of damage the fire development was simulated three-dimensionally and the fatalities to be expected were determined by means of CFD calculations and escape models. The results were displayed and evaluated comparatively as monetized risks and cumulative distribution curves using reference tunnels with corresponding safety levels.

The procedure was broken down into the following sub-steps:

- Identification of decisive hazards and definition of relevant scenarios for the quantitative analysis of the safety level
- Risk assessment for different types of open overhead noise barriers, i.e. for defined types of open overhead noise barriers the resulting risk or respectively the safety level was determined.
- Risk assessment for reference tunnels, i.e. in order to be able to work out the differences with regard to risks between an open overhead noise barrier equipped according to the requirements set by the guidelines and the corresponding tunnel, comparative calculations were carried out. Hereby, the open overhead noise barriers examined in the previous step were modelled as tunnels, i.e. in the related model the open areas were modelled as closed areas.
- As a basis for the identification of criteria applied to the determination of minimum requirements concerning the equipment of open overhead noise barriers, the risk mitigating impact of different structure-specific characteristics and safety measures were investigated. From the point of view of the recommendations to be suggested for incorporation into the technical regulations, the focus was particularly on those measures which contributed significantly to mitigate the risk in the relevant scenarios or sub-scenarios and/or which involved considerable efforts (in terms of financing, realization etc.).

As far as the methodical basis for the quantitative analyses of the safety level was concerned, the proceeding was in accordance with the research project entitled „Safety Evaluation of Road Tunnels” [FE 03.0378, 2004], [1].

3. RESULTS

In the course of the quantitative analysis *comparative* risk analyses, comparative to the safety level of a reference tunnel, were carried out for defined types of constructions. This means that not the absolute values of the risks resulting from the quantitative analyses were in the foreground but the differences for the different types of constructions and their equipment features.

To consider all relevant incident scenarios in the risk analysis, specific hazards had been identified qualitatively by means of a hazard analysis. Derived from this the following aspects were examined in detail:

- In view of possible modifications to regulatory bases, the focus of the safety level analysis and of the influence of specific elements of equipment lay on „typical“ open overhead noise barriers with a rectangular cross-sectional profile. These are laterally open (galleries) or open-ceiling structures (partly covered troughs). The characteristics of specific individual structures were not examined.
- The main focus of the analysis was on the safety of the tunnel users. In the quantitative analyses it was specified by the injury indicator “fatalities”.
- As regards the incident scenarios, the main focus of the quantitative risk-based analysis was on the fire scenarios, since the purpose of the greater part of the safety equipment required according to RABT 2006 is to reduce the extent of damage in case

of fire. Above all, such equipment elements involve immense costs and require complex implementation efforts, too.

- Priority of the analysis was attributed to fires with a thermal power between 5 MW and 100 MW. Fires with a higher thermal power (fires of hazardous goods transports, for example) were not taken into account.

Besides the characteristics by which the basic types of overhead noise barriers can be distinguished, a large number of further risk-relevant influencing factors are decisive for the safety level. These factors were included, or varied, in the quantitative analyses in order to be able to assess their influence on the risk. Examples of risk-relevant influencing factors are:

- Traffic volume (ADT)
- Type of operation (directional traffic / two-way traffic)
- Layout of infrastructural elements of the construction (size of the openings, lintel, roof pitch of galleries, …)
- Tunnel ventilation
- Environmental influences (e.g. wind)

For the type “Overhead noise barrier with lateral openings” the cases listed in Table 1 were distinguished:

Tab. 1: Calculated cases for overhead noise barriers with lateral openings

Parameter	**Overhead noise barrier, lateral openings, RV**	**Overhead noise barrier, lateral openings, GV**
Abbreviation	**RV-ESO 1**	**GV-ESO 1**
Infrastructure		
Length of construction	1'200 m	1'200 m
Type of traffic	Unidirectional traffic	Bi-directional traffic
Number of lanes per direction (standard cross-section, width b_q)	2 (RQ 26t)	1 (RQ 10.5T)
Section height, h_q	5.5 m	5.5 m
Longitudinal gradient	-3.0 %	+/-3.0 %
Ventilation system	Natural ventilation	Natural ventilation
Distance between emergency exits	300 m	300 m
Height of lateral lintel in longitudinal direction (top), h_o	0 m / 1 m	0 m / 1 m
Gradient of ceiling, α	0 % / 10 %	0 % / 10 %
Design of ceiling	No lintels / lintels across carriageway (height 1 m)	No lintels / lintels across carriageway (height 1 m)
Traffic		
ADT per tube	20'000 veh/d	20'000 veh/d
Percentage of heavy vehicles	15 %	15 %
Event		
Site of fire	Centre of structure	Centre of structure
Thermal power	5 MW / 30 MW / 100 MW	5 MW / 30 MW / 100 MW
Fire detection	120 s	120 s

Fig. 2 depicts schematically the definition of the cross-sectional parameters listed in Tab. 1.

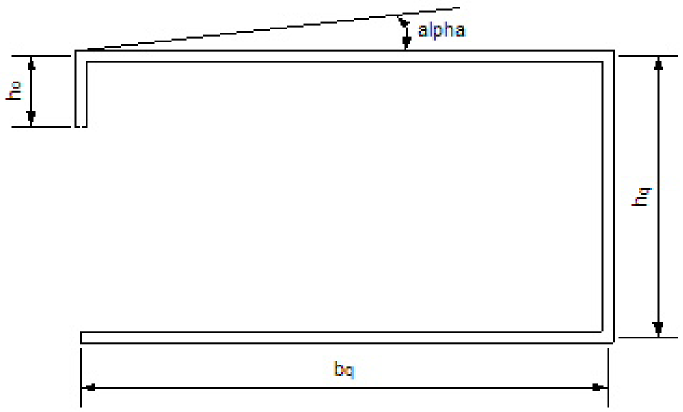

Fig. 2: Cross-section of overhead noise barrier with lateral openings

Due to the influence of the various structural characteristics like lateral or ceiling openings the results were clearly different.
Fig. 3 and Fig. 4 show the resulting overall cumulative FN-diagrams for the calculated cases of unidirectional and bi-directional traffic.

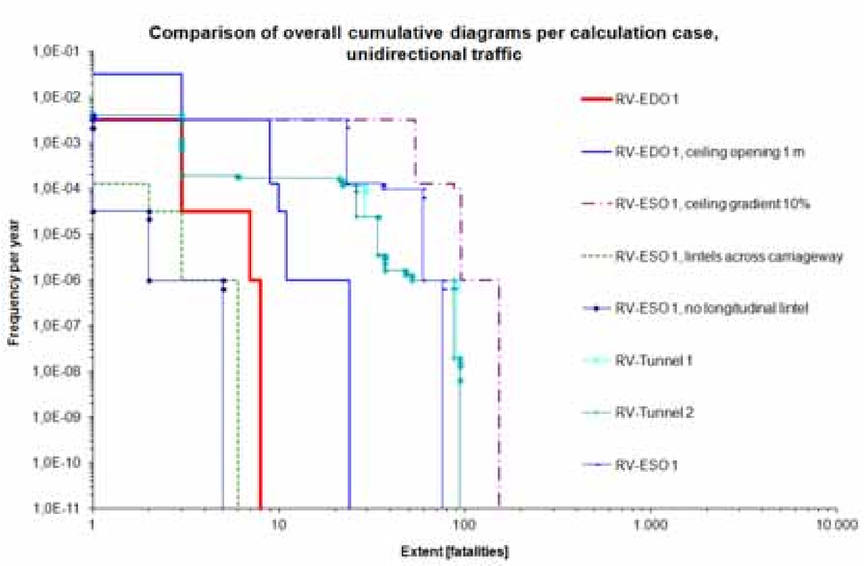

Fig. 3: Overall cumulative diagram for unidirectional traffic

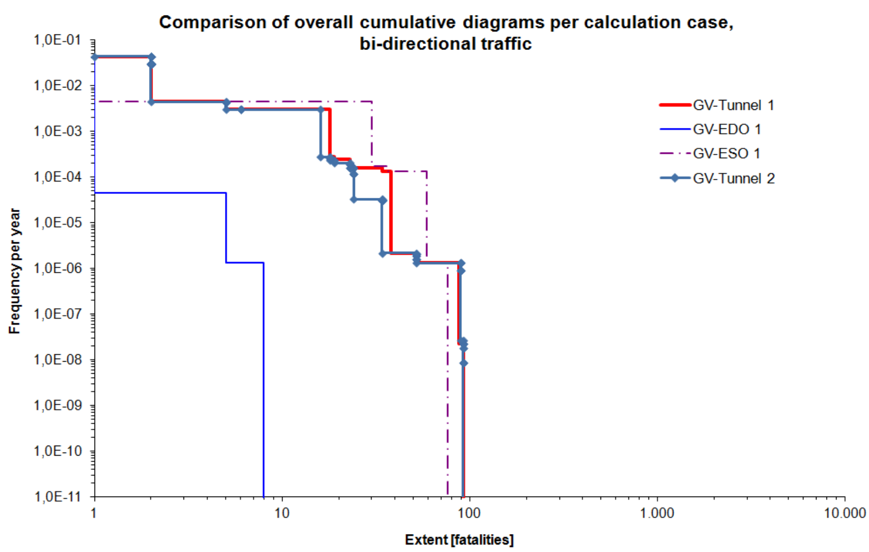

Fig. 4: Overall cumulative diagram for bi-directional traffic

With the indication of the extent (number of fatalities) the following parameters were determined in the event tree for each sub-scenario:

- Assessed (or "felt") collective risk R_e

$$R_e = \sum H \cdot A \cdot \varphi(A)$$

R_e:	Assessed risk [fatalities/year]
H:	Frequency of fire [1/year]
A:	Extent [fatalities]
φ(A):	Aversion factor [-]

- Monetized risk R_m

$$R_m = \sum H \cdot A \cdot \varphi(A) \cdot GK$$

R_m:	Monetized risk [€/year]
H:	Frequency of fire [1/ year]
A:	Extent [fatalities]
φ(A):	Aversion factor [-]
GK:	Marginal costs [€/prevented fatality]

When monetizing the risks marginal costs of € 10 million per prevented fatality were assumed [FE 03.0378, 2004], [1].

By means of a comparative analysis of the monetized risks and a further sensitivity analysis of relevant parameters, the significant differences and influencing factors were prepared and suggestions as regards criteria for minimum standards had been worked out in the fourth step. In doing so, aspects of the structure-specific differences of the safety level, the specific structure characteristics, the measure effect and implementation were discussed.

4. CONCLUSIONS AND RECOMMENDATIONS

As a last step based on the preceding quantitative and qualitative examinations regarding the safety level, recommendations were worked out concerning possible adaptations of regulatory requirements for open overhead noise barriers.

In connection with the discussions about possible, reduced requirements of RABT 2006 concerning the equipment of open overhead noise barriers compared to the present requirements, the specific hazards were analysed and the safety levels, subject to constructional characteristics, were determined and evaluated on the basis of comparable tunnels. The following recommendations were derived herefrom:

- The constructional characteristics of open overhead noise barriers generally have a risk-reducing effect in case of fire incidents because the flue gas can escape into the open, thus potentially spreading less inside the tunnel. But to a great extent this depends on the individual characteristic design of the structure. It is recommended to design the openings as large as possible to allow for a natural smoke dispersal into the open.
- A positive effect on the restriction of smoke propagation is achieved by transverse beams at the underside of the ceiling. The stronger smoke propagation is restricted in transverse direction, the lower can the special requirements of the ventilation system be, i.e. depending on the design of the transverse beams it may be possible to reduce the ventilation system requirements. Under certain conditions mechanical ventilation is not necessary at all.

- **Overhead noise barriers with lateral openings**
  In case of overhead noise barriers with lateral openings it is recommended to keep the height of the boundary beam small (transverse beam functioning as smoke barrier) (< 0.5 m) or to do completely without it, if possible. In general cases such a fire-specific safety equipment will not be necessary. The same positive effect on the safety standard of the overhead noise barrier can be achieved by increasing the inner clearance substantially or by installing an inclined ceiling (ascending towards the lateral opening). In that case as regards the tunnel users' risks the impact of the emergency exit distances, for example, on the safety level is reduced.
  If the constructional features mentioned before cannot be met, the analysis has shown that certain parts of the safety equipment required according to RABT 2006 always have to be installed. In such cases it is recommended to provide risk-based, object-specific proof of the same safety level (comparison with a reference tunnel).
  Furthermore, on the one hand, overhead noise barriers with lateral openings offer another possibility to escape for people in good physical condition, and, on the other hand, they also provide for an additional rescue path for the emergency and rescue services. Here it is recommended for unidirectional traffic sections with single-sided noise barriers to examine the closing of the adjacent traffic lane in the case of an incident in the gallery.
- **Overhead noise barriers with ceiling openings**
  Ceiling openings have a favourable effect on the restriction of the transverse propagation of flue gas and on the propagation reduction of thermal radiation. Therefore, in case of fire those road users who are close to the site of the fire are affected most. There are hardly any effective infrastructural or technical safety measures available for the tunnel users in this area. This means that the appropriate behaviour in case of fire is crucial for a successful self-rescuing.
  The analysis has shown that the size of the ceiling opening has significant influence on the resulting risks. According to the results obtained it is possible to do without a ventilation system and a related detection system, given a ceiling opening proportion of at least 25 % and a width of 2.50 m respectively. A tunnel closing system and the distances between emergency exits have also only a minor effect on the safety level of the overhead noise barrier structure.
  If the constructional characteristics mentioned above cannot be provided, the analysis has shown that certain parts of the safety equipment required according to RABT 2006 have to be installed. Here it is recommended to provide risk-based, object-specific proof of the same safety level (comparison with a reference tunnel).

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Risikoanalytische Untersuchungen zum Sicherheitsniveau offener Einhausungen (Risk-based analyses of the safety level of open overhead noise barriers)
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ON RISK ANALYSIS OF COMPLEX ROAD-TUNNEL SYSTEMS

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ABSTRACT

Quantified Risk Analysis (QRA) has become a cornerstone in the design and in particular in case of retrofit of road tunnels. Classical methods use event trees fault trees and similar for QRA. However due to the manifold of parameters and their mutual influencing, adequate event trees can only be developed for relatively simple cases. In the EU-directive 2004/54/EC (European Parliament, 2004),[1] 16 safety relevant parameters are defined. Assuming that each of these has 4 states, the resulting number of dependencies is more than one billion, which cannot be catered for employing event trees. Consequently, the here presented novel method is based on Bayesian Probabilistic Networks, which also permits to cater of the inter-dependency of the parameters.

The method was developed as a Best Praxis for Risk Analysis of road tunnels on behalf of the Norwegian and Swiss road authorities Schubert, Høj et al. (2011), [6]. Two separate Bayesian Probabilistic Networks are incorporated in the model: one for conventional traffic accidents with possible subsequent fires and another for transports of dangerous goods.

The tunnel of concern is divided into sections each with constant risk parameters e.g. invariant with respect to slope, traffic, lanes and all other relevant parameters. Portal zones as well as intersections are therefore always treated particularly.

The methodology has been implemented in a computer code TRANSIT.

As an example, a complex tunnel with several ramps connected by bifurcations has been considered and evaluated. Considering that this is an existing tunnel, the most cost efficient measure was to implement traffic speed control using cameras. Consequently, the speed limits were hardly exceeded and the fatality rate about halved.

Keywords: QRA, quantified risk analysis, tunnel, Bayesian probabilistic networks, upgrade, retrofit, cost efficiency, transports of dangerous goods, Transit.

1. INTRODUCTION

The demand for subsurface transport is increasing. This leads to complex underground systems with numerous stake holders with different expectations and requirements in terms of capacity, reliability availability, maintainability and safety.

Quantified Risk Analysis (QRA) is increasingly gaining importance in order to quantify the safety of road tunnels and hence to balance the requirements and expectation of various stake holders. Various reasons demand a QRA to be conducted. One reason may be that the tunnel has particular characteristics e.g. as defined in the EU-directive 2004/54/EC on the minimum requirements for the safety of road tunnels (European Parliament, 2004, [1]). Moreover, when upgrading existing tunnels, meeting current standards may be very costly or technically impossible. Finally, several new subsurface road systems display features beyond the current experience e.g. underground roundabout that cannot easily be assessed.

Cooperation between the federal road authorities of Switzerland (FEDRO) and Norway (NPRA) was initiated aiming at developing a joint “best practice” methodology and a corresponding tool for the risk assessment of road tunnels Schubert, Høj et al. (2011), [6]. A software tool was developed which takes basis in the proposed methodology. This tool is called TRANSIT. The present paper describes the methodology and presents the application of the methodology.

2. CONVENTIONAL APPLICATIONS OF ROAD-TUNNEL RISK ASSESSMENT

Building on the theoretical foundation developed by the JCSS in 2008, Faber et al. (2009), [2] developed a methodology for a uniform risk assessment for the Swiss road network. The results of this project form the framework and precondition for an efficient, transparent and communicable treatment of risks and they facilitate that risks from different sources are treated in the same manner and assessed on the same basis so that they are comparable, may be aggregated and transparently documented and communicated.

PIARC has been one of the main initiators for promoting safety in tunnels and has among others initiated the ERS2 project in collaboration with OECD for harmonizing the risk analysis and regulation of transport of dangerous goods (Høj and Kroon, 2003, [10]). This topic has been ratified by UNECE and the ADR prescribes the risk analysis methodology for determining five predefined groups of restrictions for transport of dangerous goods through road tunnels.

In the report PIARC C3.3 Risk Analysis for Road Tunnels PIARC (2008), PIARC has followed up on the risk analysis methods used in Europe. Several methodologies and tools for the risk assessment in roadway tunnels exist already e.g: TuRisMo (Austria), TuSi (Norway) BASt model (Germany), HQ-TunRisk, TunPrim/RWSQRA (Netherland), QRAM (OECD – PIARC) and ASTRA ADR (Switzerland). All these methodologies have their advantages in specific fields. A review and analysis of these methodologies (Høj and Horn (2010)) has showed that the requirements with regard to the modelling of specific events (e.g. accidents and fire) neither from the Directive 2004/54/EC of the European Parliament (2004) nor from FEDRO and NPRA are fully met,. The methodologies fail to model all events or relevant indicators are not considered. Another aspect is that in some methodologies the level of detail is not sufficient for the ranking of different decision alternatives to reduce the risk.

3. NEW APPROACH: BAYESIAN PROBALISTIC NETWORKS (BPN)

3.1. Introduction

The general approach utilized in TRANSIT differs significantly from the approach used in the other models mentioned above. The major difference is that the system is modelled and analysed using Bayesian Probabilistic Networks (BPN’s) which results in a hierarchical indicator based risk model.

Simplified, BPN’s can be considered as an advancement of event trees. They provide the possibility to fully represent simple event trees but also dependencies between different indicators and consequences can be considered, see illustrative example Figure 1. They are also efficient in regard to the graphical representation of complex systems so that they facilitate to make plausibility checks in regard to causal relations between different indicators. Bayesian Networks represent the current state of the art in the risk assessment.

Bayesian Probabilistic Networks (BPN) have been developed in the mid of the 1980ies with the motivation to deal with information from different sources and interpret and establish coherent models (Pearl, 1985) [4]. Today, Bayesian Networks are widely used in the engineering sector and in natural hazards management. They are used due to their flexibility and efficiency in regard to system representation.

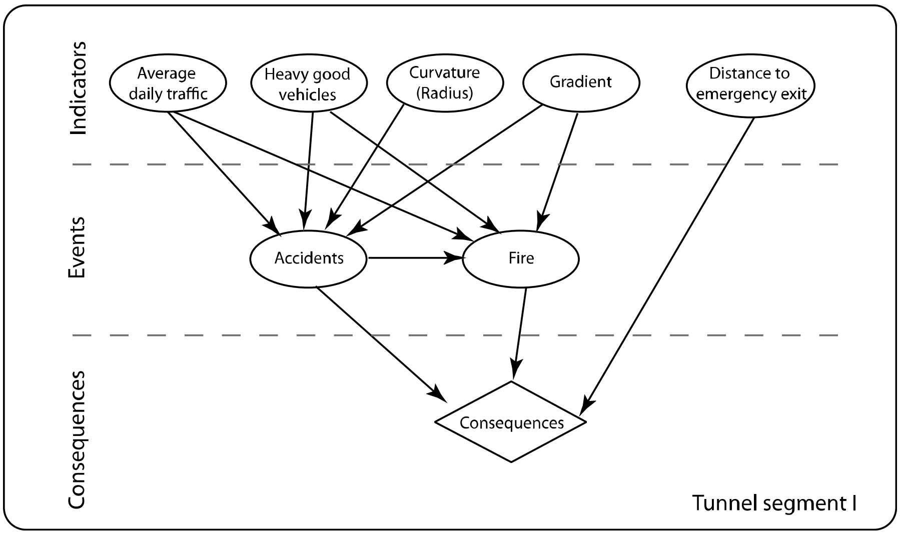

Figure 1: Simplified illustration of a generic system representation using a BPN.

3.2. Generic risk representation

The road tunnel users are exposed to various risks which have different causes. The largest contributor to the risk is collisions and other types of “normal traffic accidents”. Fire events as consequence of accidents or due to technical problems with engine or brakes are also events which must be considered in road tunnel risk assessments. Finally, rare events with potential large consequences, such as events with dangerous goods transports, must be considered as well.

In general, risk to users in the tunnel has to be considered in both the planning phase and during the operational phase of tunnels. Two different classes of measures can be differentiated: one class concerns the reduction of the exposure, i.e. the reduction of the accidents and fire frequency and the other class concerns the reduction of the consequences when a fire or an accident occurs. The main criterion in the planning phase of such measures is the cost efficiency of the measures. In order to judge the efficiency of measures, the influence of the measure on the risk has to be quantified.

A key feature of this methodology is that the uncertainties and the dependencies of the parameters, which are explicitly considered for the modelling of event frequencies and consequences, are quantified and accounted for. The system constituents are modelled using so called risk indicators which can represent the system in a generic manner, i.e. all possible configurations of the system can be represented by using an appropriate choice of the indicators. From this definition, it is clear that the choice of the indicators plays a major role in the risk assessment and of course, any choice cannot be exhaustive. These Key Performance Indicators (KPI) can be used to establish a generic system representation for a risk model for a generic tunnel segment.

The risk model for the segment is generic, that means that one risk model for all possible characteristics in a tunnel is used. The model becomes specific by introducing evidence on the specific parameters, such as annual average daily traffic (AADT), the fraction of heavy goods vehicle, etc., in the model and by performing inference calculations.

For a specific tunnel segment some or all of the considered KPI's are known and this knowledge can be transferred in the model by introducing evidence in the generic model. In this sense, the model becomes specific for this specific segment (see Figure 2). The same generic model can be used to calculate the risk under specific conditions. The risk can be calculated for each single segment as well as for the entire tunnel. Segments with higher risk in the tunnel can be identified and specific risk reducing measures for these segments can be identified.

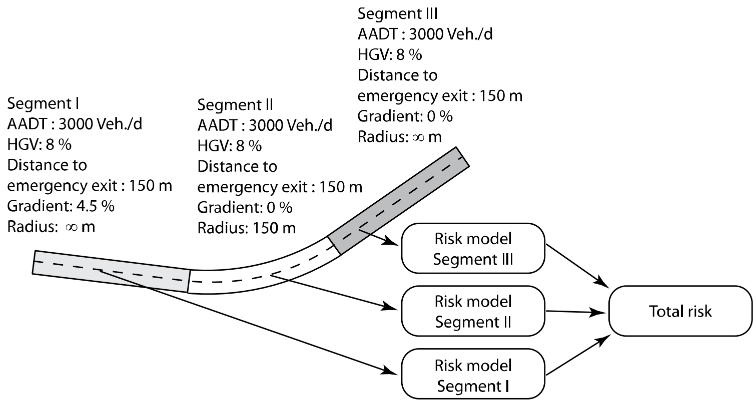

Figure 2: Illustration of the generic system representation, examples of parameters..

3.3. Bayesian Networks for accidents, fires and dangerous goods accidents

The risk model is established by employing Bayesian Probabilistic Networks. The BPN developed for accidents and fires in tunnel. The links between the nodes represent the relation between the nodes. This relation can be a probabilistic or deterministic function or a function estimated by expert opinion.

Each of the nodes contains a different number of so-called states. These states represent the different possible characteristics of the node which can be observed in reality. The node "number of lanes" contains 3 states, i.e. one lane, two lanes and three lanes per direction. By knowing the number of lanes and the number of vehicles per hour, the level of service can be calculated. One kernel node in the network is the node AMF. This node represents the "Accident Modification Factor" (AMF). The hypothesis is made that one basis or mean accident rate for the tunnel can be calculated over the entire network. Under different circumstances, this accident rate might be higher or smaller than the average rate. The AMF represents the difference of the accident rate in a specific segment from the mean value of all existing segments in the entire road network.

If it was possible to observe directly the different indicators in the data acquisition, the use of AMF would be obsolete. This would mean dedicated statistics for all combinations of traffic, tunnel lay-out, geometry, tunnel equipment etc. Since the tunnel designs are too diverse and the accidents, injuries and fatalities are too infrequent such statistics can hardly be established for all combinations. The concept of an accident modification factor (AMF) has the clear advantage that the models can be used and the results be extrapolated to conditions which are not directly observable. When statistics becomes available for some of the combinations, the existing prior distribution can be updated with this new information. The AMF is a normalized function of one or more indicators *i*, i.e. $AMF = f(i_1,\ldots,i_n)$ with a definition range of $[0, \infty]$. The AMF are assessed with different methods and models for the different considered indicators.

An additional Bayesian Network to model dangerous goods events in the tunnel is also contained in the methodology.

4. EXAMPLE OF APPLICATION

4.1. Analysed tunnel system

The risk profile of an existing road tunnel was analysed and mitigation measured proposed in order to reach the desired risk level. Cost efficient safety measures should be introduced in accordance with the ALARP principle, in addition the risk level was compared to the average risk on the motorways. As risk indicator, the main parameter was the rate of fatalities per billion vehicle kilometres.

The tunnel is composed of two dual-lane unidirectional traffic main tubes that near each end connect to ramps, see **Figure *3***. The ramps are operated with unidirectional traffic at the intersections with the main tunnel but merges to become bidirectional near the portals. The tunnel is hence composed of 10 sections. The curvatures of some the ramps are very narrow.

Further main tunnel characteristics are:

- Length: 785 m of main tunnel tubes and 2553 m long ramps.
- Slope on most sections of main tunnel below 1.2% but up to 6% at one portal; the ramps have slopes of up to 5 %.
- Main tunnel with two traffic lanes throughout and additional lanes at bifurcations connecting to ramps.
- Max traffic of 46’000 vehicles per 24h (AADT). Heavy goods vehicles (HGV): 10% main tunnel and varies between 5%, 6% and 10% on the ramps. 3 % of HGV is dangerous goods; ADR class A.

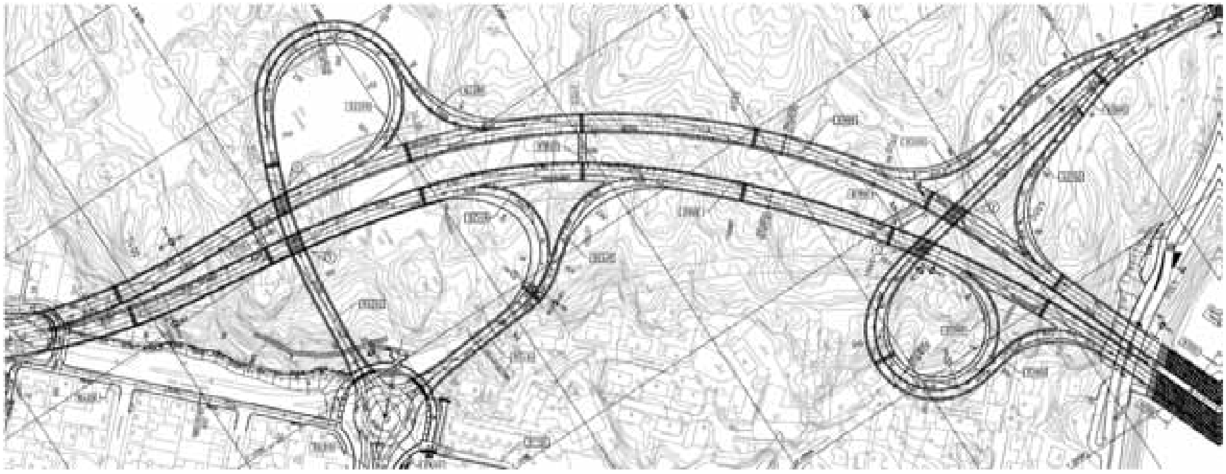

Figure 3: Tunnel with several bifurcations to and from ramps, unidirectional traffic in main tunnel but uni- and bi-directional traffic on ramps.

4.2. Methodology

Using the described methodology that is incorporated in the computer code TRANSIT, the risk on all tunnel sections was calculated for following distinct situations:

- Accidents (collisions and similar excluding fires and dangerous goods events)
- Fires (excluding fires in dangerous goods)
- Event involving dangerous goods

4.3. Risk level in original situation prior to 2007

In spite of the speed limit of 60 km/h, the typical speed in the main tunnel was 70 to 75 km/h. Using Transit, the theoretical fatalities, injuries and accidents were computed, see **Table *1***. The computed 2.125 accidents per year agreed well with past experience.

As the estimated rate of fatalities was much higher than the average on the national roads and about double of that on national 4-lane motorways, the situation was deemed unacceptable.

Table 1: Computation of the risk in the original situation up to 2007

	Fatalities / year	Injuries / year	Incidents / year
Accidents	0.1037	3.184	2.125
Fires	0.0165	0.036	0.579
Dangerous goods	0.0013	0.004	0.000
Total	**0.1215**	**3.225**	**2.704**
	Rates		
Traffic	16.24		10^6 vehicle-km/year
Accident rate	0.131		Per 10^6 vehicle-km
Fire rate	0.036		Per 10^6 vehicle-km
Fatality rate	7.48		Per 10^9 vehicle-km

4.4. Analysis of the original situation

Compared to a standard tunnel some aspects lead to reduced risk level:

- Lower traffic speed, (reference for all tunnels is 80 km/h, for motorways 100 km/t)
- Lower fraction of heavy goods vehicles; (reference 12 to 15%)
- Better light at 4 cd/m^2; (reference for all tunnels is 2 cd/m^2, for motorways 4 cd/m^2)

Other aspects lead to higher risk levels:

- Slopes up to 6% in main tunnel (causes increase in risk by 38%) and up to 5% on ramps (result in risk increase by 25%); here reference value is 2%
- Narrow curves on ramps
- Bifurcations.

The influence of the bifurcations are clearly visible e.g. in the eastern part of the eastbound main tunnel, see **Figure *4***.

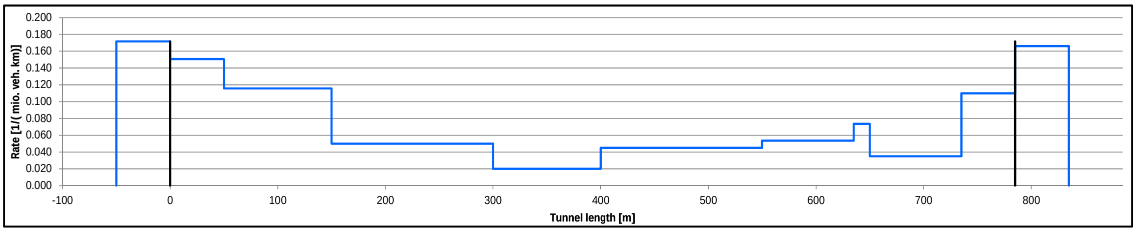

Figure 4: Accident frequency in eastbound main tunnel

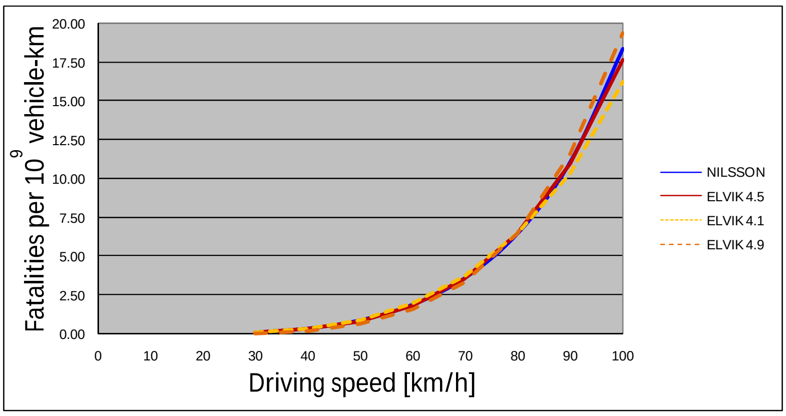

Figure 5: Relationship between driving speed and fatalities

Considering that the tunnel is already constructed and that the speed limits are not respected, it is interesting to examine further the influence of traffic speed.

The frequency and the consequences in terms of injuries and fatalities depend on the average travel speed. Elvik (2004), [8] et al. has developed such a model which agrees with the earlier model established by Nilsson (1997), [7]. By reducing the drive speed form about 75 km/h to 60 km/h, it is anticipated that the fatality rate is about halved, see **Figure *5***. Similar models have been established for the injury rate.

4.5. Result of mitigation measures

Based on the analysis of the original situation, the cost efficient mitigation measure was to ensure that the speed limits were respected. Therefore in 2007, an automatic traffic control with speed cameras was installed. After this the drivers respected the relatively low speed limit of 50 to 60 km/h i.e. reducing the driving speed by 10 to 15 km/h. In the main tunnel with a speed limit of 60 km/h, typical traffic speeds of 63 to 64 km/h were measured.

The computed risks are shown in **Table *2***. The predicted 1.179 incidents per year agree well with the experience for the period 2007 to 2011 that had 4 incidents with injuries.

As the computed fatality rate is below that for national roads and close to the one for national motorways, the introduced mitigation measures were judged successful.

Table 2: Computation of the risk in the new situation after 2007

	Fatalities / year	Injuries / year	Incidents / year
Accidents	0.0336	1.592	1.179
Fires	0.0161	0.036	0.536
Dangerous goods	0.0016	0.005	0.000
Total	**0.0513**	**1.633**	**1.715**
Rates			
Traffic	16.24		10^6 vehicle-km/year
Accident rate	0.073		Per 10^6 vehicle-km
Fire rate	0.033		Per 10^6 vehicle-km
Fatality rate	3.16		Per 10^9 vehicle-km

5. CONCLUSIONS

A sound methodology is developed and presented in this paper representing the best practice in the field of traffic safety assessment of road tunnels in accordance with the state of the art in the field of risk assessment. The methodology facilitates the risk-based decision making with respect to risk-reducing measures during the planning and during the operation of the tunnel. The methodology gives comparable and reproducible use-independent results.

The general approach in this project differs significantly from other methodologies for the risk assessment in road tunnels. Bayesian Probabilistic Networks (BPN), which are used to model the events, are a best practice methodology in the field of risk assessment and they facilitate the assessment according to recent scientific standards. TRANSIT represents the tunnel system in a generic manner, i.e. risks are assessed in segments, which are defined as a function of the tunnel and traffic characteristics. TRANSIT facilitates the risk assessment on different levels of detail. If only a few details on the tunnel and traffic characteristics are known, the analysis can still be performed. Missing information on risk indicators is replaced by a priori distributions. When more specific information is available, the level of detail of the analysis can be improved.

The example of application has demonstrated that even complex tunnel networks can be analysed using this methodology and the tool Transit. The risk level of the tunnel, which has been in operation since 2002, was well estimated. Moreover, the situation for the period 2007 to 2011 subsequent to the implementation of the mitigation measure was also well estimated. For this existing tunnel, the efficiency of the implementation of traffic speed control using speed cameras was verified. As a consequence, the speed limits were hardly exceeded and the fatality rates about halved. The example should be regarded as a successful application of TRANSIT, the success of the application of speed control cameras, on the other hand, may be related to local conditions.

6. ACKNOWLEDGEMENT

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EVALUATION AND INTERPRETATION OF F/N-CURVES: DEVELOPMENT OF A NEW TOOL FOR TRANSPARENT AND TRACEABLE DECISION MAKING

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ABSTRACT

The evaluation of risks by f/n-curves is a graphical method to present the numbers of fatal accidents in a traffic system together with the numbers of fatalities which have occurred or which could be expected from a quantitative risk analysis [3]. The interpretation of f/n-curves, resulting from frequently performed quantitative risk assessments (QRAs) for tunnels and underground facilities, is a difficult task regarding the resulting requirements for the design or the operation of a traffic facility. This may on some occasions already be a problem for the designer himself but is a task of even higher requirements for an operating authority of such a structure, which in many cases have little experience with QRAs and the corresponding simulation model, such as CFD-Simulations for smoke expansion or escape simulations. Especially when two or more settings or configurations of safety equipment are compared to each other, the interpretation sometimes becomes rather "instinctively", especially when the corresponding f/n-curves are interlacing and cutting across each other. In the past, some simplifications have been used for the evaluation of f/n-curves, such as the accumulated risk values. The problem is that these values mathematically do underestimate the influence of incidents with low probabilities but high damage. So-called "aversion factors" have been introduced to compensate for this problem, but often add up to the fuzziness of the whole process. The following paper describes a possible solution for this problem using a mathematical approach for comparison and decision support. The algorithm as well as the corresponding tool was developed in the course of the SOLIT² research project in Germany which is funded by the German Ministry for Economics and Technology (BMWi). In the following the authors describe the mathematical approach and show some examples of its application.

Keywords: f/n-curves, quantitative risk analysis, tunnel, safety, security

1. INTRODUCTION

1.1. General remarks

The performance oriented quantitative evaluation of safety measures for tunnels is increasingly and – to some extent –already part of our regulations and guidelines. For instance in Germany such tunnels which have a "special characteristic" beside of the standardized cases have to be assessed and evaluated with a quantitative risk assessment under the regulations of the German "RABT"-guideline (German Guideline for equipment and operation of road tunnels based on EU-directive No.), [8]. In case dangerous goods are transported through a tunnel, such assessments have become mandatory throughout the whole European Community.

With the results of such assessments already at hand the discussion usually starts about the conclusion to be drawn from the corresponding f/n-curves and particulary regarding the shape of the graph. If the assessment is carried out against a specific benchmark, such as a risk-acceptance curve for ADR-assessments (***A**ccord européen relatif au transport international des marchandises **D**angereuses par **R**oute)*, the evaluation process is rather easy if the shape of the graph does (or does not) interlace or reach beyond the respective acceptance curve. It is also very easy, if different curves for alternatives solutions – for instance in case of a comparison of different technical settings or safety measures – show high levels of variation when compared with each other. But on some occasions the applied and competing mitigation measures produce similar performances within the chosen scenarios and boundary conditions leading to a nearly similar performance within the assessment. In this case it might become very difficult to identify the optimal curve and thereby the optimal measure or configuration for the specific structure or tunnel.

In the past simplifications and workarounds were developed for such cases, with the accumulated risk value – the total weight of the curve (surface integral of the curve) – being the most prominent one. Main problem with the application of especially this value is that it mathematically underestimates incidents with low probabilities but very high damages within the summation. Therefore so called "aversion-factors", especially developed to provide more of an equilibrium regarding the weighting of highly and lowly probable incidents, have been introduced and implemented from other sciences. Unfortunately, these factors do add to the overall fuzziness of the result at hand, since there is no general approach for developing such factors [7]. In theory such a factor can be defined and applied in an arbitrary way by the author of a study. Sensitivity analyses regarding the influence of aversion factors are also lacking within the scientific community. Thereby the tracing of a result as well as gaining transparency regarding the assessment and evaluation process becomes rather difficult, especially for operating authorities which may have little experience with quantitative risk analysis.

1.2. The project SOLIT²

In 2009 the German Federal Ministry for Economics and Technology funded the research project SOLIT² (Safety of life in tunnels 2). As one of the project`s main goals the quantification of a compensation potential of fixed fire fighting systems in traffic tunnels was targeted in comparison to other safety measures by a German consortium, consisting of FOGTEC, BUNG –Engineers, TÜV South, STUVA and the Institute for Tunnelling and Construction Management at Ruhr-University Bochum (RUB-TLB). The idea was to find a setting of safety measures, possibly including a fixed fire fighting system, which provides an equal level of risks compared to typical road tunnel equipment settings following the regulations of the German RABT, while requiring lower amount costs for investment, operation and maintenance. Alternatively, a setting was targeted that provides a lower level of risks, while requiring the same amount of costs for investment and maintenance. Hereby RUB-TLB was assigned with the development of a lifecycle costing model for tunnel equipment enabling its user to carry out the respective comparison in terms of costs and investments. Additionally, a mathematical solution was developed for the aforementioned decision support problem. The results of this development are described in the following.

2. DEVELOPMENT OF AN ALTERNATIVE APPROACH FOR THE EVALUATION OF QUANTITATIVE RISK ASSESSMENTS

2.1. Requirements for an evaluation method

With the general remarks in mind some basic assumptions can be stated regarding the development of a possible solution of the decision problem at hand:

- A corresponding algorithm has to deliver a procedure that can easily be applied by any user for comparison of specific results
- The algorithm has to deliver a reproducible and transparent procedure
- Further, the algorithm has to be executed with the help of attributes so that the evaluation can be carried out with project oriented criteria

Multi criteria decision models generally meet these requirements while offering the opportunity to describe and to analyze complex decision situations [2]. By evaluating all advantages and disadvantages in a prior study [13][14][15], the choice for an evaluation method was made in favor of the Analytic Hierarchy Process (AHP). The AHP is suitable for a precise structure of complex decision problems. The method is based on decision relevant alternatives and goals and considers both, qualitative and quantitative data. For practical use, the method includes a clear structure. According to [1], the AHP can be easily applied, the use for single persons and groups as well, the advancement of agreement and consensus, and finally the communication and transparency of results.

2.2. The Analytic Hierarchy Process (AHP)

The AHP was developed by Thomas Saaty in the USA in the 1970s [9][10][11][12]. It is characterized by the three main parts: analytical procedure, hierarchical structure and a processual decision [5][17]. Analytic procedure means that the method is working with mathematical-logical functions which are comprehensible for all project participants. A hierarchical structure has to be applied to the decision problem so that it can be split into different levels of comparison. The process-related character allows the method to be restarted as many times as needed in order to reproduce decisions or to describe the whole decision making process. Furthermore, it is possible to imply quantitative and qualitative information during the decision process.

For a meaningful evaluation result, different information has to be weighted in order to show the significance of the decision. For the pair and alternative comparison Saaty introduces a 9-value-scale [4]. This scale includes also the use of reciprocal scale values. E.g. if one element is 3 times more important than another element it means that the other element possesses the value 1/3. Due to the fact that those pair comparisons are often made in a subjective way, it might be possible that they are inconsistent. For instance, if criterion A is three times more important than criterion B, and B is two times more important than C, the decision maker could evaluate criterion A three times more important than C (whereas it has to be six times). In that case, the made evaluation is not correct and would lead to a wrong result. But to a certain very limited extent inconsistencies are allowed and do not endanger the whole decision [16].

For checking consistencies, Saaty defines the consistency index (CI) and the consistency ratio (CR). With the help of the eigenvalue-method it is possible to calculate the inconsistency and to detect wrong comparisons. The reference point given by Saaty for CR is 0.1. If the value of 0.1 will be exceeded, the decision process is regarded to be inconsistent so that the logic and interpretability of the results are not given anymore. The decision maker then has to correct the correlating mistake and to evaluate the whole process again. For providing a traceable and transparent decision, a sensitivity analysis then has to be carried out. The main goal of this analysis is to show the influence of weight changes (read: prioritization of specific criterions) which may lead to a change in the ranking of the alternatives. This analysis is a very effective tool to analyze the stability of results, especially when one alternative is prioritized in the result of an AHP evaluation by narrow margin. For the fundamental mathematical procedure the reader is referred to fundamental literature, such as [9][10][11][12].

2.3. Analysis of f/n-curves using the Analytic Hierarchy Process

In the following the authors will show the theoretical approach of such an application. As already stated, it is possible to estimate the accumulated risk value for typical f/n-curves based on the surface integral. In consideration of the shown Analytic Hierarchy Process and its algorithm the authors investigate how single areas of an f/n-curve could be weighted stronger or weaker for the comparison and the identification of the most ideal curve and thereby the most ideal technical setting. In other words: By applying AHP to the comparison of f/n-curves a decision maker is enabled to analyze specific areas of different curves for a deeper investigation of the risk based f/n-diagram. To simplify the description of the overall approach, the authors will refer to the curve or the diagram as a whole. Naturally all mathematical calculations are carried out with the original data regarding probabilities and corresponding damage, gained from the underlying quantitative risk analysis.

2.3.1. Hierarchical Structure of the Decision Problem

First, in consideration of the AHP and its boundary conditions a hierarchical structure has to be developed. For that, in the first level "single risk areas" are defined by splitting the f/n-curve into several areas for evaluation. Of course, it is possible to divide every single area into subareas if a refinement becomes necessary, creating further sublevels. An example of a QRA-related AHP-hierarchy is shown in figure 1.

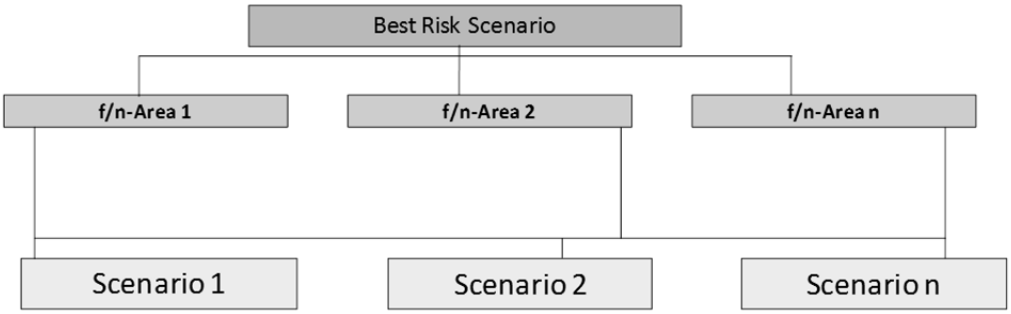

Fig. 1: AHP-Risk Hierarchy

2.3.2. Calculation of the collective risk values of all scenarios

In the next step, the accumulated risk values R_i of all f/n-curves have to be calculated. The reason is that, when using the AHP input data has to be normalized, so a decision maker could get a ranking of the alternatives/criteria (1). Finally, the sum of all accumulated risk values has to be calculated (2).

$$w_{R_i} = \frac{\frac{1}{R_i}}{\frac{1}{R_1}+\frac{1}{R_2}+\dots+\frac{1}{R_n}} \tag{1}$$

$$R_G = \sum_1^n R_i \tag{2}$$

2.3.3. Definition of single risk areas

Then the f/n-curve has to be chosen which includes the theoretical highest damage value $N_{k,max}$. The lowest and highest damage values present the limits for the definition of the single risk areas. Within these limits the decision maker splits the f/n-curve into several areas, further called "Risk Areas" (N_{RA_j}) (3) which are oriented according to the damage value $N_{k,max}$. All further f/n-curves have to be split accordingly.

$$Number\ of\ Risk\ Areas: NRA$$

$$Risk\ areas: N_{RA_j}$$

$$N_{RA_j} = \frac{N_{k,max}}{NRA} \tag{3}$$

In figure 2 it is shown how a single f/n-curve can be splitted here into 4 NRA`s.

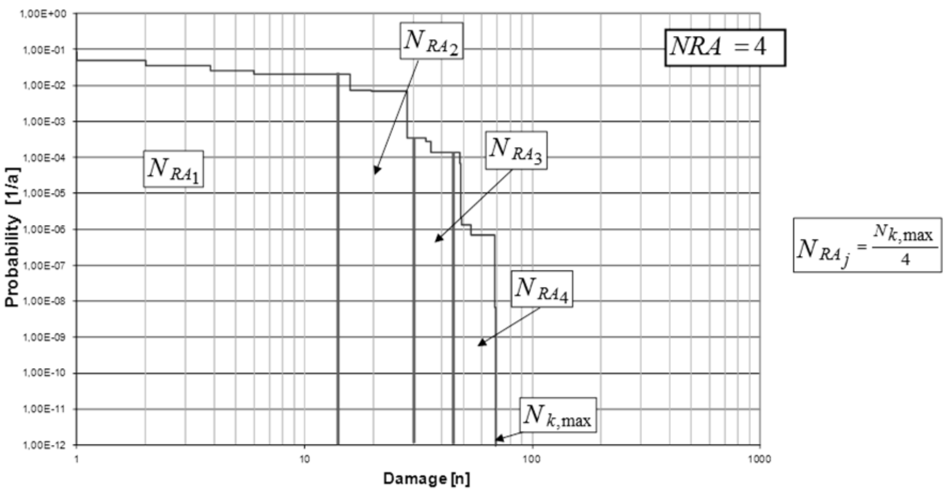

Fig. 2: Splitting of an f/n-curve

2.3.4. Calculation of single expected risk values

After all areas are defined the accumulated risk values of every single area have to be calculated. For an appropriate application of the AHP-method it is necessary to weight these areas because of the imminent pair-wise comparison for identifying the most important risk area. The actual weight has to be defined in consideration of the calculated surface sums. For the local weight of every single area the accumulated risk values of all f/n-curves have to be summed up (R_G) (2). In a second step all accumulated risk values for every single area of all f/n-curves ($R_{RA_j}(R_i)$) (4) have to be evaluated whereas W_{mn} is the probability, H_m the frequency and A_{mn} the fatality of an event. The last step is described by the division of the summed risk values for the single areas through the sum of all expected risk values ($\mathrm{WE}_{N_{RA_j}}$) (5). This mathematical procedure has to be done for every area, so that a local normalized weight can be calculated.

$$R_{RA_j}(R_i) = H_m \cdot W_{mn} \cdot A_{mn} \tag{4}$$

$$\mathrm{WE}_{N_{RA_j}} = \frac{\sum_{i=1}^{n} R_{RA_j}(R_i)}{\sum_1^n R_i} \tag{5}$$

2.3.5. Weight of the scenarios

Next, the quantitative weighting of the scenarios with regard to the single risk areas has to be carried out. For that, the accumulated risk values of every single area ($R_{RA_j}(R_i)$) are compared in reference to the scenarios (6).

The ratio has to be calculated with reciprocal values following the principle: The higher a value the lower its benefit.

$$w_{R_{RA_j}(R_i)} = \frac{\frac{1}{R_{RA_1}(R_i)}}{\frac{1}{R_{RA_1}(R_i)} + \frac{1}{R_{RA_2}(R_i)} + \ldots + \frac{1}{R_{RA_n}(R_i)}} \tag{6}$$

2.3.6. Calculation of the total weight

With the local weights of the main-criteria the global weight has to be calculated (same for the sub-criteria in a next step). Doing so every minor level of criteria has to be multiplied with the local weight of the superior level. The formula for the calculation of the global weight for an element i ($w_{rel}(i)$) for the n^{th} hierarchical level is:

$$w_{rel}(i) = w_n \cdot w_{n-1} \quad (7)$$

Finally, the local alternative weights are multiplied with the global weights of superior criterions so that the decision maker is getting global alternative weights. With a final summation of the global alternative weights per alternative the preference index (w) can be estimated, which describes the importance of every single alternative.

2.4. Example of an application of the Analytic Hierarchy Process

2.4.1. General Remarks

Within the previous chapters the rather theoretical approach of applying AHP to the identification of a preferred solution was described. This approach alone neither clarifies the mentioned decision problem nor does it help the decision maker to trace his decision or to make up for more transparency. The benefit of using this approach becomes obvious when applied to a realistic scenario. Therefore a simple example is created as follows. We assume that for a specific tunnel under a specific scenario three different configurations of safety measures are compared with each other. In Figure 3 three possible f/n-curves as a result of a previously conducted quantitative risk assessment are shown.

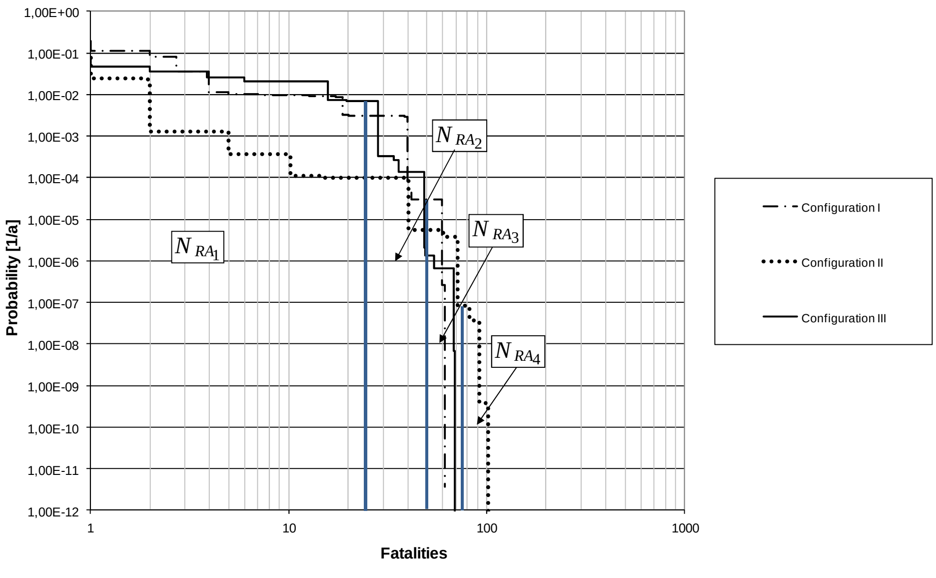

Fig. 3: f/n-curves of three different tunnel safety settings

Again, one has to keep in mind that all calculations are carried out with the underlying data, but that the authors are referring to the resulting diagram to make the process of application and evaluation more transparent. Also, one has to regard that the authors chose a rather obvious disparity between the different results to show the possibilities with the application.

2.4.2. Evaluation of the results using AHP

As typical for the evaluation process, maximum damages as well as accumulated risk values are observed in the beginning. Although configuration 2 has the highest damage value (N_2 = 100) configuration 1 and 3 display a higher accumulated risk value, so that configuration 2 might be preferred. As the AHP is applied to the data of the QRA at hand, the total weights of all configurations have to be calculated. For this example the decision maker created four risk areas (figure 3). The results are shown in table 1, as well as the corresponding accumulated risk values.

Tab. 1: Calculation of the total weight W

	Configuration 1 R_1= 0,613		Configuration 2 R_2 = 0,180		Configuration 3 R_3 = 0,545	
	Local weight	Total weight	Local weight	Total weight	Local weight	Total weight
Risk area 1	0,944	0,173696	0,944	0,579616	0,944	0,190688
Risk area 2	0,054	0,005562	0,054	0,038556	0,054	0,009828
Risk area 3	0,001	0,000067	0,001	0,000026	0,001	0,000907
Risk area 4	0,001	0,000496	0,001	0,000080	0,001	0,000496
		0,1798 = 17,98 %		0,6183 = 61,83 %		0,2019 = 20,19 %

According to Tab. 1 we assume configuration 2 as the best alternative with a total weight of about 62%. This result is nearly equal to the result if the accumulated risk values are taken into account (R_2=0,180). The advantage here is that the whole decision problem is now transferred into a hierarchical structure. By doing this the results can now be analyzed with the help of a sensitivity analysis. The goal of such an analysis is to check made decision by changing the individual weights of the different criterions, respectively risk areas. To exemplify the possibilities of such an analysis Figures 4 and 5 display the sensitivity analysis for the risk areas 3 and 4.

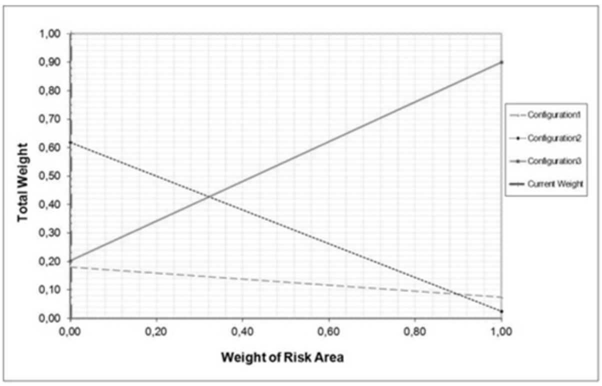

Fig.4: Sens.-analysis of risk area 3

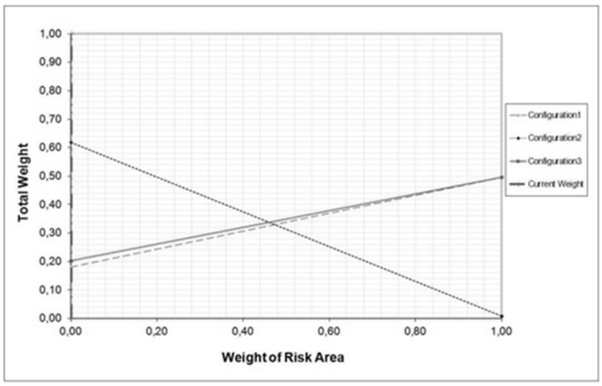

Fig.5: Sens.-analysis of risk area 4

Here it is noticeable that a higher importance of the corresponding areas would induce a change of the overall ranking of alternatives. In other words: If the decision maker would decide to attach more importance to higher damages (raise the importance of areas 3 and 4) then configurations 1 and 3 have to be preferred since their performance is much better within the corresponding risk areas. That said such an analysis enables the user to compare different configurations with keeping the focus on specific areas of damage, but without having to use simplifications that modify the results mathematically. The input data remains clean and without additional fuzziness so that the center of the decision making process can now be moved around (laying the focus on highly probable incidents vs. incidents with low probability of occurrence but dramatically high outcome).

Last but not least, each criterion is weighted to 100% in the following step. Now, the calculated total weight states that within risk areas 1 and 2 configuration 2 becomes the best alternative, while within risk areas 3 and 4 configuration 3 respectively 2 is the best alternative to chose.

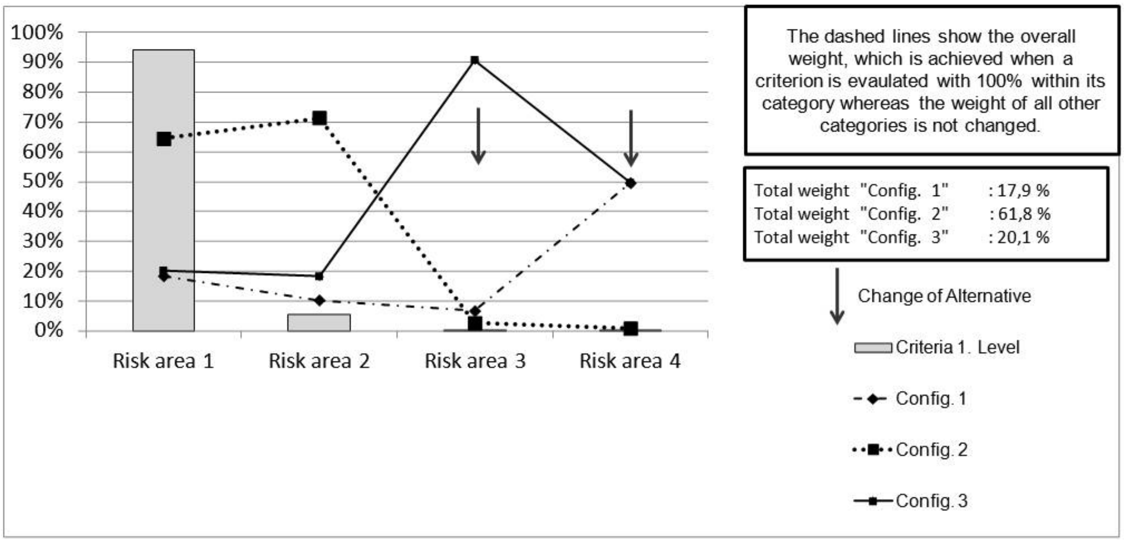

Fig.6: Performance-Analysis for the first level

3. CONCLUSION AND OUTLOOK

The analysis of quantitative risk assessments includes complex decision situations which require different perspectives as well as deepened knowledge of the situation at hand and the underlying methods and procedures. The present article illustrates the possibility for a new approach of evaluating the corresponding f/n-curves especially regarding difficult situations of evaluation and decision making. The mathematical procedure of the AHP allows for comprehensible, reproducible and transparent choices, without the need for simplifications and additional factors that add up to the uncertainty of the result. At a first glance the algorithm seems to produce more complexity for the decision problem. But due to this strictly mathematical approach it can be transformed into easy-to-handle software-tools. Currently the authors are working on such a tool as a further step of development. It will allow a flexible and individual adaptation of the evaluation hierarchy for a specific project. Results are expected within the next months.

Furthermore, AHP delivers the possibility to implement other criterions in an equal fashion, such as lifecycle costs or structural assessment. At present the development of such a decision model is done by the authors as part of the work within the SOLIT²-project.

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OPTIMIZATION OF ROAD TUNNEL REFURBISHMENT MEASURES BASED ON A COST-EFFECTIVENESS ANALYSIS

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ABSTRACT

The ventilation system of an existing Swiss twin tube road tunnel no longer meets the requirements of the current ASTRA (Bundesamt für Strassen, Federal Road Authority) ventilation guideline 13001 and several items of equipment have reached the end of their life cycle and need to be replaced. Adjusting the present ventilation system to the guideline requirements would be cost-intensive.

A quantitative risk analysis using the BAST and the OECD/PIARC CH models has been performed to determine an alternative system that is compliant with the guideline's safety level (given by the ASTRA system) while having a good cost-effectiveness ratio.

Several measures were examined, but apart from the measure based on the guideline, only one of them met the required safety level. However, this measure had to be excluded due to various negative aspects, which cannot be quantitatively measured in the risk analysis. Based on the examination, the authors recommend a measure that can be implemented as an intermediate stage and later be adapted to the normative requirements.

Keywords: ventilation design, quantified risk analysis, cost-effectiveness analysis

1. INTRODUCTION

A Swiss twin tube road tunnel (length > 3km) with unidirectional traffic (low traffic congestion) and a transverse ventilation system (air injection and extraction distributed over the entire tunnel length) no longer meets the requirements of the current ASTRA (Bundesamt für Strassen, Federal Road Authority) ventilation guideline 13001 [1]. Moreover, several items of equipment have reached the end of their life cycles and need to be replaced. The tunnel name is not mentioned as ASTRA has not yet approved the results of the study.

The above mentioned ASTRA guideline specifies for this tunnel that a local smoke extraction system is required with remotely controlled mechanical dampers and control of the longitudinal ventilation with jet fans. Refurbishing the present ventilation system to the guideline requirements would be cost-intensive. Therefore, a quantitative risk analysis has been performed to determine whether the safety level according to the guideline can be achieved with lower-cost alternative ventilation systems. In addition, a structural measure has been evaluated which uses the present ventilation system but cuts the distances between emergency exits in half. The measure that meets the safety requirements set forth by the guideline, while offering a favorable cost-effectiveness ratio, will be implemented.

This paper aims to show the methods which have been used within the quantitative risk analysis and presents the results of the examination.

2. ASTRA GUIDELINE 13001 [1]

This guideline describes the system selection, sizing and equipment of tunnel ventilation systems for Swiss road tunnels. For a unidirectional tunnel with low traffic congestion, a simple portal-to-portal longitudinal ventilation system can be used in tunnels of up to 2000 m in length – possibly even of up to 3000 m in length, provided a) the daily traffic flow per lane is lower than 16’000, b) the daily truck flow per lane is less than 800, and c) the gradients in the tunnel are greater than +3.0% (uphill). Above a tunnel length of 3000 m, the emergency ventilation must have a local smoke extraction system with remotely controlled mechanical dampers. This is decisive for the tunnel in question.

3. QUANTIFIED RISK ASSESSMENT

3.1. Approach

In risk analyses for road tunnels, three types of scenarios are usually examined.

- scenarios with collisions (without fire)
- scenarios involving fire (without dangerous goods)
- scenarios involving dangerous goods

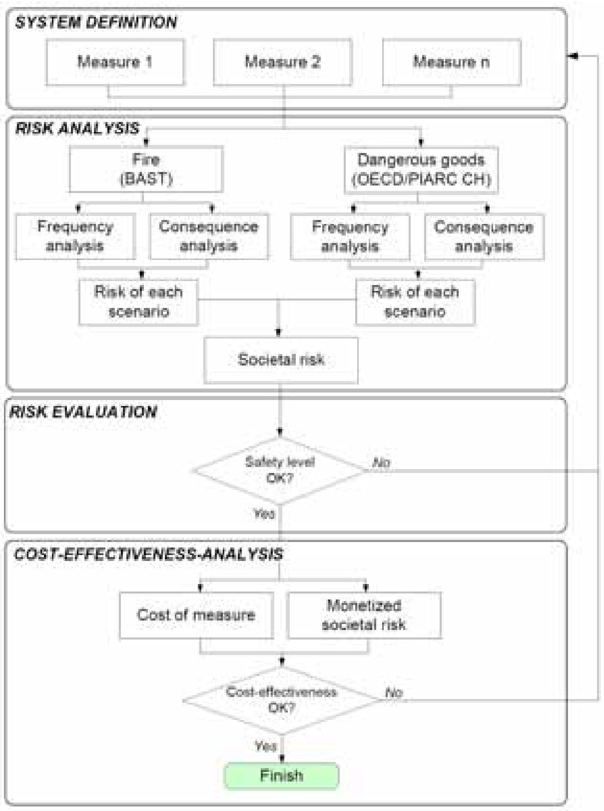

Figure 1: Approach of risk assessment

For this analysis, only fire scenarios and scenarios involving dangerous goods are relevant, since the examined measures cannot reduce the risk due to collision. This risk is therefore identical for all measures.

Within the scope of the **system definition**, practicable measures are identified and described in detail. As a boundary condition it is specified that the tunnel usage must not be changed after the implementation of the measure.

For each defined measure, a **risk analysis** is performed, using the German risk model from the BAST (Bundes-anstalt für Strassenwesen) [2] for fire scenarios and the OECD/PIARC CH model [3] for dangerous goods scenarios. For each scenario, the frequency (events per year) and the consequence (fatalities) are determined and the risk, which is the product of the two, is calculated.

The aggregated risks for all damage scenarios (fire scenarios (BAST model) and dangerous scenarios (OECD/PIARC model CH)) determine the overall risk of the measure. This overall risk, also known as societal risk, can be expressed as an expected value (fatalities per year) or depicted in a frequency-consequence diagram (F-N diagram). This diagram illustrates the ratio of the frequency (per year and per 100 m of tunnel) and severity (number of fatalities) of all scenarios in each measure on a logarithmic scale, thereby cumulating the frequencies of the scenarios in each measure.

The **evaluation** of the societal risk of the defined measure is based on a comparison with the societal risk of a measure including all requirements according to the ASTRA guideline. In Switzerland there is an absolute risk limit available for dangerous goods. This limit is also included in the risk evaluation of each measure.

The risk limit for dangerous goods is illustrated by graphs in an F-N diagram (see chapter 3.4), which divides the diagram into three ranges (given by the Schweizerische Störfallverordnung StFV [4]): The acceptable range is the range in which risks are considered negligible; the transition range is the range in which risks should be reduced, if operationally, technically and economically reasonable; and the unacceptable range, where measures absolutely need to be taken to shift the risk at least to the transition range.

Within the scope of the **cost-effectiveness analysis** for all measures, the societal risks are monetized (marginal cost for preventing one fatal victim is set to 5 million CHF) and the appropriate expected investment, operating and maintenance costs per year are determined. The cost-effectiveness ratio is calculated as shown in the following formula, which considers the monetized risks and costs with regard to the actual state (distributed supply air and exhaust ventilation along the tunnel).

$$\text{cost-effectiveness ratio} = \frac{\Delta C}{\Delta R_m}$$

ΔC = cost difference; ΔR_m = monetized risk difference

The measure to be implemented meets the safety level according to the normative requirements and features an efficient cost-effectiveness ratio of less than 1.

3.1.1. BAST model [2]

Currently there is no official risk model for Swiss road tunnels to calculate fire scenarios. Thus, to enable a quantitative calculation of risks in road tunnels, in 2011 ASTRA launched a research project for the development of a respective model. Until the implementation of this model, ASTRA has determined that the BAST model should be applied.

The BAST risk model was developed for German road tunnels and features a standardized event tree for the frequency analysis of fire scenarios. In the event tree, the event location (portal area and tunnel inside), the traffic conditions (flowing traffic or congestion), the functioning of the fire detection / ventilation system and fire load (5 MW, 30 MW, 50 MW, 100 MW) are considered. The branches in the event tree result in 32 different paths (subsequent scenarios), which all characterize a possible scenario involving fire.

In the consequence analysis, the extent of the damage expressed as fatalities is calculated for the 32 damage scenarios. This requires the use of ventilation and evacuation simulations, which the user of the model needs to perform. Based on the various visibility ranges, tunnel areas are defined from which people can or cannot save themselves.

3.1.2. OECD/PIARC CH model [3]

The QRAM standard model by OECD/PIARC [5] allows for a quantitative determination of the risk to people due to the transportation of dangerous goods in tunnels and on open roads. For the OECD/PIARC CH model, the standard model was adjusted to Swiss conditions (for example dangerous goods ratio) and refined in various aspects based on experience and findings (e.g. the evacuation model). The parameters and respective mathematical calculation models are in line with each other in order to meet the StFV evaluation criteria. The risk analysis covers scenarios involving flammable and toxic liquids and gases (propane, acrolein, ammonia and CO_2). Unlike the standard model, the OECD/PIARC CH model does not consider chlorine, since the respective release scenarios included in the standard model do not apply to Switzerland.

The model is mirrored in the software and is less methodically accessible to the user than the BAST model. The calculation of frequency and consequences of dangerous goods scenarios are based on event trees and probit functions. Probit functions are used to relate the level of injury (fatality) and exposure duration to a dangerous goods event of a given intensity.

3.2. Tunnel data and some key parameters

The tunnel with unidirectional traffic consists of two parallel tubes of >3000 m in length. The two tubes, each with two lanes, are interconnected at set intervals (maximum distance between interconnections approximately 360 m). Apart from the portal areas an exhaust duct is located above the lanes as well as a fresh air duct and a service duct below the lanes. The exhaust ducts are separated approximately at mid-tunnel. The tunnel is not subject to limitations regarding dangerous goods transportation. Due to maintenance work and functional tests, the tube is operated with bidirectional traffic for approximately 70 h per year.

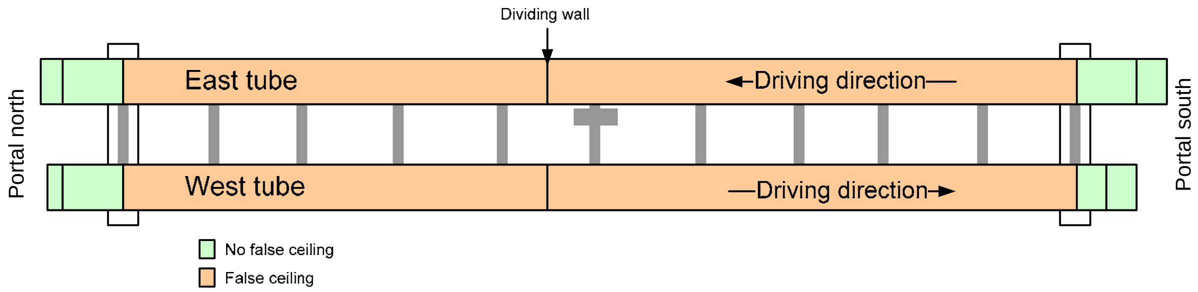

Figure 2: Unidirectional tunnel

Further key parameters for the risk analysis are listed in the table below.

TUNNEL, TRAFFIC and ACCIDENT DATA	
Tunnel length	> 3000 m
Tunnel cross section	~50 m^2
Longitudinal gradient	4% - -2.7%
Annual average daily traffic (AADT) per tube	ca. 43'000 veh/day
Traffic congestion frequency	50 h/year
Accident rate (unidirectional traffic)	0.16 per mill veh-km 0.08 per mill HGV-km
Accident rate (bidirectional traffic)	0.29 per mill veh-km 0.145 per mill HGV-km
VENTIALTION AND EVACUATION DATA	
Response time of fire detection system	1 min
Response time of the ventilation system	2 min
Visibility	≥5 m
Peoples' reaction time after fire detection	0.5 min
Escape speed of a person	1.1 m/s
FIRE DATA	
Fire load [6] in 5 min with linear increase in 10 min with linear increase	5 MW (passenger cars) 30, 50, 100 MW (HGV and buses)
Yield soot (5 MW) [7]	0.095 [kg/kg]
Yield soot (30, 50, 100 MW) [7]	0.037 [kg/kg]

Table 1: Key parameters

Notes on some key parameters:

For visibility ranges below 10 m, a drastic reduction of the escape speed can be expected and disorientation will begin. Below a visibility range of 5 m, movement is severely impaired. For the purpose of the evacuation simulation, it is assumed that people can save themselves if the visibility range is greater than 5 m, and the escape speed is set to 1.1 m/s. [2]

The soot yield values used in the analysis were deduced from fire tests involving vehicles. [7]

3.3. System Definition

For the risk analysis, five measures were examined. A brief description of these measures follows.

3.3.1. V0 (actual state)

V0 describes the current state of the ventilation system. The ventilation system is divided into two parts (north and south) in terms of aerodynamics. The supply air is fed into the traffic space through a supply duct and subsidiary pipes mounted approximately every 4 m.

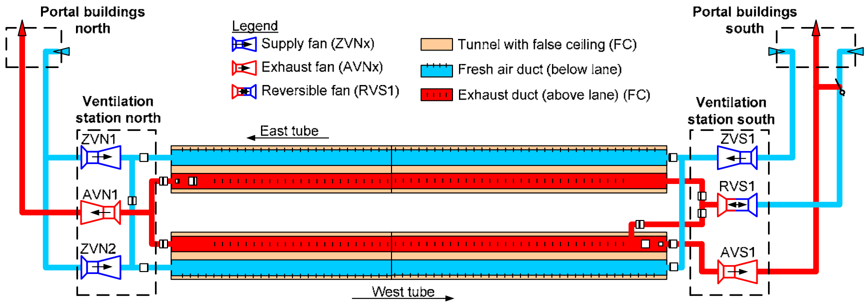

Figure 3: Ventilation system (actual state)

Generally, exhaust air is drawn through slots in the ceiling (every 14.5 m). A total of three supply and two exhaust fans are mounted as well as a reversible fan which can be operated as a supply as well as an exhaust fan. Several items of equipment have reached the end of their life cycle and need to be replaced or refurbished (ventilation control system, fans etc.). These are taken into account in the cost-effectiveness analysis.

3.3.2. V1

V1 covers the distributed exhaust air of the current state (V0). In addition, jet fans are mounted near the portals (north and south) in the sections without the false ceiling. The jet fans allow for easy control of the longitudinal flow.

3.3.3. V2 (target state)

V2 meets the ASTRA 13001 requirements. It contains jet fans in the portal areas (north and south) and a local smoke extraction system with remotely controlled mechanical dampers. The dampers are mounted 100 m apart. The smoke or gas is withdrawn from the traffic space close to the location of the fire event through dampers opened over a 200 m length of the tunnel. This means, in case of an event, three dampers need to be opened.

3.3.4. V3

V3 is similar to V2 with the existing exhaust fans (V0) being adapted to the required operating point. V3 features a number of negative aspects compared to V2 (for example no 100% tube separation, temperature resistance of exhaust fans, etc.), which cannot be quantitatively considered in the risk analysis. While V3 reaches the safety level of V2, it is not completely compliant with the guideline.

3.3.5. V4

V4 contains the ventilation system of the current state (V0), however, the distances between emergency exits are cut in half with regard to the existing situation. This results in 12 additional interconnections in addition to the 11 already existing.

3.4. Results

The following figure illustrates the expected societal risk values for all measures for the twin tube road tunnel. For all measures, the risk resulting from dangerous goods scenarios (OECD/PIARC CH model, lower bar) and the risk resulting from fire scenarios (BAST model, upper bar) are depicted. The risk aversion factor is not considered in the results from the BAST model, for the OECD/PIARC CH model does not include this factor. The figure shows that the societal risk for V0 is, as expected, the highest. V1 almost reaches the safety level of V2 (V3). The risk for V4 is only slightly lower than for V0. In V4, the risk due to fire is reduced by about 30%, while the risk due to dangerous goods scenarios is only reduced by about 3% compared to V0. V1 and V2 show a considerably higher risk reduction compared to V4 with respect to V0. The bars illustrate that for all measures, the dangerous goods ratio has a significant impact on the social risk.

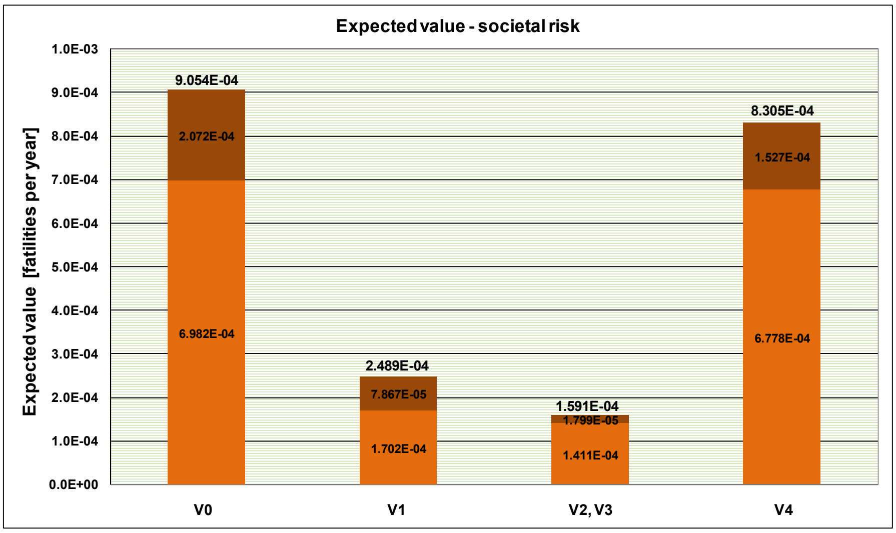

Figure 4: Expected societal risk values

The figure below illustrates the societal risk ratios with respect to V0 and to V2.

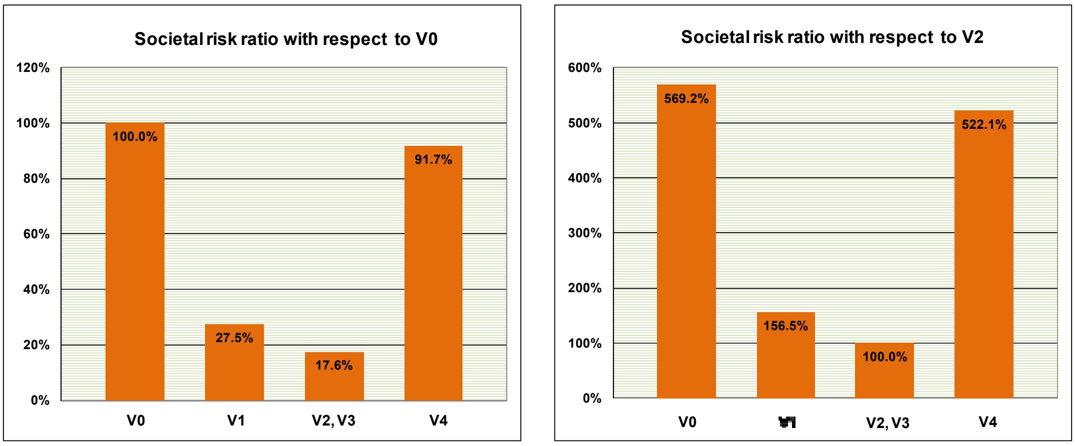

Figure 5: Societal risk ratio with respect to V0 and V2

The societal risk in V0 can be reduced to approximately 28% for V1, to approximately 18% for V2 (V3) and to approximately 92% for V4. This means the safety level for V2 is 5.7 times higher than for V0, 1.6 times higher than for V1 and 5.2 times higher than for V4.

The societal risk of all measures in the F-N diagram is depicted in the following figure.

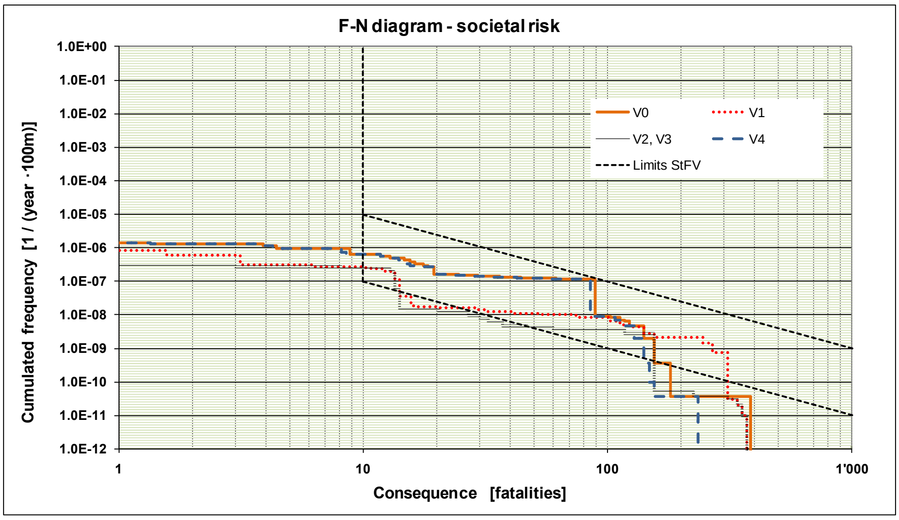

Figure 6: F-N diagram for societal risks

The figure shows that V0 and V4 almost reach into the non-acceptable range defined by the StFV. It needs to be specified that the StFV applies to risk involving dangerous goods only. However, in the graph, fire risks are included as well. Generally, V2 (V3 equal V2) is the lowest graph in the diagram with the exception of low frequencies (right hand area in the diagram). This is due to the OECD/PIARC CH model that ends the calculations for the individual measures at different extent levels, thus causing overlaps. The risks are very low in this area and have negligible influence on the expected societal risk values. When considering the results from fire scenarios only, V2 (V3 equal V2) is always the lowest graph.

Even though the alternative measures (V1, V4) do not meet the required safety level of V2, a cost-effectiveness analysis with reference to V0 has subsequently been performed. The annual investment costs were determined by means of dynamic investment appraisal (annuity factor).

Table 2: Cost-effectiveness ratio

Measure	Investment, operating, maintenance costs [CHF/year]	Societal risk [fatalities/year]	Δ Cost [CHF/year]	Δ monetized societal risk [CHF/year]	Cost-effectiveness ratio
V0 (actual state)	322'044	9.054E-04	-	-	-
V1	352'532	2.489E-04	30'488	3'283	9.3
V2 (target state)	1'150'825	1.591E-04	828'781	3'732	222.1
V3	879'829	1.591E-04	557'785	3'732	149.5
V4	434'460	8.305E-04	112'416	375	300.2

The cost-effectiveness ratio shows that V1 offers the best ratio; however, the measure does not meet the required safety level of V2. The ratio in V3 is better than the ratio for V2.

All values are greater than 1, which means that, theoretically, no measure is cost-efficient. But meeting the required safety level takes precedence over cost-effectiveness (see Figure 1).

4. DISCUSSION AND CONCLUSION

The analysis reveals that V0 (actual state) offers the lowest and V2 (target state) generally the highest safety level. While V3 reaches the same safety level as V2, it contains non-quantifiable negative aspects. A sensitivity analysis (different moments of escape, traffic congestion frequencies, etc.), which is not the subject of this paper, came to the same conclusion. It needs to be specified, however, that parameter variations will result in a change in societal risks.

Furthermore, the results show that the acceptance level according to the StFV is met by all measures in question, even when taking into account fire scenarios. This leads to the conclusion that the ASTRA 13001 guideline requires a higher safety standard than the StFV.

This statement refers to the tunnel in question and the presumed parameter values only and shall not be understood as a general rule.

The OECD/PIARC CH model demonstrates that the risks from dangerous goods scenarios are crucial for the societal risk (fire and dangerous goods). This is due to the fact that the tunnel is predominantly operated with unidirectional traffic, and fire scenarios (the BAST model) only result in fatalities when there is traffic congestion (i.e. 50 h per year).

Halving the distance between the emergency exits compared to V0 does not lead to a significant change in societal risk. For fire scenarios (BAST model), this is mainly due to the fact that in the unidirectional traffic tunnels escape conditions with the chosen parameter values can be substantially improved only for the 50 MW and 100 MW fires. In the BAST model, these scenarios are not weighted heavily and therefore have little impact on the societal risk. The slight change with regard to dangerous goods can currently not be explained by the authors. Further clarifications by the developer of the model are required.

The cost-effectiveness analysis clearly illustrates that V2 is far from meeting the criteria on cost-effectiveness (about 220), meaning the low reduction in absolute risk compared to V0 comes at excessive costs. This holds true for V3 (about 150) as well. V1 offers the lowest ratio (about 9), V4 the highest (about 300), while both measures do not meet the required safety level.

The BAST method does not include certain parameters relevant for the calculation of the extent, which may have a significant impact on the results. Missing parameters include data on burnt material and soot yields as well as on the fire growth rate. The OECD/PIARC CH model can only be influenced by the user to a small degree, since the risk calculations for the scenarios are being performed within the system. Only fundamental presumptions such as traffic characteristic, ventilations system, etc. can be made by the user, for the program is calibrated to the acceptance levels of the StFV.

Based on these results, the authors recommend that, as an intermediate stage, V1 be implemented in the course of a tunnel renovation and later on be adapted to V2. The implementation of V3 does not appear to be advisable, since this variant does not meet various requirements set forth by the ASTRA 13001 guideline. Furthermore, V3 is not suitable as an intermediate stage since it generates disproportionate extra costs with respect to the adaptation to V2 as well as significant traffic obstruction during the construction period.

The decision which measure is to be implemented has not yet been taken by ASTRA.

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RVS 09.03.11 – UPGRADING OF THE AUSTRIAN TUNNEL RISK MODEL TuRisMo

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ABSTRACT

The Austrian Tunnel Risk Model TuRisMo was published in the Austrian guideline RVS 09.03.11 [1] in 2008. Since then, this method has been applied for a risk-based assessment of many road tunnels in Austria as well as in other European countries. However, definitions fixed during the development of the risk model set limits to its application in specific cases. Certain tunnels and some specific problems cannot be investigated with the existing model. Therefore it is intended to improve the model, in particular by implementing new simulation tools to achieve a more flexible applicability to all kinds of tunnels as well as to enhance the reliability and accuracy of the results by implementing more parameters in a more specific way. The results of the research project under way shall be published in an updated guideline RVS 09.03.11.

Keywords: Tunnel safety, risk analysis, risk model, smoke propagation simulation, evacuation simulation

1. THE AUSTRIAN TUNNEL RISK MODEL TuRisMo

In 2004 – as a consequence of the big tunnel fires in Montblanc, Tauern and Gotthard tunnel – the EC issued the Directive 2004/54/EC on minimum safety requirements for road tunnels [2] on the trans-European road network.

This Directive established the risk based approach as a complement to the traditional prescriptive approach to tunnel safety. Article 13 of the EC-Directive obligates the EU member states to use at national level, a detailed and well-defined risk analysis methodology, corresponding to the best available practices. More specifically, in annex 1 a set of parameters is defined, which have to be taken into account.

On the level of the Austrian Research Association Road-Rail-Traffic a working group had already started to develop a quantitative tunnel risk model. Expanding its focus on the requirements of the EC-Directive, the working group elaborated the Austrian tunnel risk model TuRisMo, which was published as RVS 09.03.11 [1] in 2008.

The Austrian Tunnel Risk Model – TuRisMo – is the standard method for a quantified, system-based risk analysis in Austria. It focuses on frequently occurring mechanical accidents and fire accidents with small and medium sized fires.

For the development of TuRisMo great emphasis was put on the implementation of a realistic data base. Hence an in-depth study of comprehensive tunnel accident data was carried out covering 447 tunnel accidents with personal injuries in order to define specific input data for various characteristic tunnel types. The Austrian Tunnel Risk Model combines a set of different methodical tools to analyse the whole system of safety relevant influencing factors. The method consists of two main elements: A quantitative frequency analysis and a quantitative consequence analysis.

The risk model covers the personal risk of tunnel users. The result of the risk analysis is the expected value of the societal risk of the tunnel investigated. The respective shares of risk due to mechanical effects, fires and hazardous goods are shown seperately.

An event tree analysis including a representative set of characteristic accident scenarios is performed to calculate the frequencies of these scenarios

These scenarios differ significantly from each other as regards type of accident, vehicle involvement, involvement of dangerous goods and influence of fire.

For each scenario in the event tree the corresponding model value for the extent of damage is defined.

- Extent of damage of mechanical accidents:
  The consequences of each scenario are estimated based on the results of the evaluation of tunnel accident data.

- Extent of damage of fires:
  The extent of damage of fires is estimated with the support of an evacuation simulation model in combination with a one-dimensional ventilation model.
  In the ventilation model two different scenarios (5 MW, 30 MW) und two different ventilation regimes can be selected
  - longitudinal ventilation
  - transversal ventilation (with influence on longitudinal air velocity)

The Austrian tunnel risk model as defined in RVS 09.03.11 is a standardized method which on the consequence side provides characteristic damage values for tunnel accidents and tunnel fires for a set of model tunnels, which are representative for the Austrian tunnel collective. As explained above these values were elaborated on the basis of statistical evaluations (for mechanical accidents) and simulations (for fires) during the development of the method and have been compiled in tables in the guideline. For the application of the model the user has to establish an event tree for the investigated tunnel, quantifying it by implementing suitable standard probabilities and standard consequence values taken out of the guideline.

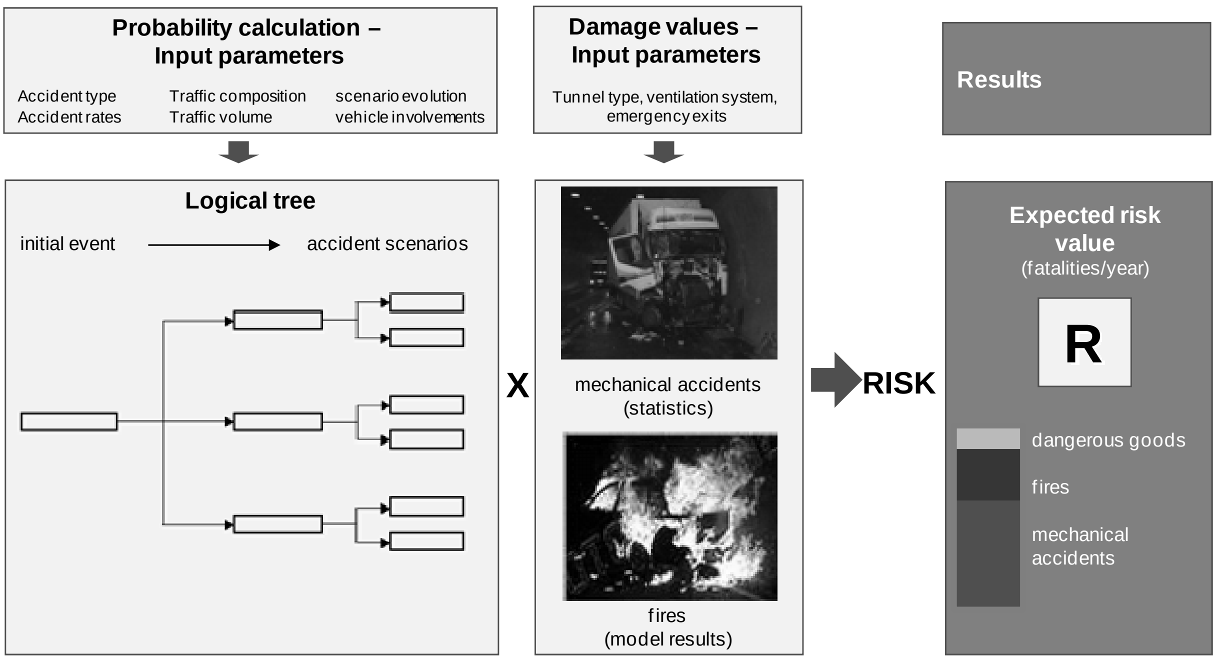

Figure 1: Structure of the Austrian Tunnel Risk Model

However, the application of the standardized values of the model presumes that the investigated tunnel fulfils specific conditions and requirements defined in the Austrian tunnel design guidelines, because these were taken as a basis for the calculation of the standardized risk parameters of the risk model.

This allows a rather simple and straight forward application of the risk model, however at the same time limits its use to standard tunnels, which fulfil crucial prescriptive requirements. For expert users it is nevertheless possible to investigate different types of specific characteristics too, by modifying specific parameters on the basis of individual considerations or sub models.

Consequently, the application of the risk model is limited, the most relevant limitations are listed in chapter 2 of RVS 09.03.11 (e.g. tunnel cross sections with 2 lanes only, not suited for combined ventilation systems, on complex tunnels).

2. EXPERIENCES IN THE PRACTICAL APPLICATION OF THE RISK MODEL

In Austria, many tunnels were investigated on the basis of TuRisMo assessing the influence of key safety parameters (e.g. like the distance of emergency exits) and classifying them in one of four danger classes according to their risk level. TuRisMo was also applied for risk analysis studies in other European countries, like in Slovakia, Slovenia, Greece, Croatia and Portugal. Furthermore the countries Slovakia and Slovenia decided to use TuRisMo as basic risk model for their tunnels as well, implementing some specific modifications to take national peculiarities into account.

However, with the expanding application the limits and shortcomings of the model came up as well, which in particular are relevant for the following applications:

- Investigation of road tunnels, which were designed on the basis of meanwhile outdated guidelines.
- Investigation of complex tunnels and tunnel systems.
- Investigation of specific safety relevant design parameters or specific boundary conditions (like for example, extraordinary meteorological conditions).

In particular the following aspects cannot be investigated in the risk model according to the existing RVS 09.03.21:

- Longitudinal gradient:
  The model calculations for the fire damage values of RVS 09.03.11 were performed with low gradients (app. 1 %); for tunnels with higher gradients it was assumed, that the specification of the ventilation system is such, that the target values of the Austrian ventilation design guidelines (RVS 09.01.32) are met and the smoke propagation can be controlled accordingly. Tunnels not fulfilling these requirements and other peculiarities like specific effects of steep gradients or tunnels with varying gradients cannot be investigated.

- Specific influence on air flow – conditions (e.g. traffic movement in bidirectional tunnels):
  The damage values for fires used in the model were calculated based on standardizes assumptions for air flow conditions in the first phase of an event; in practice – however – the air flow in the first minutes is dominated by the traffic movements still taking place in particular in a bidirectional tunnel. Hence the location of the fire, the traffic density and movements in both directions and the time requirement for stopping the traffic have great influence on direction and velocity of air and smoke movements in the tunnel in the first phase of an event.

- Influence of tunnel cross section:
  The simulations underlying the fire damage values of RVS 09.03.11 were performed with a standard 2 lane vaulted tunnel cross section (for systems with smoke extractions: with an intermediate ceiling); studies of the influence of different tunnel cross sections on fire risk show, that there is a relevant influence of the height, width and shape of the tunnel cross section on risk. Hence there is a need for a more detailed investigation of the rectangular cross sections and tunnel cross sections with more than 2 lanes. Results from research projects in Germany [3] indicate for instance, that there is a negative influence of a lower ceiling (like in case of a rectangular cross section) on fire risk.

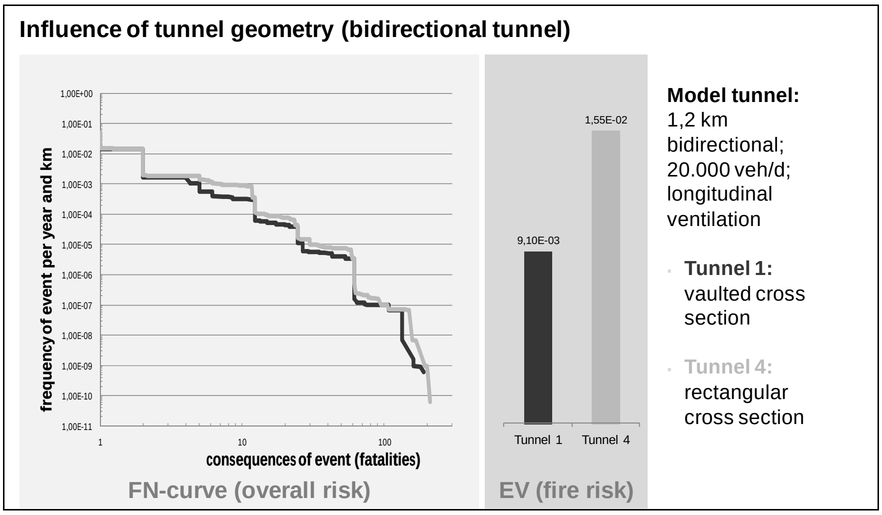

Figure 2: Influence of tunnel cross section on risk in a bidirectional tunnel with longitudinal ventilation [3]

- Fire scenarios bigger than 30 MW:
  For several reasons only 5 MW and 30 MW fires were included in the existing risk model. Most risk analysis methods on international level also include bigger fire scenarios (with – however – low probabilities). Furthermore – e.g. for the evaluation of specific improvements of the ventilation system – it is suitable to include in the risk analysis a fire scenario bigger than the design fire of the ventilation system. Therefore a 100 MW fire scenario will be implemented in the method.

- Complex tunnels / tunnel systems:
  Tunnels with changing cross sections, with ramps or with combined ventilation systems cannot be investigated with the existing risk model. The investigation of such a complex tunnel requires specific simulations for the calculation of damage values for fires and therefore cannot be handled with a method based on model tunnels. However, such tunnels often require a risk-based approach.

- Specific safety measures like improved incident detection/tunnel closure:
  With currently applied assumptions for incident detection and tunnel closure (i.e. fixed time frame for fire detection and no detection of congestions) the scenario development after an initial incident cannot be reproduced in a realistic way in tunnels where features like automatic incident detection or detection of congestions (in combination with efficient means for tunnel closure) are available.

Furthermore other tunnel risk models were developed which include the application of complex simulations on object level, allowing a more specific and detailed investigation of safety parameters but at the same time involving more effort for the investigations.

3. NEW RESEARCH PROJECT STARTED

Since its publication in 2008, the risk model has become a valuable, widely used tool for road tunnel risk assessment, however with some shortcomings in its practical application. Therefore, the "Austrian Research Association Road-Rail-Traffic" decided to start a new research project on road tunnel safety.

The main objectives of this project are twofold: on the one hand, the methodical approach shall be enhanced, and the model itself shall be expanded in order to cover more relevant parameters in a more specific way. Additionally, the complete model and the conditions for its application shall be defined in a way that it can be applied directly for the investigation of complex tunnels. On the other hand, the improved model shall be used to improve the standardized "old" model as well, in order to enlarge its range of application. The improvements envisaged are in particular relevant for tunnel fires.

Further objectives of the study are:

- Actualisation of the data base of the risk model (for mechanical accidents).
- Systematic parameter study for relevant influence factors in order to gain more knowledge and – if possible – quantitative data about their influence on risk.
- Improvement of evaluation capabilities for risk mitigation measures.
- Check of the option to implement the effects of assistant rescue.

On the basis of the results of the research project the RVS 09.03.11 shall be modified and expanded.

4. IMPROVED METHODICAL APPROACH FOR THE CALCULATION OF FIRE RISK

4.1. Combined smoke propagation model

The 1-dimensional smoke propagation model used during the development of TuRisMo shall be replaced by a new combined 1D / 3D smoke propagation model. The idea is to first perform a 1-dimensional simulation in order to calculate the longitudinal airflow in the tunnel resulting of global influencing factors which have no direct influence on local effects such as smoke stratification at the fire location. The subsequent 3-dimensional simulation of smoke propagation then takes into account the 'local influencing factors' such as cross section, inclination, presence of vehicles (turbulences) etc. based on the longitudinal velocities calculated before. The influencing factors included in the 1-dimensional and the application on the 3-dimensional model are illustrated in Figure 3.

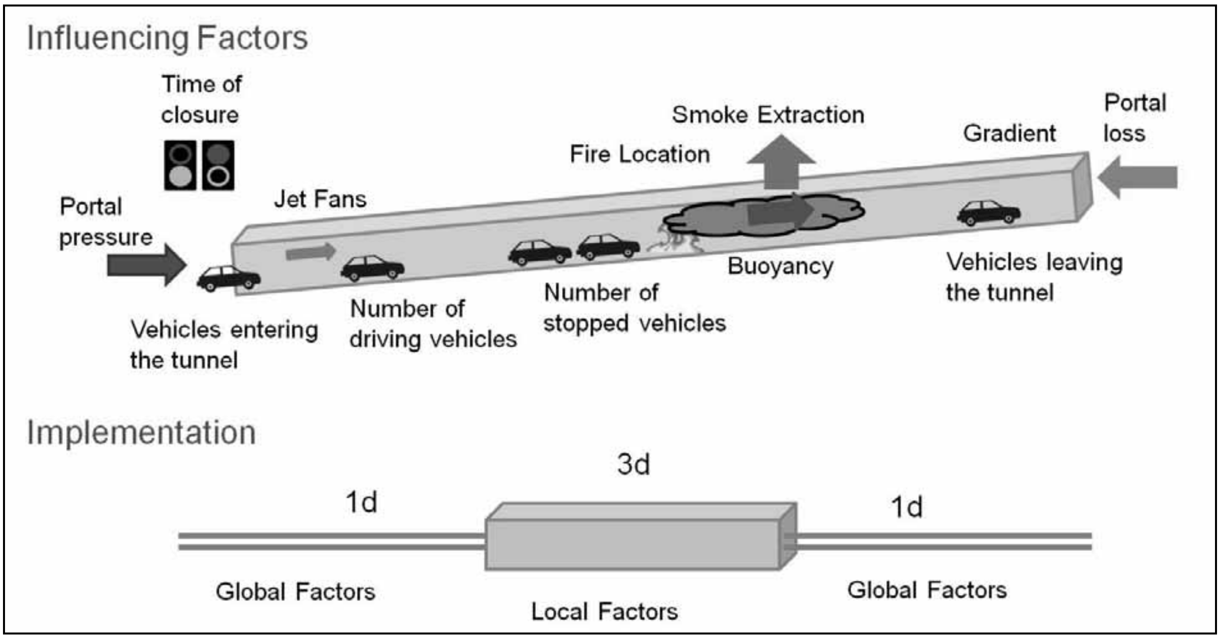

Figure 3: Influencing factors taken into account in the new 1D / 3D smoke propagation model

<u>Parameters included in 1D model</u>

- Drag at the tunnel walls and equipment
- Portal effects (loss of momentum at portals, wind pressure)
- Influence of moving vehicles (piston effect) and standing vehicles (drag)
- Influence of ventilation system (spin up time for jet fans and exhaust machine, position, etc.)
- Thermal forces of hot gases in the tunnel
- Heat exchange with tunnel walls (conduction effects)

Naturally the geometric properties such as overall tunnel length, cross section, circumference, inclination, ambient temperature etc. were included in the 1d model for a proper description of the resulting transport equations.

<u>Parameters included in 3D model</u>

- Exact local tunnel geometry (cross section at fire location)
- Gradient around the fire location
- Stopped vehicles in the vicinity of the fire location (causing turbulences)

The velocity development obtained in the 1-dimensional simulation is applied as boundary condition in a distance large enough to not interfere with the smoke stratification.

4.2. Integrated evacuation simulation model

For the calculation of the fire damage values in TuRisMo the evacuation simulation software buildingExodus [4] was applied. For that purpose the results of the smoke propagation simulations (time dependant smoke concentrations at a height of 1,6 m) had to be transformed into the evacuation model. On the other hand many applications of buildingExodus for road tunnel environments showed, that for this specific purpose many features of this simulation software are not required. Therefore it was decided to directly implement a simplified evacuation tool in the smoke propagation model. The following features were included in this simplified evacuation tool:

- Reduction of evacuation grid to 1 dimension. This allows to reduce model complexity and computational demands while the loss of precision is minimal. The low influence of this dimensional reduction results from the fact that the distance to the nearest emergency exit is normally much larger than the tunnel inner diameter. Furthermore bottleneck effects at doors where queuing would require a 2-dimensional grid normally do not occur in road tunnels as the density of agents is not large enough (in contrast to railway tunnels!).
- Accumulation model by D. A. Purser [5] to calculate the accumulated dose of toxic gases and their effect on human physiology. This model was selected because the application of accumulation based vs. limit based models has shown that limit based models (i.e. 'if visibility is lower than 5m than self-rescue fails') may give inconsistent results, especially in tunnels with smoke extraction.
- Obscuration triggeres start of self rescue. This means that agents start moving as soon as the visibility at walking level (head level of 1.6m) drops under a certain level which is a more realistic approach than the definition of a fixed alert time when all agents start to evacuate. The time is limited by a (realistic) alert time when all people are requested to leave the tunnel.
- Direct data transfer for higher precision and optimisation of work flow. As the data transfer from the output files of the simulation of smoke propagation to the evacuation environment was limited to a specifically parameterized method the whole transfer was extremely time consuming and lacking accuracy because of the required (non linear) transformation. The new tool on the other hand can directly access the result sheets and import the local concentrations without any preconditioning resulting in higher accuracy.
- Definition of representative populations with different types of agents. As the algorithm calculates zones with/without self rescue for each type of agents the simulation has to be run one time only in contrast to evacuation environments where a statistical set of agents is simulated at each run.
- Shift of the fire location vs. the configuration of emergency exits. This has shown to have big influence on the calculated number of victims and is therefore included in the evacuation model. Therefore the fire location is moved along the tunnel accessing the smoke data of the nearest simulation.

Overall the newly developed evacuation tool can achieve better precision with a reduced amount of work for each individual scenario. This allows to increase the total number of scenarios (fire locations in the tunnel, traffic scenarios) which can be covered within the risk analysis and therefore obtain better and more representative results.

4.3. Enhanced use of statistical traffic data

So far the fire risk damage values were calculated on the basis of the AADT, hence for an average situation. In future it is envisaged to take at least 3 different traffic scenarios into account: one each for low, average and high traffic situations. These values shall be defined on the basis of statistical traffic data of one complete year of the investigated tunnel or of representative adjacent road sections. This approach allows to take effects into account which directly depend on the traffic situation at the time of the fire such as the resulting longitudinal velocity or the length of queuing vehicles behind the fire location. Especially in bidirectional tunnels these locations may have a large impact on the calculated number of victims.

5. OUTLOOK

The development of the new risk model is almost completed; the combined smoke propagation model and integrated evacuation simulation have been successfully tested in test calculations as well as for specific tunnels. The new model works and delivers comparable results to the existing model.

As a next step, systematic parameters studies will be performed to investigate the influence factors addressed in chapter 2 more in detail and to gain experience in the application of the expanded model.

The final step will be the modification and completition of the standard damage values of the RVS and the documentation of the new model in the updated guideline. The model shall be finished by end of 2012.

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EXPERIMENTAL INVESTIGATIONS ABOUT VISIBILITY IN A FIRE ACCIDENT USING A SCALE MODEL TUNNEL

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ABSTRACT

This study investigated the visibility of occupants in a tunnel fire experiment using a large-scale model tunnel. It is important to understand how well the occupants can see during a fire in a tunnel to simulate evacuation and assess the safety of a tunnel in case of fire. The value of visibility can only determine whether occupants in a fire can evacuate or not, due to loss of visibility caused by smoke and being unable to move before dying from smoke inhalation. The ventilation system in a tunnel may make it safer for occupants to evacuate in a fire. In Japan, the borderline for the extinction coefficient is 0.4 m^{-1} before occupants cannot evacuate. However, this is based on building experiments, and building fires are different from tunnel fires. Therefore, we investigated the situation of occupants using a fire in a large-scale model tunnel, by asking the subjects to enter the experimental fire and then fill out a questionnaire. The model tunnel was 1 m high, 2 m wide and 41.4 m long, which is a scale ratio of 1/5. In this study, about half of the subjects thought that they could evacuate under the smoke layer, but almost all of them thought they could not evacuate when the extinction coefficient was 0.37 m^{-1}.

Keywords: scale model tunnel, tunnel fire, similarity law, visibility, smoke behavior, evacuation environment, risk analysis

1. INTRODUCTION

Fires are a serious disaster, and it is important to design refuges in places where there are many people in case of fire. When occupants are faced with a fire in a road tunnel, they must decide whether they can evacuate. This is divided into the psychological aspect of occupants' feeling (psychological factors) and the occupants' environmental aspect (physical factors). The physical factors that are currently used to design refuges are temperature, poisonous gas and smoke. The former two are used in disaster prevention in European tunnels. However, in a tunnel fire, there may be many people along the length of the tunnel, and one major factor in sensing danger in a tunnel fire is that the psychological situation of occupants changes when they see the smoke, which is a physical factor, and then decide to evacuate. Therefore, occupants determine whether to evacuate under psychological factors, which are influenced by physical factors, hence this relationship is very important [1], [2]. In this study, the subjects experienced a tunnel fire in a large-scale model tunnel, then filled in a questionnaire about whether they thought they could evacuate from the tunnel fire or not. The visibility in the tunnel corresponding with the results of the questionnaire was measured by using optical smoke density. The pictures of smoke movement were taken by a video camera. We examined the relationship between the optical smoke density in the tunnel and the possibility of evacuation of occupants in a tunnel fire.

2. LARGE-SCALE MODEL TUNNEL

Figure 1 shows a view of the large-scale model tunnel, which was 41.4 m long (*x*-coordinate), 2 m wide (*y*-coordinate), and 1 m high (*z*-coordinate). The model tunnel was rectangular in cross section, and was designed considering the laws of similarity. Table 1 lists the parameters of the tunnel, which was on a scale of about 1/5.

Figure 1: Large-scale model tunnel

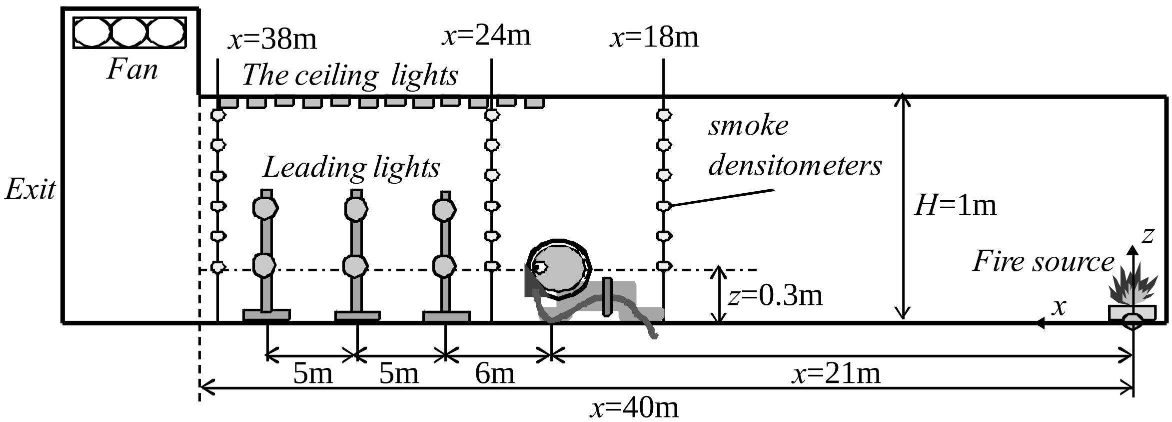


Figure 2: Schematic diagram of the longitudinal section of the tunnel

In model experiments, it is important to produce turbulent flow in the model tunnel as well as a full-scale tunnel. The model tunnel in this study was large, with a Reynolds number *Re* in the tunnel of 40,000 or more, and hence complete turbulent flow was achieved in the tunnel.

The heat transfer from thermal fumes to the tunnel walls is an important governing phenomenon in a tunnel fire. This heat transfer is governed by conduction heat transfer characteristics for the wall materials, and by convection heat transfer characteristics for the surface of the walls. Table 1 indicates the Biot number *Bi* and the Fourier number *Fo* concerning the thermal characteristics of tunnel walls. The Biot and Fourier numbers of the model tunnel in this study are close to those of an actual concrete tunnel. Autoclaved lightweight aerated concrete (ALC) panels were used as the wall material of the tunnel in this study.

Figure 2 shows a schematic diagram of the model tunnel. A stainless steel combustion vessel was installed as a fire source in the center, 40 m from the open end of the tunnel, with a fan located as shown. The position of the fire source is the origin of coordinates.

Table 1: Specifications of large-scale model tunnel and full-scale tunnel [3]

		Large-scale model tunnel	Full-scale tunnel (example)
Shape	Height H [m]	1.0	5.0
	Width W [m]	2	10.0
	Cross-sectional area [m^2]	2	50.0
	Equivalent hydraulic diameter [m]	1.316	6.667
Scale ratio	γ	1/5	1
Froude number	Fr	0.160	0.160
Reynolds number	Re	4.2×10^4	4.7×10^5
Biot number	Bi	41.2–117.6	21.9–62.5
Fourier number	Fo	6.41×10^{-8}	2.37×10^{-8}

n-heptane and toluene were used as liquid fuels for the fire source. The mass loss rate of the fuel was measured by an electronic balance. The heat release rate of the fire source was calculated from the mass loss rate. The temperature inside the model tunnel was measured by K-type thermocouples of 0.1 mm diameter with a small time constant, which were placed on the ceiling and central longitudinal section. Six smoke meters were installed at 0.1 m intervals from 0.4 m to 0.9 m above the tunnel floor at three locations: 18 m, 24 m, and 38 m from the fire source.

Concentration of smoke (Cs), which is a kind of optical smoke density generally used in studies on tunnel fires, was used to measure smoke density. Cs density was averaged by the tunnel's width. It was calculated as an extinction coefficient in the Lambert-Beer equation as follows:

$$Cs = -(1/l) \ln (I/I_0)$$

where, I: intensity of incident light, I_0: intensity of transmitted light (non-smoke), and l: distance traveled by light through the gas ($l = W = 2$ m).

In both the real tunnel and model tunnel, (I/I_0) between two corresponding points must be identical for the same influence of smoke on visibility. Accordingly, Cs density of a full-scale tunnel, Csf, Cs density of the model-scale tunnel, Csm, and γ as the scale ratio (= 1/5) have the following relation:

$$Csm = Csf \ / \ \gamma$$

That is, $Csf = 0.4$ m^{-1} in full scale is $Csm = 2$ m^{-1} in model scale. Note that Cs and the extinction coefficients in the following sections are identical to Csf which was converted from the experimentally obtained value of Csm.

3. EXPERIMENTS

3.1. Experimental conditions

In this study, we considered only non-ventilation velocity, in which the exit near the fire source is closed. Table 2 shows the experimental conditions. Two kinds of fuel (case A and case B) were used as the fire source to vary the smoke generation rate. The average heat release rates of the two fire sources were almost the same, but the fuel in case A generated much more smoke, and the extinction coefficient became 0.37 m^{-1} as the smoke spread, but was only 0.1 m^{-1} in case B in the same situation. Converting the average heat release rate into full-scale using Froude's law of similarity for a scale ratio γ = 1/5, the fire scale, which was about the heat release rate for a minibus fire, was obtained.

Table 2: Experimental cases

Experimental case	Fuel n-heptane : toluene	Burning area [m^2]	Average heat release rate (quasi-stationary) [MW]	Average heat release rate (converting to full-scale) [MW]
Case A	0 : 10	0.085	0.20	11
Case B	3 : 7	0.085	0.18	10

3.2. Questionnaire for subjects, and experimental contents

In this experiment, all the subjects wore a protective mask, entered the tunnel at the x = 21 m point, observed the situation during the fire experiment, and then answered the questionnaire on whether they thought they could evacuate or not. Video cameras were installed in the same place to photograph the situation experienced by the subjects. In addition, questionnaires were distributed during the experiment, with four multiple-choice responses to avoid ambiguity: (i) possible, (ii) probably possible, (iii) probably impossible and (iv) impossible.

We explained the experiment and how to stop it to all of the subjects, and obtained consent to participate from all of them. In the experiment, we wanted to simulate the eye level of evacuees in a full-scale tunnel fire, which we estimated to be a height of 1.5 m. Therefore, the subjects' eye level for the large-scale model tunnel was a height of 0.3 m.

4. EXPERIMENTAL RESULTS AND CONSIDERATIONS

Figure 3 shows pictures taken in the tunnel at 60 s, 90 s and 180 s after ignition. The pictures were photographed at a height of z = 0.3 m corresponding to a full-scale height of 1.5 m, from the opposite direction of the point where the fire was started. The left-hand picture is case A while the right is case B. The pictures taken at 60 s in both cases show that the smoke has reached the ceiling at x = 21 m. In case A, the ceiling lights were covered by thick smoke of Cs density = 0.6 m^{-1}. Figure 4 shows the smoke distribution in the z direction at x = 18 m corresponding to the times in Fig. 3. The smoke distribution at x = 18 m was the closest value to the smoke density observed and recorded optically by the subjects. All the values of the smoke distribution were converted to full scale. This figure shows that in case A the smoke remained stratified and arrived at x = 18 m. In case B, although the smoke was thinner in Fig. 4 (ii), the results were similar. However, in case B the ceiling lights could still be observed.

The picture at 90 s in case A shows that the ceiling lights of the tunnel were obscured by smoke and the area around the subjects was very dark. Figure 4 for case A and case B shows that the height of the smoke was lower than that at 60 s, but the smoke was still stratified at

x = 18 m. We could only faintly see the exit in this case. In case B, the area around the subjects was still visible, the lights were slightly covered by the smoke.

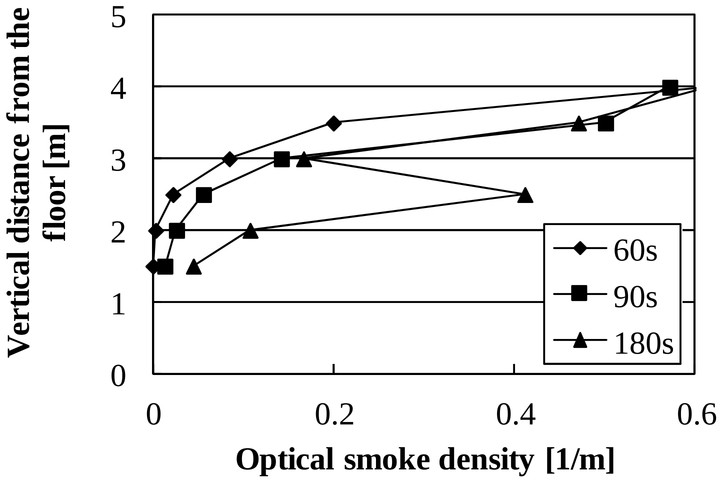
The picture at 180 s in case A shows that the closest lights close to the exit, which were installed at x = 37 m, z = 0.3 m and 0.5 m, were completely covered by thick smoke. This is because the thick smoke descended from the ceiling to the floor in the tunnel at a point far from the fire source, and then curled under the stratified thermal fume layer toward the fire source. Figure 4 for case A shows the same behavior. The picture at 180 s in case B shows that it was hard to see the lights closest to the exit, which were installed at x = 37 m and z = 0.5 m, for the same reason as in case A. Furthermore, Fig. 4 for case B shows that the thin smoke also curled back under the stratified thermal fume layer toward the fire source.

(i) case A, 60 s (ii) case B, 60 sec

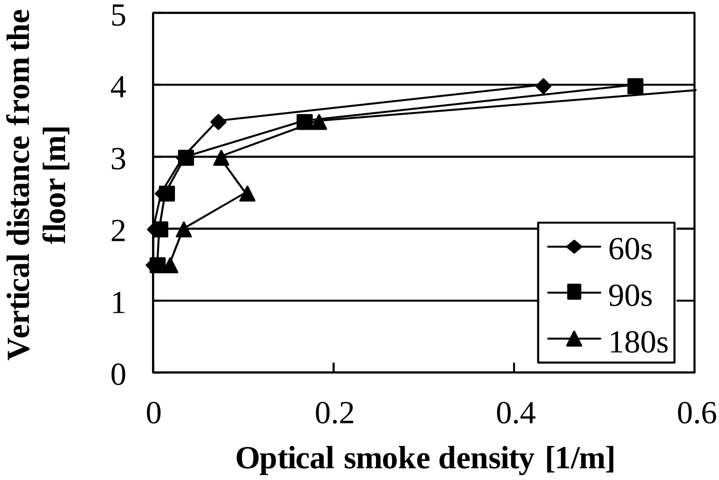
(iii) case A, 90 s (iv) case B, 90 sec

(v) case A, 180 s (vi) case B, 180 sec

Figure 3: Pictures at x = 21 m, z = 0.3 m



(i) case A



(ii) case B

Figure 4: Optical smoke density in *z* direction at *x* =18 m

To examine the influence of the physical factors upon the psychological factors, we compared the results of the tunnel fire experiments with the results of the questionnaire given to the subjects. Smoke diffusion was defined as the situation when smoke descended below eye level (z = 0.3 m) and spread through the tunnel.

Figure 5 shows the questionnaire results of all of the subjects, which were filled in between 40 and 60 s (before the smoke arrived at x = 21 m), between 125 and 145 s (when the smoke was stratified) and between 230 and 240 s (when the smoke diffused). Before the smoke arrived at x = 21 m, it was found that all of the subjects thought that evacuation was possible or probably possible in cases A and B. When the smoke was stratified, the number of subjects who thought it was impossible to evacuate increased compared to the previous situation.

During smoke diffusion, it was found that almost all of the subjects thought that evacuation in the tunnel fire was impossible in case A. Therefore, almost of the subjects thought that evacuation was impossible when Cs = 0.37 m^{-1}. Furthermore, in case B, it was found that 80% of all of the subjects thought that evacuation was impossible when Cs = 0.10 m^{-1}. Hence, in the case of smoke diffusion, it was found that almost all of the subjects thought that evacuation was impossible, even if the smoke density in the tunnel fire was low.

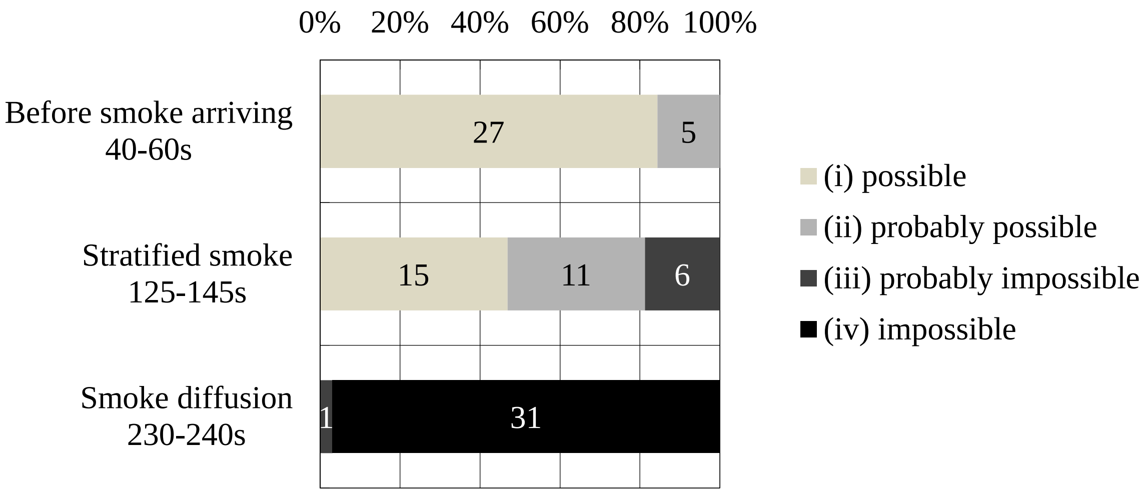
The experiment thus revealed that the subjects considered that evacuation in the tunnel fire was possible in the stratified smoke and impossible during the smoke diffusion.

5. CONCLUSIONS

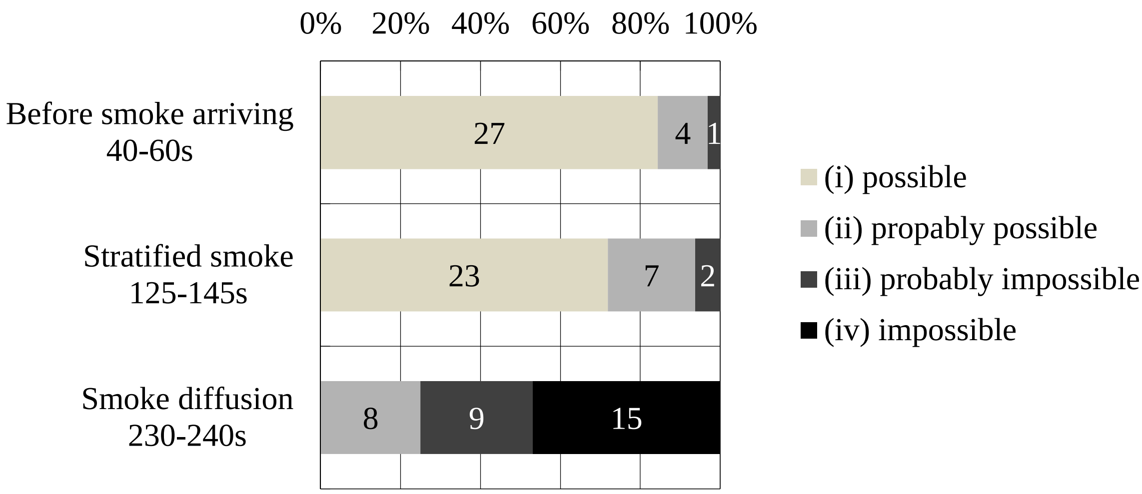
The main results of this study are summarized as follows.

1. When the smoke is stratified, 80% of all of the subjects thought that evacuation was possible or probably possible.
2. No one thought that evacuation was impossible during smoke diffusion of Cs = 0.37 m^{-1}.
3. 80% of all of the subjects thought that evacuation was impossible or probably impossible during smoke diffusion of Cs = 0.10 m^{-1}.
4. In the case of smoke diffusion, almost all of the subjects thought that evacuation was impossible, even if the smoke density in a tunnel fire was low.

Thus, when investigating evacuation in tunnels, we must consider the differences between stratified and diffusing smoke.



(i) case A



(ii) case B

Figure 5: Results of the questionnaire

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A STUDY OF THE CHIMNEY NATURAL EXHAUST EFFECT FOR ROAD TUNNEL FIRES – AN EVALUATION USING A NUMERICAL SIMULATION OF A FULL-SCALE TUNNEL –

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ABSTRACT

In this study, we simulated the heat exhaust efficiency during a fire due to installation of chimneys in a model tunnel, scaled it up to a full-scale tunnel by using the LES simulator FIRELES, and verified the heat exhaust efficiency and smoke exhaust efficiency for varying parameters such as chimney shape. The simulation results verified the similarity of non-dimensional heat exhaust efficiency between the model tunnel and full-scale tunnel, the characteristics of air absorption from the exhaust vent area and the bottom part of a chimney, and the heat exhaust efficiency and smoke exhaust efficiency for varying heights of chimneys and aspect ratios of exhaust vents.

Keywords: tunnel fire, chimney, large-eddy simulation, FIRELES, aspect ratio, heat exhaust efficiency, air inducer

1. INTRODUCTION

One way to improve the evacuation environment in case of a tunnel fire is to install chimneys in the tunnel ceiling and to remove the smoke by using the buoyancy force of thermal fumes, called the "natural exhaust effect." In a previous study[1)], we conducted a fire experiment in a model tunnel and showed that the quantity of thermal fumes exhausted through a chimney is proportional to the 3/2nd power of the rise in temperature ΔT of thermal fumes in front of the vent, regardless of the distance from the fire source to the chimney and scale of fire.
This paper derives simplified model equations for the heat exhaust effect of a chimney and performs a scaled-up simulation for a full-scale tunnel, and compares the simulation results between a full-scale tunnel and a model tunnel. To improve the effectiveness of removing thermal fumes, we verified the heat exhaust efficiency by varying the area, height, and shape of chimney vent and compared the results with exhaust smoke efficiency.

2. MODELING OF HEAT EXHAUST EFFICIENCY

The heat exhaust efficiency by installing a chimney, that is, the heat exhaust flow rate Q_e, depends on the thermal fumes (including heat flow rate, temperature rise, velocity, thickness, etc.) and chimney shape (section area, length, etc.). **Figure 1** shows a schematic diagram of a chimney. It is assumed that the average wind velocity in the tunnel remains low and the velocity in the chimney is uniform as a portal. Due to the pressure difference between the chimney inlet at the ceiling of the tunnel and the chimney outlet at the ground, the force driving the air flow inside the chimney toward the outlet is expressed as:

$$F_p = A_e(p_1 - p_0) + \rho_0 g h A_e \tag{1}$$

where, A_e is the inside sectional area of the chimney, p is the differential pressure based on the static pressure under no airflow and FIRELES conditions, subscript "$_1$" is inlet and "$_0$" is outlet, and ρ_0 is air density. The first term on the right-hand side of the equation is the differential pressure of pressure p, and the second term is the difference of static pressure.

Assuming that the conditions inside a chimney are the same as those of the inlet, gas weight can be expressed as:

$$F_g = \rho_1 g h A_e \tag{2}$$

The difference between equations (1) and (2) is the force pushing the air inside the chimney against gravitational force. Assuming that the flow is constant, if the inflow loss and pipe friction coefficient are balanced, the flow velocity inside chimney U_e is obtained as:

$$U_e^2 = \frac{2}{\zeta}\left(\frac{p_1 - p_0}{\rho_1} + gh\frac{\rho_0 - \rho_1}{\rho_1}\right) \tag{3}$$

where, ς is a total loss coefficient of the inflow inside the chimney. Since the flow velocity in a chimney under natural smoke extraction is low, it is considered that plug-holding will not occur. Denoting the layer thickness of heat flow as H_p, average temperature as T_1, and average flow velocity as U_p, the pressure on ceiling part p_1 will be:

$$p_1 = p_0 + (\rho_0 - \rho_1) g H_p \tag{4}$$

Thus, equation (3) becomes:

$$U_e^2 = \frac{2}{\zeta} g(h + H_p)\frac{\rho_0 - \rho_1}{\rho_1} \tag{5}$$

Since H_p is smaller than h, equation (3) can be rewritten as:

$$U_e^2 = \frac{2}{\zeta} gh\frac{\rho_0 - \rho_1}{\rho_1} \tag{6}$$

where T_0 is absolute temperature for air. ΔT represents the rise in temperature of thermal fumes near the smoke-extraction vent. Assuming that the difference in height is h even if the chimney is not vertically straight, the above equation will be valid. The inflow to a chimney is not only thermal fumes: if the heat exhaust flow rate increases, the inflow might also include fresh air from underneath the thermal fumes, in which case the temperature in the smoke-extraction vent will be lower than the temperature of the thermal fumes. Those impacts can be combined into exhaust thermal fume coefficient ***c*** and expressed as follows:

$$U_e = c\sqrt{gh\frac{\Delta T}{T_0}} \tag{7}$$

The heat exhaust flow rate Q_e is

$$Q_e = C_p \rho \Delta T A_e U_e \tag{8}$$

Equation (5) and the state equation gives:

$$Q_e = cC_p\rho_0 T_0 A_e\sqrt{gh}\frac{(\Delta T / T_0)^{3/2}}{1 + \Delta T / T_0} \tag{9}$$

If the rise in temperature is small and it is assumed to be $\Delta T / T_0 << 1$, we obtain the equation:

$$Q_e = cC_p\rho_0 T_0 A_e\sqrt{gh}(\Delta T / T_0)^{3/2} \tag{10}$$

This equation shows that the heat exhaust flow rate is proportional to the 3/2nd power of the rise in temperature. Here, we look at dimensionless temperature rise ΔT. From the state equation for an ideal gas, the density ratio of normal air to thermal fumes can be expressed as:

$$\frac{\rho}{\rho_0} = \frac{T_0}{P_0}\frac{P}{(\Delta T + T_0)} \tag{11}$$

Since there is little difference between the absolute pressure of normal atmosphere and thermal fumes, the equation can be expressed as $P = P_0$ and the density ratio will be equal to the absolute temperature ratio. Accordingly, by denoting T_0 as the reference temperature, non-dimensional temperature rise ΔT^* can be expressed as:

$$\Delta T^* = \frac{\Delta T}{T_0} \tag{12}$$

Next, we consider dimensionless heat exhaust flow rate Q_e^* When standardizing the internal energy flow rate $C_p \rho_0 T_0 A \sqrt{gH}$ for air of normal temperature T_0 flowing at a uniform velocity $\sqrt{gH}$ in the cross section of the tunnel, the non-dimensional heat exhaust flow rate Q_e^* can be written as:

$$Q_e^* = \frac{Q_e}{C_p \rho_0 T_0 A \sqrt{gH}} = c\frac{A_e}{A}\sqrt{\frac{h}{H}} \cdot \frac{\Delta T^{*3/2}}{1+\Delta T^*} \tag{13}$$

Assuming $\Delta T^* << 1$, equation (13) becomes:

$$Q_e^* = c\frac{A_e}{A}\sqrt{\frac{h}{H}} \cdot \Delta T^{*3/2} \tag{14}$$

Equations (13) and (14) show that the heat exhaust flow rate at the chimney is proportional to the exhaust vent area A_e, and to the 3/2nd power of the rise in temperature of thermal fumes in front of the vent. It is also proportional to the 1/2nd power of chimney height h.

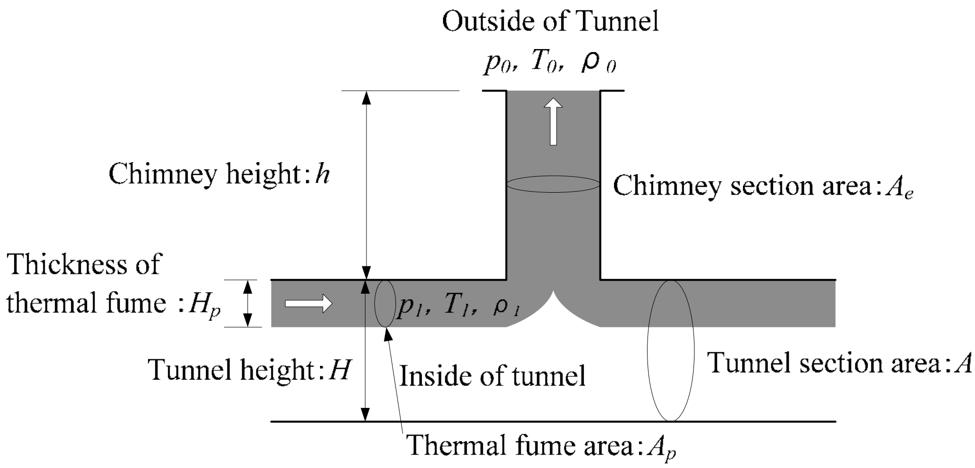

Figure 1: Schematic diagram of a chimney

3. EVALUATION OF THE FULL-SCALE TUNNEL SIMULATION

3.1. Comparison of model tunnel and full-scale tunnel

3.1.1. Characteristics of tunnels

The full-scale tunnel assumed in this study has a rectangular section as shown in **Figure 2**. **Tables 1** and **2** list the major dimensions and component materials. With a gradient of 0% and initial windless conditions, a wind-blocking wall (heat-insulated structure) was installed across the tunnel close to the fire source to make the thermal fumes produced from the fire source flow in one direction. The simulator FIRELES was developed by one of the authors to provide an alternative to full-scale tunnel experiments for evaluating the evacuation environment in tunnel fires. FIRELES sufficiently simulates full-scale tunnel fire experiments and has been used as an evaluation tool for tunnel disaster-prevention system design.[2)]

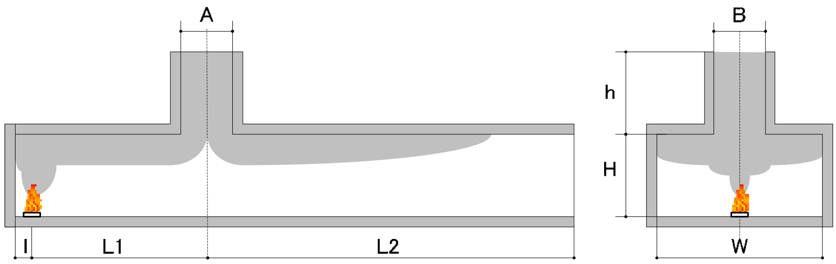

Figure 2: Model tunnel

Table 1: Comparison of tunnel data

Item		Model tunnel	Full-scale tunnel	Model tunnel of Viot & Vauquelin[3)]
Dimensions	Height H [m]	1.0	5.0	0.250
	Width W [m]	1.926	10.0	0.50
Scale ratio	γ	1/5	1	1/20
Data for chimney	Vent A/B [m]	0.6/0.6	3.0/3.0	0.125/0.1, 0.5/0.025
	Height h [m]	1.0	5.0	0–0.5

Table 2: Tunnel materials and data

Data	Model tunnel	Full-scale tunnel
Material	ALC	Concrete
Height H [m]	1.000	5.000
Wall thickness t [m]	0.037	0.500
Specific heat c [J/(kgK)]	1.21×10^3	1.05×10^3
Density ρ_w [kg/m^3]	5.84×10^2	2.89×10^3
Heat conductivity λ [W/(mK)]	0.17	2.56

3.1.2. Scale of fire

The scale of fire for the full-scale tunnel to compare with the model tunnel was set as shown in **Table 3** with reference to the fire scale[4)]. The simulation results are dimensionless as shown by the previously mentioned equation.

Table 3: Fire scale

Model tunnel [kW]	10, 20, 40, 70, 100, 150, 200
Full-scale tunnel [MW]	5, 10, 20, 30, 40

3.1.3. Simulation results

Figure 3 shows the non-dimensional heat exhaust flow rate and non-dimensional temperature rise ΔT^* derived from equations (13) and (14) based on the results of full-scale simulation. As shown in the **Figure 3** below regarding the model tunnel and the full-scale tunnel, the heat exhaust efficiency were ranked by dimensionless and which could have similar result. This time, the exhaust thermal fume coefficient $\boldsymbol{c}$ shown in equations (13) and (14) was calculated based on each simulation result. The solid line in **Figure 3** is the result derived from the averaged values of the simulation results and those recalculated by equation (13), and the dashed line (straight line) is the result derived in the same way by equation (14). The exhaust thermal fume coefficient ***c*** was 0.608. Regarding the solid line, the increase of heat exhaust temperature reduced the air density. Therefore, the rate of increase of the quantity of heat exhausted gradually lowers and separates from the dashed line. These results confirmed the validity of equations (13) and (14) previously proposed.

Next, **Figure 4** shows the relationship for non-dimensional heat exhaust flow rate Q_e^* by back-calculating exhaust thermal fume coefficient ***c*** for each fire scale simulated by equation (13). Non-dimensional heat exhaust flow rate Q_e^* is proportional to the 3/2nd power of non-dimensional temperature rise ΔT^*. However, the figure below shows that exhaust thermal fume coefficient ***c*** is distributed from 0.5 to 0.7.

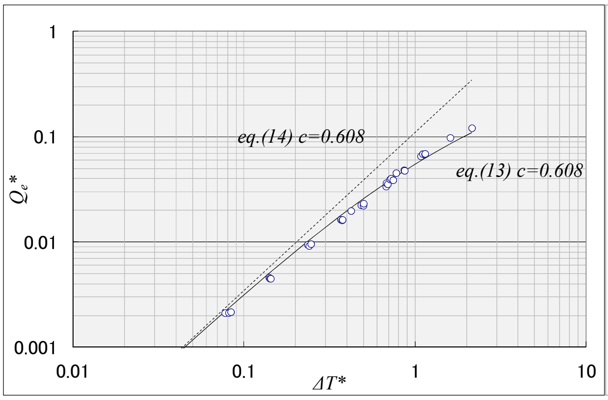

Fig. 3: Non-dimensional heat exhaust flow rate Q_e^* for model tunnel

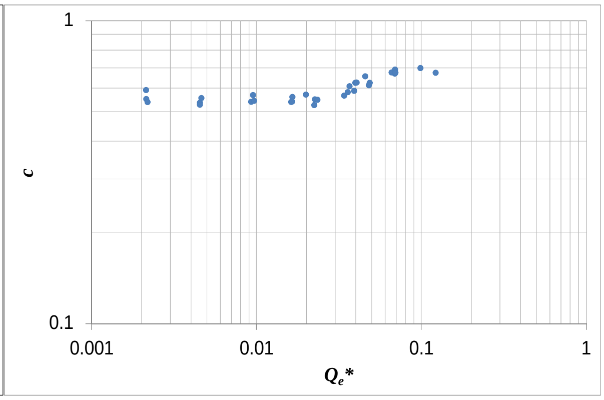

Fig. 4.: Relationship between non-dimensional heat exhaust flow rate Q_e^* and exhaust thermal fume coefficient ***c***

3.2. Comparison of heat exhaust efficiency

3.2.1. Area of outlet and heat exhaust efficiency

This section examines the variation of heat exhaust flow rate Q_e due to a change of chimney outlet area A_e. The shape of the outlet, which is installed across the width of the tunnel, is square, the same as the cross-sectional shape of the chimney, which is 5 meters high. The heat release rate of the fire source is 20 MW and the size of cross section and structure data are the same as in **Figure 2**. **Table 4** shows the dimensions of the exhaust vent.

Table 4: Dimensions of exhaust vent

Type	a15	a175	a20	a25	a30	a35	a40
A/B [m]	1.5/1.5	1.75/1.75	2.0/2.0	2.5/2.5	3.0/3.0	3.5/3.5	4.0/4.0
A_e [m^2]	2.25	3.0625	4	6.25	9	12.25	16

Given that A_e /A is non-dimensional chimney section area A_e^*, **Figure 5** shows the relationship between non-dimensional heat exhaust flow rate Q_e^* and A_e^* and the results based on equation (13) as previously mentioned. As shown in the figure, the results from equation (13) and simulation show that the difference in the slope of the curve (the difference of perfect power) is -0.284. The difference arises from exhaust thermal fume coefficient ***c*** set up in equation (13). ***c*** is not a fixed multiplier and is affected by chimney section area A_e.

3.2.2. Shape of smoke-extraction vent and heat exhaust efficiency

Next, we examine the heat exhaust efficiency for various width-to-length ratios of the exhaust vent area. Aspect ratio *AS*, which denotes the size ratio of the vent, is defined as:

$$AS = \frac{Vent\_length}{Vent\_width} \quad (15)$$

Table 5 shows the aspect ratio of the smoke-extraction vent for the evaluation by simulation. The smoke-extraction vent is installed in the center of the tunnel width. The chimney has the same cross-sectional shape as the smoke-extraction vent. The heat release rate of the fire source in all cases is 20 MW and the size of cross section and structure data are the same as in **Figure 2** and **Table 1**.

Table 5: Aspect ratio *AS* and shape of smoke-extraction vent

№		①	②	③	④	⑤	⑥	⑦
Aspect ratio *AS*		0.25	0.444	0.694	1	2.25	4	5.840
Vent	*Length A* [m]	1.5	2	2.5	3	4.5	6	7.25
	Width B [m]	6	4.5	3.6	3	2	1.5	1.241

According to **Figure 6**, the simulation shows that an increase of non-dimensional heat exhaust flow rate Q_e^* reduces the aspect ratio *AS*. However, the result from equation (13) shows that heat exhaust flow rate Q_e^* is fixed and the difference in the slope of the curve (the difference of perfect power) is -0.180, and the aspect ratio also affects exhaust thermal fume coefficient ***c***.

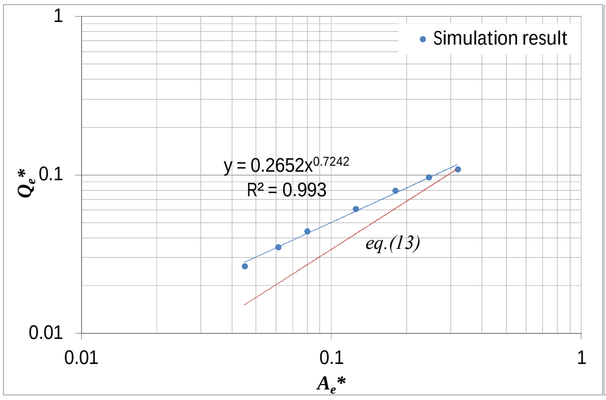

Fig. 5: Change in exhaust vent area and heat exhaust flow

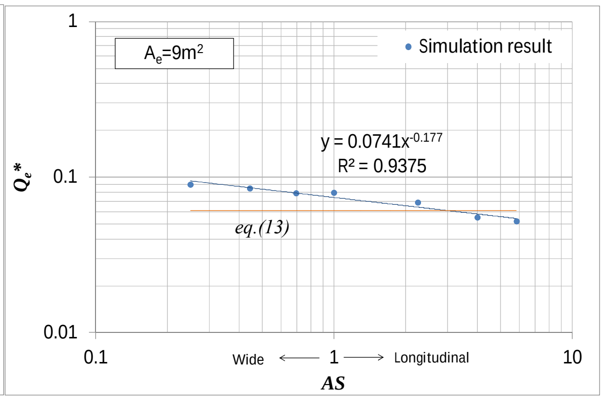

Fig: 6. Aspect ratio and heat exhaust flow rate

3.2.3. Height of chimney

Here, we verify the changes in non-dimensional heat exhaust flow rate Q_e^* for various values of chimney vent area (2.25 m^2, 9 m^2, 16 m^2), fire source scale (5 MW, 10 MW, 20 MW) and chimney height *h* (5 m, 10 m, 20 m) to clarify the relationship between the chimney height *h* and heat exhaust flow rate Q_e^*. Here, $h/\sqrt{A}$ denotes non-dimensional chimney height H^*. **Figure 7** shows an example for a fire source scale of 10 MW. As shown, an increase of heat exhaust flow rate Q_e^* increases the non-dimensional chimney height H^*. Comparing the result calculated by equation (13) and the perfect power, the difference is -0.243 and it affects exhaust thermal fume coefficient ***c***.

4. EVALUATION OF HEAT EXHAUST EFFICIENCY

In the previous section, we considered chimney height, aspect ratio, chimney vent area, and fire scale to evaluate heat exhaust efficiency. The evaluation showed that ***c*** in equation (13) is not fixed and is affected by chimney height, aspect ratio, and chimney vent area. The relations can be expressed by:

$$c\left[A_e^*, AS, H^*\right] \propto A_e^{-1/4} \cdot AS^{-1/5} \cdot H^{*-1/4} \tag{16}$$

By substituting these into equation (13), we obtain:

$$Q_e^* = C' \cdot A_e^{*3/4} \cdot AS^{-1/5} \cdot H^{*1/4} \times \frac{\Delta T^{*3/2}}{1+\Delta T^*} \tag{17}$$

The calculated values of new thermal fume coefficient *C'*, using equation (17), are distributed between 0.684 and 0.36 due to the change in fire scale, area of exhaust port, aspect and chimney height (**Figure 11**). To understand these factors, **Table 6** summarizes the distribution of each parameter. As a result, we found that the dispersion of *C'* increases due to changes in H^*. The reason for this is considered as follows. This case is a combination of *H*, A_e, and fire scale, and there may be possible influences on the bottom air inducer and changes in friction loss of the inside of the chimney.

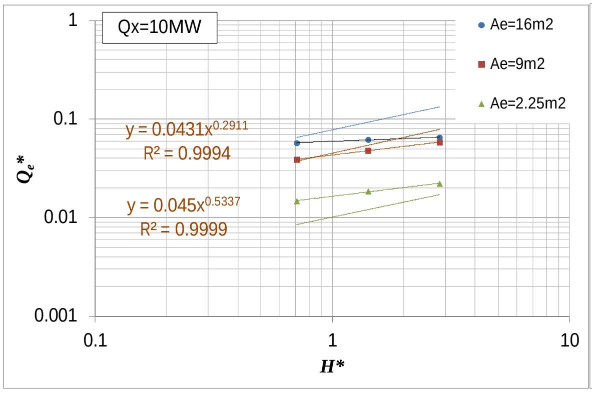

Fig. 7: Chimney height and heat exhaust flow rate

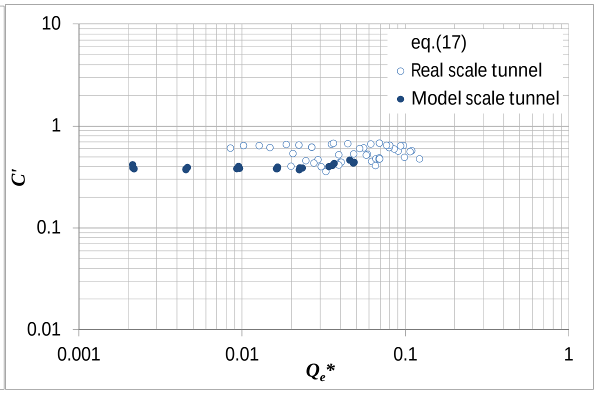

Fig. 8: Heat exhaust flow rate and ***C'***

Table 6: Range of *C'* shown in **Figure 11**

Parameter	Maximum	Minimum	Standard deviation
A_e^*	0.675	0.577	0.0343
AS	0.684	0.571	0.0366
H^*	0.682	0.360	0.0949

5. CONCLUSIONS

The simulation of changes of fire scale showed the following.

1) Equation (13) describes the heat exhaust flow rate from a chimney. Exhaust thermal fume coefficient ***c*** was 0.608 when only the scale of fire source was changed.

Changing the data of the chimney yielded the following results:

2) C' of equation (13) is affected by changes in Ae, AS and H* of the chimney. We therefore propose equation (17) to improve the accuracy of the calculation.
3) When the height of the chimney H* changes, the dispersion of c' of equation (17) is too large, and a close study of the friction loss of the chimney and the bottom air inducer is necessary.

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THE INFLUENCE OF PRESSURE GRADIENTS ON VENTILATION DESIGN – SPECIAL FOCUS ON UPGRADING LONG TUNNELS

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ABSTRACT

In most cases, large differences in pressure exist between the portals of long road tunnels as they often connect areas exhibiting different meteorological situations. While the forces resulting from the pressure gradient are taken into account in design and planning of new tunnels, problems may arise when existing tunnels require upgrading. In most cases such tunnels are ventilated by a transverse ventilation system or a system with massive point extraction. These requires an exact control of the air or smoke flow in the case of an emergency and hence an enormous technical effort to achieve the ventilation goals. This paper focuses on the problem of pressure gradients in long alpine tunnels, the technical solutions available, and on what needs to be considered when designing such installations in tunnels undergoing upgrading.

Keywords: ventilation design, transverse ventilation system, long tunnels, pressure gradients

1. INTRODUCTION

In general, long road and rail tunnels often connect regions exhibiting different meteorological conditions. This is certainly the case where long mountain ridges are traversed, but is also common elsewhere. Pressure gradients have a large influence on ventilation design as they act as additional forces on the air column inside the tunnel.

Most long tunnels are ventilated by means of a transverse ventilation system or are equipped with an air exchange system somewhere inside the tunnel. Where an incident leads to smoke production it is imperative to control the air velocity in the tunnel in order to guarantee that full smoke extraction occurs at planned locations (i.e. at the dampers).

For new tunnels all the requisite boundary conditions are adequately taken into account during design. Problems can occur, however, when existing tunnels have to be upgraded in order to comply with new regulations in tunnel safety. Emergency requirements with respect to the upgrading of tunnel ventilation systems have changed markedly in recent years [1], [2]. The most important change concerns the requirement for massive point extraction for the smoke. This is now achieved using one or more dampers which are fully opened in the proximity of the fire.

The control of airflow in the region of the fire may be accomplished in several ways, either by applying jet fans inside the tunnel (the normal case) or by applying Saccardo type nozzles which utilize existing axial fans [3]. However, especially when existing tunnels have to be upgraded, the presence of existing civil works or structures may severely restrict ventilation update. For example, lack of adequate space in the existing traffic room of the tunnel very often means that the most appropriate jet fans cannot be used, or existing exhaust duct cross-sections may strongly limit the possibility of utilizing the positive effects of full transverse ventilation systems. In most cases a compromise has to be reached between the need to achieve an optimum technical update of the ventilation system in the given situation and the desire for maximum compliance with safety regulations.

2. PRESSURE DIFFERENCES AT PORTALS AND SHAFT

Various regulations demand that portal pressures be taken into account in the design of a ventilation system. The Austrian guideline RVS 09.02.31 [5] requires that absolute pressure, wind velocity and wind direction at the tunnel portals all be monitored for a period of one year. Depending on the risk level of the tunnel, either the 95th percentile or the 98th percentile value of the pressure difference between the portals has to be used when defining the forces acting at the portal. Any difference in portal altitude is corrected for by means of standard atmosphere figures. Unfortunately, such measurements are accompanied by a considerable amount of uncertainty.

The most critical points are:

- The measurement equipment itself is only accurate to within 30 Pa to 50 Pa
- Uncertainties in the assignment of the correct altitude for the measurement location.

Assuming a portal with a cross section of 50 m², the total uncertainty resulting from both the potential inaccuracy of the measurement equipment and from problems of assigning correct altitude might well lead to inaccuracies in measurement in the order of 30 Pa to 60 Pa, or some 3000 N,. In relation to the values normally recorded this represents quite a high level of uncertainty. The effect on ventilation design can thus be considerable.

Long-term measurements at Austrian road tunnel portals revealed the following:

Table 1: Differences in portal pressures in some Austrian road tunnels

Name of the tunnel	Length [m]	95^{th} Percentile direction 1	98^{th} Percentile direction 1	95^{th} Percentile direction 2	98^{th} Percentile direction 2
A10, Tauerntunnel	6,546	254 Pa	312 Pa	235 Pa	271 Pa
A9, Gleinalmtunnel	8,320	268 Pa	317 Pa	89 Pa	129 Pa
S16, Arlbergtunnel	13,972	206 Pa	264 Pa	209 Pa	241 Pa

Direction 1: N-S or W-E, direction 2: S-N or E-W

As shown in **Table 1** the pressure differences are quite marked and should clearly be taken into account in ventilation design. In most cases extra ventilation equipment is needed to overcome the negative impact of the resulting atmospheric forces.

3. TECHNICAL SOLUTIONS

As most long tunnels use ventilation systems employing massive point extraction, the control of the air/smoke velocity inside the tunnel is the key working issue. Longitudinal air/smoke flow inside the tunnel can be influenced in a variety of ways [3]. The following offers a basic classification:

- Devices which add momentum in the direction of the tunnel axis
- Devices which add momentum and mass in the direction of the tunnel axis
- Devices which inject mass into the tunnel but without adding momentum in the direction of the tunnel axis

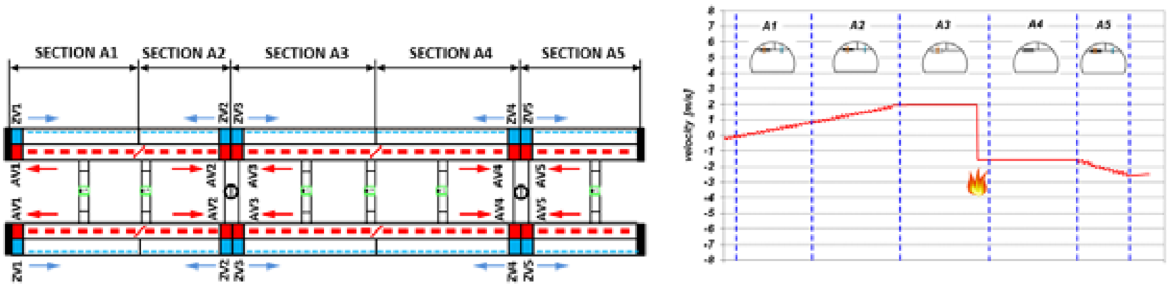
The type of device used depends strongly on existing boundary conditions such as available space inside the tunnel, the technical equipment available, and last but not least, the associated costs. In the end, the final choice of equipment will depend on the nature of the resulting forces which have to be handled within the tunnel (mainly the pressure differences between the portals or portals and shafts) and whether such equipment is at all feasible given the expected costs.

The following sections give an overview of possible solutions, problems encountered during installation and operation, and of existing constraints with respect to operating range.

3.1. Mass injection and extraction without momentum in direction of the tunnel axis

Most long road tunnels contain several ventilation sections. This makes it possible to inject air into and/or extract air from the various tunnel sections in order to build up a pressure gradient along the tunnel axis. As a result of this pressure gradient both the flow velocity as well as the flow direction inside the tunnel can be influenced. This method was standard in most of the long road tunnels with transverse ventilation in Austria up to 2000. At that time air/smoke flow inside the tunnel was directed by the existing ventilation systems but as closed loop systems were not then employed it could not be controlled sufficiently. Thus a fixed setting needed to be defined for each fan according to the various fire scenarios. This method worked as long as equally distributed smoke extraction was standard in the long tunnels. However, following the big fires in European tunnels in the late 1990's, ventilation philosophy changed from a system of distributed smoke extraction to one of massive point extraction.

The first use made of a closed loop control system in a long road tunnel in Europe was in the 10 km long Plabutsch tunnel in 2003 [4]. The Plabutsch tunnel uses a fully transverse ventilation system and has 5 ventilation sections. In each section one fan is responsible for both fresh air supply and exhaust air extraction. In the case of fire the damper closest to the fire location is opened and smoke with a volume flow of 120 m³/s to 160 m³/s is extracted. In order to reach the required ventilation target all axial fans within one tube are included in the automatic operation control system. **Figure 1** provides a sketch of the ventilation system as well as of how the fans work together in order to reach the ventilation target.



fire in	SECTION A1		SECTION A2		SECTION A3		SECTION A4		SECTION A5	
	fresh air	exhaust air	fresh air	exhaust air	fresh air	exhaust air	fresh air	exhaust air	fresh air	exhaust air
SECTION A1	-	100%	-	-	0%-100%	0%-100%	0%-100%	0%-100%	0%-100%	0%-100%
SECTION A2	-	-	-	100%	-	-	0%-100%	0%-100%	0%-100%	0%-100%
SECTION A3	0%-100%	0%-100%	-	-	-	100%	-	-	0%-100%	0%-100%
SECTION A4	0%-100%	0%-100%	0%-100%	0%-100%	-	-	-	100%	-	-
SECTION A5	0%-100%	0%-100%	0%-100%	0%-100%	0%-100%	0%-100%	-	-	-	100%

Figure 1: Sketch of the ventilation system of the Plabutsch tunnel and the operation scheme for the fans in the case of fire.

The benefit of such a system is that it utilizes the existing axial fans. No new mechanical installations are needed. The drawback is to be seen in the fact that the air is injected without adding momentum in the direction of the tunnel axis. As the inertia of the air mass within a 10 km long tunnel is quite large, the system takes some time to react properly. The biggest drawback , however, is that for the system to work adequately the pressure difference between the portals must not be higher than some 50Pa to 100 Pa.

3.2. Mass injection and extraction with momentum in the direction of the tunnel axis

The utilization of the momentum of injected air represents an improvement on the above approach . In most cases such systems use Saccardo type nozzles in order to produce the required momentum in the tunnel. Hence, they act like big jet fans, but they also add mass in the tunnel. Such systems can be used in tunnels where axial air supply fans already exist. This is the case in tunnels with a fully transverse ventilation system as well as in tunnels undergoing upgrading where additional axial fans can be relatively simply installed, e.g. at portal regions.

The momentum of the injected air is proportional to its mass and the velocity difference (injected air minus tunnel air speed). Hence, either the capacity of the fan (volume flow) or the velocity of the incoming jet of air acts as a constraint. The capacity is simply defined by the existing axial fans. An upper threshold value for the velocity of the injected air impinging on the road surface is given by the need for driver safety, i.e. the safety of those who might be under or close to the nozzle when it goes into operation. **Figure 2** shows a sketch of such a system. **Figure 3** shows the elements needed for the injection. In order to guide the air from the fresh air duct into the traffic space large dampers are opened. Within a close distance downstream of the damper the duct is closed by a hinged door. The pictures are from the installation in the Katschberg tunnel, where two fresh air injection systems per tube serve to control air/smoke flow in the case of fire and to handle the barometrical pressure differences at the portals.

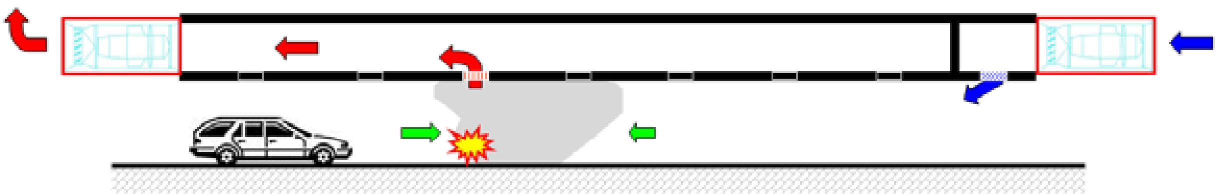


Figure 2: Sketch of a Saccardo type fresh air injection system

Figure 3: Fresh air injection system installed in the Katschberg tunnel, Austria

Table 2 contains the parameters of two installations along the A10 Tauern highway in Austria. The greater the number of Saccardo type nozzles installed, the more complex the control system.

Table 2: Parameters of currently installed fresh air injection systems in Austria

Tunnel	Difference in portal pressures (95th Percentile)	Number of fresh air injection nozzles per tube	Volume flow [m³/s]	mean exit velocity at the nozzle [m/s]
Katschberg Tunnel	170 [Pa]	2	2 x 90	35
Tauern Tunnel	254 [Pa]	3	2 with 150 1 with 135	two with 30 one with 27

The limitation of such installations is mainly to be seen in the fact that in each of the active nozzles air mass is brought into the tunnel. This increases the air velocity and hence reduces the efficiency of the next active nozzle, as only the difference between injected and existing air velocity has an impact.

Wherever it is necessary to increase the number of injection nozzles it will also be necessary to extract air between the injection points. Figure 4 shows the sketch of such a system. In this case a pressure difference of 264 Pa has to be dealt with. The tunnel consists of six ventilation sections, all of them with fully transverse ventilation. In each section a fresh air fan with a volume flow of 300 m³/s and an extraction fan with a volume flow of 290 m³/s is available. In the case of fire, the fresh air fans are used to supply the Saccardo type nozzles.

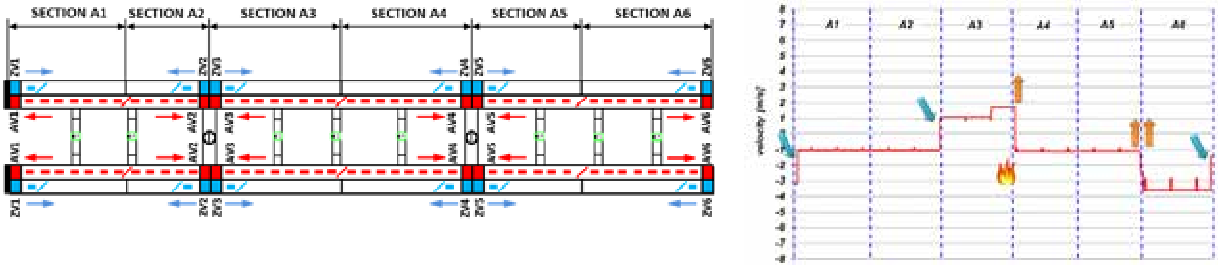


Figure 4: Sketch of a fresh air injection system with three active injection nozzles

When using Saccardo type nozzles for air injection one has to bear in mind that the incoming air might have a high velocity and hence have a noticeable impact on driving conditions in close proximity to the nozzle. Restricting the speed of the incoming air would of course tend to counteract the desired system benefits. A compromise will always have to be made in terms of optimizing the volume and speed of the incoming air and the angle of the jet. Theoretically, the more horizontal the air injection is, the smaller the loss of momentum. But owing to the Coander effect wall friction losses increase markedly as soon as the angle between wall and jet centerline is smaller than 20-25°. **Figure 5** shows the calculated values for the air injection system installed in the Katschberg tunnel. As can be seen, the velocity within the tunnel tube reaches quite high values where the jet impinges on the main stream (~20 m/s). These values were confirmed by measurements performed during the commissioning phase of the tunnel.

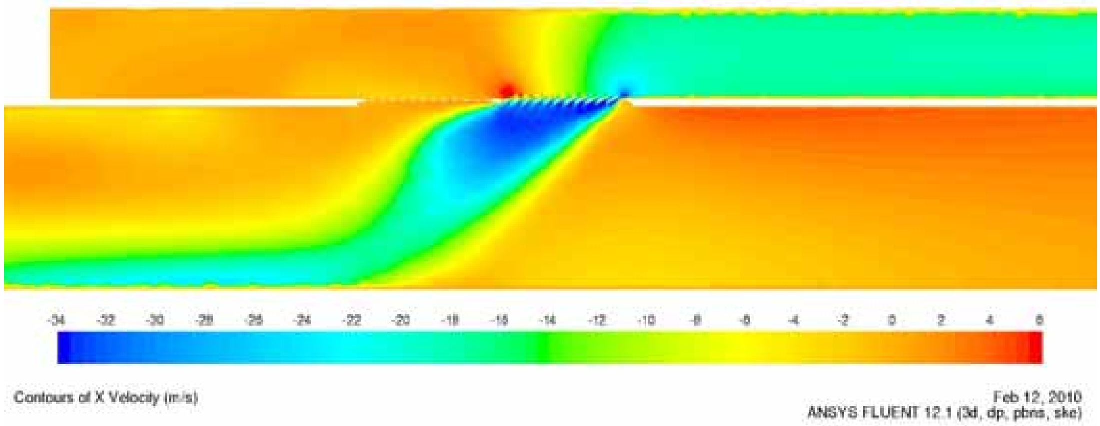


Figure 5: Air velocity in the region of the air injection

3.3. Jet fans in the tunnel tube

From a ventilation point of view, the installation and operation of jet fans inside the tube would be the simplest way to control the tunnel airflow. The bigger the pressure difference is between the portals, the more fans (or bigger fans) are needed. This results in two conflicting options:

1. Accepting space restrictions within existing tunnels and installing (relatively small) jet fans. To be effective, this would require a huge number of jet fans which in turn would result in high maintenance costs and would also necessitate regular closure of the tunnel for periods of maintenance, i.e. reduced levels of service.
2. Widening the existing cross-section of the tunnel. This always entails an enormous effort owing to the construction difficulties involved (problems with tunnel lining etc.).

In general, at least in Austria, the first option is ruled out due to the relatively high maintenance costs involved and the associated reductions in tunnel service. Thus, the second option is in most cases the only solution. In order not to destroy the tunnel lining in too many locations inside the tunnel, only a few fan niches are erected. In such cases, due to the high meteorological pressure differences between the portals the required fan thrust can be considerable. The usage of relatively large inverter-driven fans (~2,700 N thrust, 1.8 m diameter, 90 kW power at shaft), is thus essential.

In such cases the fan niches are similar to emergency breakdown niches, in that they allow for enough space for operation and maintenance without restricting car traffic. **Figure 6** provides a sketch of such a fan niche. Guiding walls on both sides of the fan are intended to reduce the flow losses resulting from niche installation.

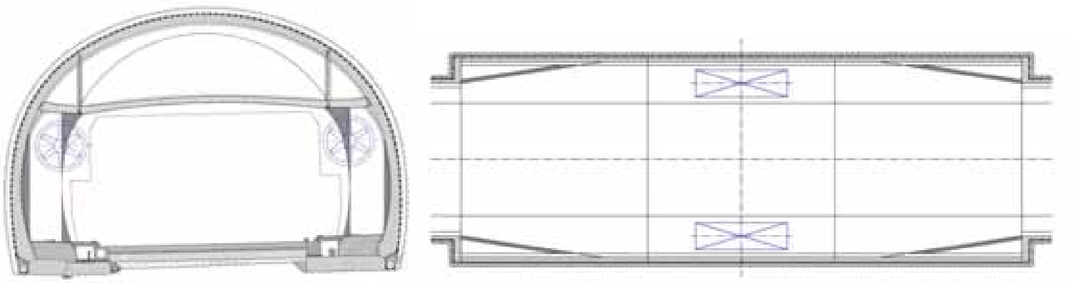


Figure 6: Sketch of a fan niche, cross section (left)

The operation of high thrust fans always results in a strong additional force in the tunnel. Hence, during operation, the airflow in the region of the fans is strongly disturbed and the air velocity can be quite high. This creates an additional risk for tunnel users, mainly for motor cyclists.

3.3.1. Numerical simulations of the impact of large jet fans on moving vehicles

At present in Austria,, several installations employing large and powerful jet fans are being planned for use in a few long road tunnels. To date, however, none of them has been put into operation. Thus, in order to have some idea about the velocities acting on a moving vehicle a series of numerical calculations were performed.

3.3.1.1 Numerical model and boundary conditions

The geometry examined here represents a typical profile for a tunnel with a transverse ventilation system (see **Figure 6**), and has a cross-section of 46.8 m². For the current investigations, the only region of interest is that comprising the ventilation niche itself, including the jet fans, and the appropriate adjacent domain upstream and downstream. The overall length of the tunnel geometry considered here is 400 m. The ventilation niches have a length of 37.5 m and include guiding boards with a slope angle of 10°.. The jet fans are situated 3.3 m above the road surface and approximately 1.3 m from the sidewall of the niche. These jet fans have a length of 6 m, an outer diameter of 1.8 m and an inner diameter of 1.5 m. CFD calculations were performed in order to determine the velocities affecting a passing motorcyclist in the tunnel. Geometrical representation of the motorcyclist is achieved by applying prismatic volumes. For simulation purposes, these were placed near the pavement in a variety of positions along the longitudinal direction (driving direction). This CFD model had frontal and side areas similar to those of a common motorbike and was permeable, so that the resulting velocity within the considered volume could be determined.

Two different calculation cases were performed. The first one simulates operation in the case of fire and the second one simulates conditions under normal operation.

It was assumed for the fire case that the initial air flow induced by meteorological pressure differences between the tunnel portals had to be reduced to an air velocity of 1.0 m/s (**Figure 7**). Hence, the jet of the fan is directed against the main air flow (deceleration operation).

In the case of normal operation it is assumed that the tunnel air flow has to be accelerated to a velocity of 1.8 m/s in order to meet the air quality requirements given in [5]. In this case the jet fan blows in the same direction as the main air flow in the tunnel (acceleration operation).

The calculations were performed by using a hybrid mesh with approximately 6.8 million elements. In order to resolve the region in close proximity to the wall, the mesh consisted of tetrahedral and pyramidal elements as well as of prism layers. Due to the high Reynolds numbers ($Re > 10^5$) in the cases considered, the turbulence was simulated with the high Reynolds k- ε -model proposed by Launder and Spalding [6]. In addition, a logarithmic wall function was also applied. A finer mesh than that used in the remaining domain, was used for discretization of the ventilation niche, and in particular for discretization of the jet fans and the prismatic dummies representing the motorcyclist.

Figure 7 illustrates the computational mesh for the ventilation niche and also shows the flow situation with the reduction in tunnel air flow. For the acceleration case the main wind speed is in the same direction as the exit jet of the jet fans.

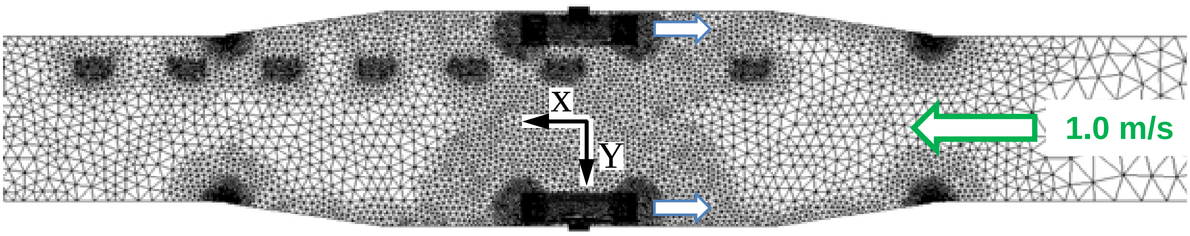


Figure 7: Sketch of the flow situation in the case of fire, with deceleration of the tunnel air flow

A mass flow boundary condition at the entrance area of the computational domain was used in the air flow simulations. . In order to determine the impact of the jet fans a fan model governing the relationship between pressure rise and flow rate across a fan element was applied. In this model the fan blade is considered to be infinitely thin. This means that the pressure jump and the flow rate are introduced via a circular plan. The relationship between pressure rise and flow rate is assumed to be linear. In addition it is assumed that due to the static blades the fan swirl velocities induced by the fan blades become totally straight in the flow direction. The static thrust of the jet fan is 2,700 N.

3.3.1.2 Results

The following figures (**Figure 8** and **Figure 9**) depict the streamlines of the two different operating situations (normal operation and operation in the case of fire).

Both jet fans deliver a maximum flow rate of approximately 120 m³/s for the fire case. Under normal operating conditions the flow rate is nearly 88 m³/s. This leads to a backflow of some 32 m³/s in the region of the ventilation niche (see **Figure 9**). A backflow also occurs in the case of fire, where a deceleration of the tunnel air flow is assumed. In this case the whole flow rate of the jet fans circulates within the ventilation niche (see **Figure 8**).

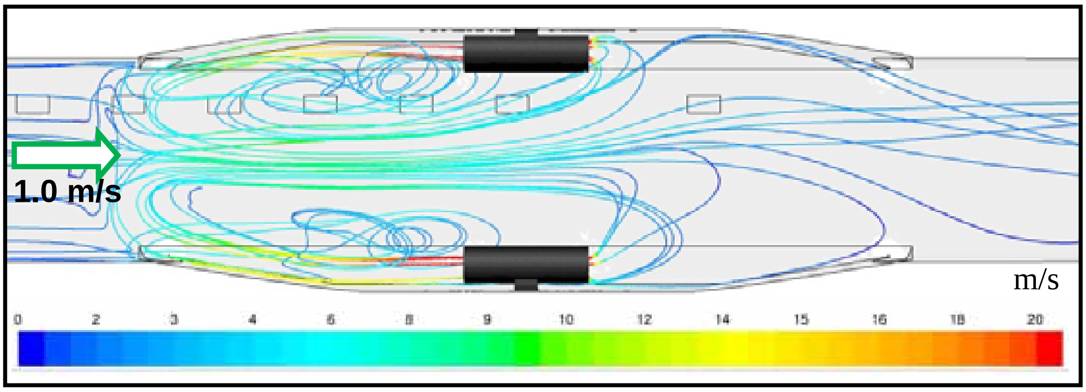


Figure 8: Streamlines in the region of the ventilation niche for the fire case, colored according to the velocity.

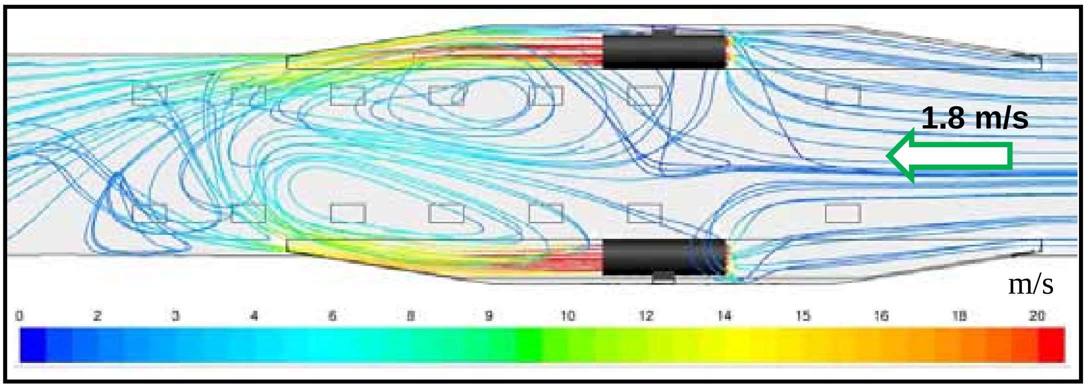


Figure 9: Streamlines in the region of the ventilation niche for normal operation, colored according to the velocity.

Due to the circulation of the air flow and the restriction behind the ventilation niche transverse velocities appear in the region of the ventilation niche and vary in longitudinal direction. In order to obtain the required information concerning the transverse (side) and frontal forces affecting a motorcyclist, the velocity vectors within the prismatic dummies were computed for the various dummy locations and then decomposed into their frontal and cross wind components.

Figure 10 and **Figure 11** depict for both simulation cases the side and frontal velocities with respect to dummy position in the tunnel. The origin (0 m) denotes the center point of the ventilation niche as well as the center of the jet fans. Positive velocity values are defined for crosswinds towards the tunnel wall as well as for frontal winds against the driving direction. On passing the ventilation niche the cross wind velocities change direction several times. The maximum value for the side velocity is lower than 2 m/s. The maximal frontal velocity is 6 m/s and occurs in the contraction region of the fan niche.

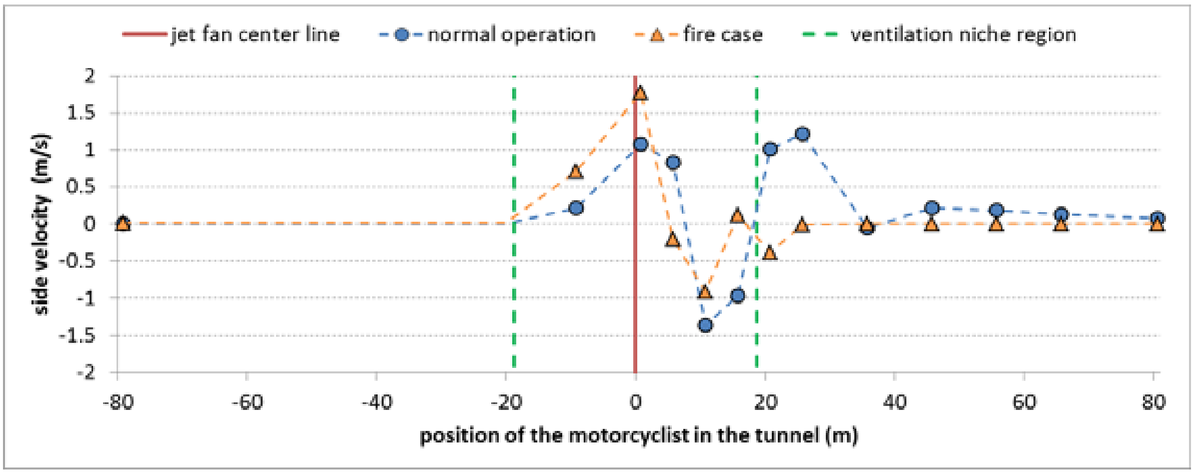


Figure 10: Side velocity component acting on the notional motorcyclist volume as a function of position inside the tunnel.

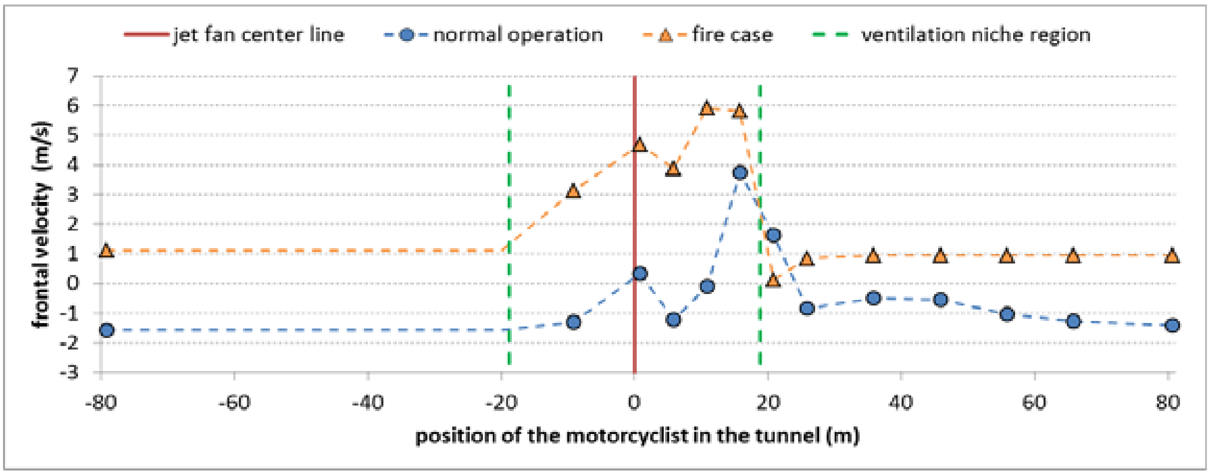


Figure 11: Frontal velocity component acting on the notional motorcyclist volume as a function of position inside the tunnel.

3.3.1.3 Discussion

The above method assumes that a passing motorcyclist does not influence the flow pattern inside the tunnel. However, in reality a passing motorcyclist does generate a specific flow pattern (depending on the driving speed). This interferes with the flow field in the fan niche, hence the impact of the jet fan-induced velocities is reduced.

The fluctuation magnitude of the velocities near the jet fans can be compared to that felt by wind gusts or to the turbulence caused by a passing lorry in two-way traffic in a tunnel. Nonetheless, such velocity fluctuations arise unexpectedly and might therefore still pose a threat to passing motorcyclists. However, when the jet fans are in operation, appropriate information signs or flashing lights could be used in order to mitigate such a potential hazard.

4. CONCLUSION

Long tunnels are often subject to large pressure differences between portals. This can result in additional air flow within the tunnel. In rare cases the resulting velocities can reach 10 m/s. Such situations present a formidable challenge when designing the tunnel ventilation system. As most of the long tunnels are ventilated by transverse systems with massive point extraction, the control of the air speed inside the tunnel is a crucial safety factor, especially with respect to smoke extraction in the case of fire. In order to bring these forces under control additional ventilation equipment may need to be installed. In new tunnels such installations are automatically taken care of in the planning and design phase of the ventilation system. A problem arises however, when existing tunnels undergo refurbishment and the ventilation system and safety installations are upgraded to the state of the art. In such cases the extent to which a state of the art system is achieved will always depend on the level of compromise required between what is technically necessary or desirable and what is in practice feasible.

Adding jet fans to existing tunnels with transverse ventilation systems would be the simplest way to control air speed. But for a variety of reasons this is not possible in many cases. For example, the thrust required might only be achievable by installing a large number of fans and hence produce high maintenance costs. In contrast, utilizing an existing ventilation installation for air injection with or without momentum along the tunnel axis, results in relatively low maintenance costs, but it has other disadvantages which have to be considered.

In the presence of high pressure differences between tunnel portals a number of methods are available for achieving ventilation targets. All of them have pros and cons and all are subject to specific limitations concerning their range of operation. In practice, finding an ideal solution requires analysing each situation case by case. It is always a question of finding the most suitable balance between a number of factors such as technical feasibility, installation and maintenance costs, and impact on tunnel users.

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CONTROL OF SMOKE PROPAGATION IN A WIDE ROAD TUNNEL WITH SIDE WALL JET FANS THROUGH A DEDICATED VENTILATION STRATEGY

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ABSTRACT

This paper deals with a specific emergency longitudinal ventilation strategy dedicated to wide cut and cover road tunnels where jet fans can only be installed along the side walls due to the limited height of the tunnel. This strategy has been developed to cope with the phenomena of low velocity that may appear in the middle of the tunnel cross-section for this typical tunnel configuration and jet fan installation. This could lead to significant back layering when this occurs in the region of fire. The solution is to inhibit the nearest bank of fans upstream of the fire. This ventilation strategy has been proposed and successfully installed in the A1 (M) Hatfield Tunnel in the UK. The design and the on site acceptance tests results are presented in this paper.

Keywords: ventilation design, wide cut and cover tunnels, emergency ventilation

1. INTRODUCTION

Most of the city tunnels that have been built in Europe during the seventies and the eighties need to be refurbished in order to satisfy the current safety requirements set by new regulations. In most of the cases, the ventilation systems have to be re-designed to achieve the smoke control requirements.

In early 2009 , the Highways Agency awarded the Skanska Balfour Beatty Joint Venture (SBBJV) the contract for the widening of the M25 which included the refurbishment of the A1 (M) Hatfield Tunnel. This contains two bores each 1.1 km long, 19.6 m wide and 5.7 m high.

One of the key elements of the work was replacing the existing fans in the tunnel which were life expired. The new design requirements for an incident were considerably higher than the existing fans would provide. Moreover, due to the limited height of the tunnel, it was only possible to install jet fans on the side walls. The reference design proposed was based on 26 "banana jet fans" per bore, in order to meet the critical velocity for a 100 MW fire. The Designer for the tunnel undertook modelling and was unable to confirm the design parameters could be met by this method. Indeed, as a consequence of the tunnel width, the longitudinal flow generated by the fans showed a low velocity in the centre part of the cross section. This would have led to a risk of backlayering even if the average longitudinal velocity was above the critical velocity. Another option the designer considered was the use of a Saccardo ventilation system. It was clear that not only would this increase costs, but more importantly new plant buildings would be required to house the fans. As the tunnel is positioned under a shopping centre, the only feasible location for the new buildings would be to extend the tunnel at each portal and build over the carriageway; obtaining planning permission for this even if granted, would be a lengthy process.

Egis Tunnels were then approached in February 2009 to find a solution. The proposed system is based on straight jet fans with a dedicated ventilation control strategy where the nearest bank of fans upstream the fire is inhibited, this is to increase the distance between active fans and the fire.

2. DESIGN EVALUATION

2.1. General design consideration

In most of the non-urban double bore unidirectional tunnels, risk analysis show that the risk of congested traffic is very low. In the case of fire, vehicles downstream the fire can then leave the tunnel in most cases. Considering that, a longitudinal ventilation strategy can be applied for the smoke control as per recommendations and regulations ([1] and [2]). The principle consists of pushing smoke downstream of the fire and is illustrated on the following figure.

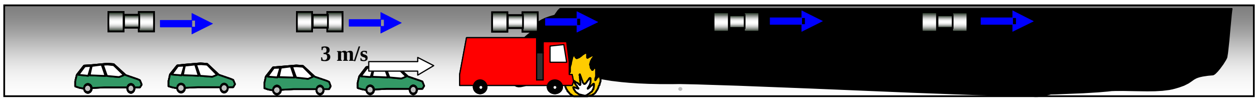

Figure 1: Longitudinal ventilation strategy in case of fire

As well known, the longitudinal airflow velocity has to be strong enough to prevent back layering (smoke propagation upstream of the fire) and this objective is reached if this velocity is at least equal to the critical velocity [3].

The technology commonly used to create the longitudinal airflow is based on sets of jet fans installed along the tunnel. This generally corresponds to the best cost benefit solution. However, local undesirable aerodynamic effects may appear in the vicinity of the fans and tend to degrade the homogenization of the longitudinal velocity throughout the tunnel cross-section.

In the case of a wide cut and cover tunnel with jet fans installed along the side walls, those undesirable effects become significant and have to be carefully considered during the design of the ventilation system. Indeed, in such a configuration, the longitudinal velocity profiles show low velocities in the middle of the cross section downstream of a bank of fans as shown in the following 3D simulation results.

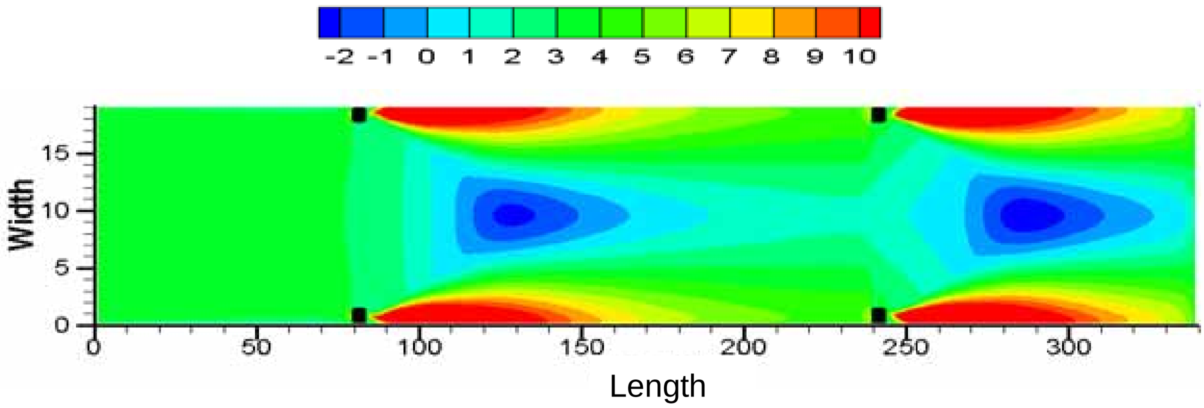

Figure 2: Longitudinal velocity field created by the jet fans

This phenomenon is the result of two main effects:

- The difficulty to transfer the momentum from the jet to the middle of the tunnel.
- The significant airflow absorbed and dragged by the jet fan suction which tends to reduce the velocity in the remaining part of the cross-section.

The consequence is a risk of backlayering even if the ventilation system is designed to keep an average longitudinal velocity above the critical velocity.

2.2. Design methodology

In order to establish the correct ventilation strategy to cope with the issues raised in section 2.1, a specific methodology has been applied to the design process. This design methodology is based on the following steps:

1. Perform CFD modelling in a limited part of the tunnel without any vehicles and without any fire. This is to find the most relevant design solution for the fan arrangement and establish a ventilation control strategy to minimize the effects of low velocity in the middle of the cross-section in the region of fire.
2. Perform 1D calculations using various jet fan configurations and associated ventilation control strategy determined during the first step. These calculations provide an accurate estimate of volume flow rates and average velocities at cross sections for different scenarios (e.g. location of fire, adverse wind pressure, traffic conditions etc.). A comparison with the critical velocity can be made at this stage to check if the ventilation system needs more or less jet fans.
3. Perform a final 3D simulation, this time including vehicles to check that the level of backlayering for the worst ventilated situation calculated by 1D model in the second step is negligible. This calculation is performed by using the volume flow rate calculated by the 1D model for the boundary condition of entry portal.

2.3. Design results

This section presents the results obtained for each step of the design presented in the previous section and applied during the design of the ventilation system for the Hatfield Tunnel Refurbishment project. For this tunnel the longitudinal ventilation system for each bore contains 7 banks of jet fans, 160 m apart. One bank consists of 1 pair of jet fans at each side wall as shown in **Figure 3**. Each jet fan has a thrust capacity of 1000 N.

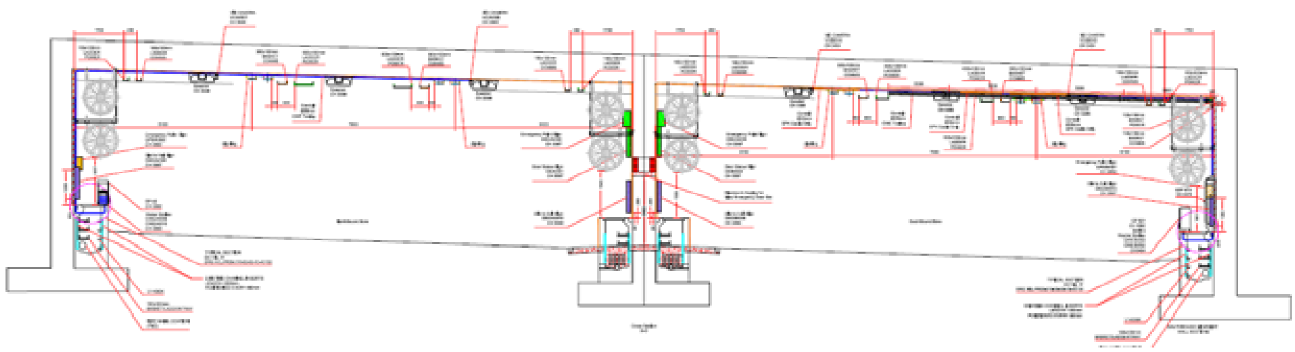

Figure 3: Hatfield Tunnel – Cross Section at a Fan Bank

2.3.1. First step: 3D CFD analysis of flow distribution in the cross-section

It is possible to imagine several solutions to reduce the problem of low velocity in the middle of the tunnel.

One of the solutions is to deflect the jet at the outlet of the fan. This can be done by using Banana jet fans. However, accurate simulations performed by the initial Designer of the Hatfield project showed that it was not sufficient. This solution might be slightly improved by increasing the angle of the Banana, as was proposed, but this was without any guarantee from the fan manufacturer that the flow path would have followed the angle of the fan at the outlet. This was because the jet fan consisted of a silencer of only one diameter length and moreover the distance between the side wall and the dynamic gauge was too short to permit installation of banana fans with a greater silencer length or a banana angle exceeding 10°.

An alternative solution, instead of deviating the air flow by using Banana fans, is to inhibit the nearest banks upstream of the fire. CFD results of this solution are presented on the following figure. These were obtained with Phoenics CFD software [4] with an inlet boundary condition at the entry portal of 3 m/s. These results show that backflow has been eliminated in the region of the fire, as the distance between the fire and the nearest activated upstream bank is at least 160 m. The uniformity of velocity over the cross section is also significantly improved raising the velocity in the middle part of the tunnel cross-section to a level above the required critical velocity.

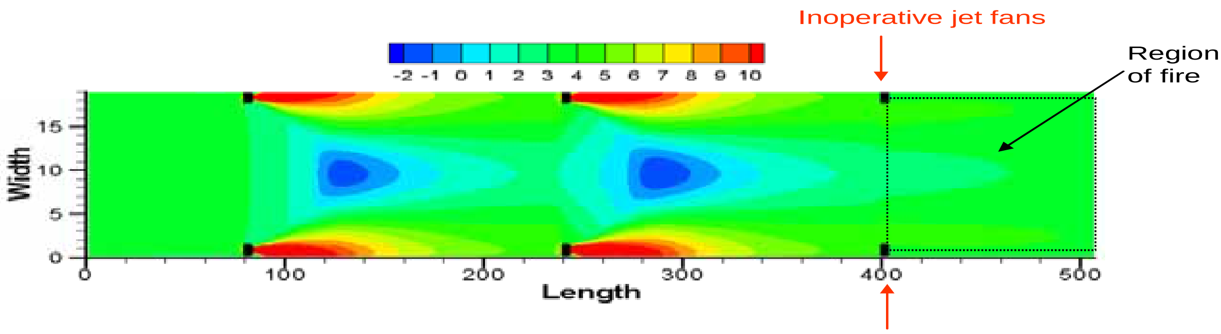

Figure 4: Longitudinal velocity field in the region of the fire - Nearest jet fans bank upstream of the fire shut down

This solution means that the location of the fire has to be detected accurately to inhibit the appropriate jet fans banks upstream of the fire. The refurbished Hatfield tunnel is equipped with a linear heat detection system with an accuracy of 10 m.

2.3.2. Second step: Assessment of the average longitudinal velocity with 1D simulation

For the second step, 1D simulations were performed with Camatt software [5] to check whether the average longitudinal airflow velocity could achieve the required critical velocity with the thrust capacity and the number of jet fans initially proposed. The simulations were performed not only for studying the effect of differing fire sizes and locations on the number of vehicles blocked in the tunnel but also by paying particular attention of the number of fans available. These are reduced due to the fact that the nearest downstream bank can be destroyed by the fire, 10% fans (3 fans) could be initially not available for maintenance reasons and as defined by the proposed ventilation strategy the bank of fans immediately upstream of the fire is inhibited.

The results obtained are summarized in the following figure. They have been obtained with a fan efficiency of 64% evaluated prior 1D simulations with accurate 3D simulations. It is shown that the longitudinal velocity is always higher than the design criterion which was fixed at the critical velocity plus a safety margin of 1 m/s. For the design objectives fixed by the risk analysis, the lowest longitudinal airflow velocities observed by those calculations are the following:

- 50 MW fire with adverse wind pressure of 15 Pa : 3.3 m/s
- 100 MW fire without adverse wind pressure : 3.6 m/s

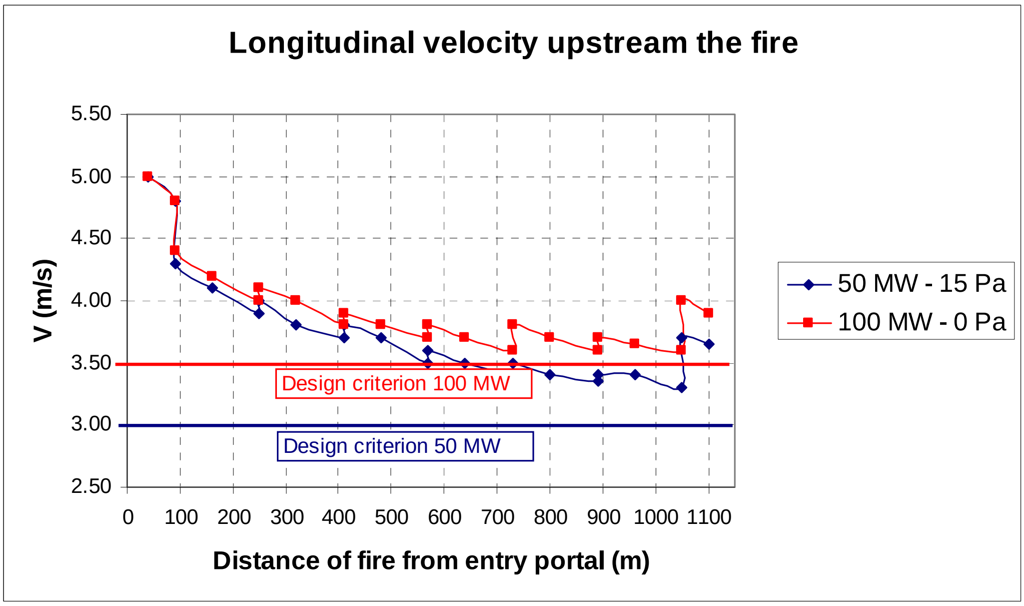

Figure 5: Longitudinal air velocity calculated upstream the fire

2.3.3. Third step: Final 3D CFD design verification

To complete the design and obtain final validation of the proposed strategy prior to installation in Hatfield Tunnel, additional CFD simulations were performed with Phoenics including an HGV fire of 100 MW with vehicles inside the tunnel. The location chosen was not far from the exit portal, this is where the lowest longitudinal average velocity is observed by 1D simulation (3.6 m/s used also as inlet boundary condition for CFD calculation). This situation actually corresponds to the worst case as the flow rate absorbed and dragged by the nearest upstream bank of fans becomes significant when compared with the total longitudinal flow rate. In such a case, the risk of low velocity in the middle of the cross-section is increased.

Figure 6 shows the 50°C isotherm when the fire and the ventilation have reached the steady state. This isotherm never spreads upstream of the fire. This result demonstrates that smoke can be controlled with the proposed ventilation strategy without any significant backlayering that may affect the safety of people in the tunnel.

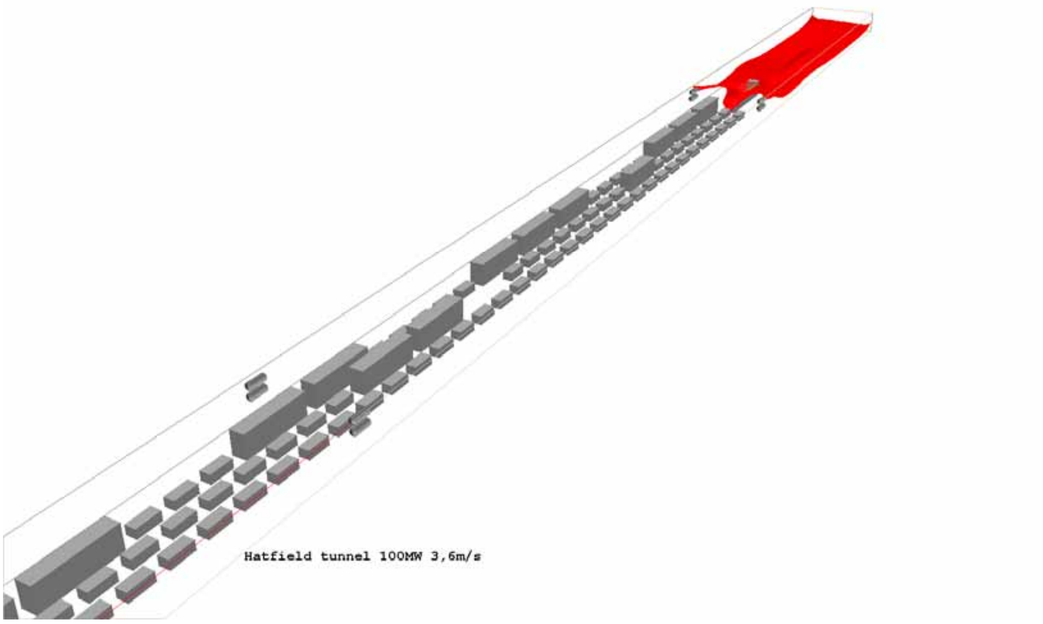

Figure 6: Isotherm of 50°C – 100 MW fire – Average longitudinal velocity = 3.6 m/s

3. TEST VERIFICATION

3.1. Description of the test protocol

After installation of jet fans in Hatfield tunnel and implementation of the ventilation control strategy in the SCADA system, aerodynamic tests were performed during the site acceptance test/commissioning phase of the project.

The tests were undertaken in an empty tunnel. The measurements were performed for the worst longitudinal ventilation flow rate when the average longitudinal velocity is stabilized at about 3.3 m/s corresponding to the lowest velocity that can be obtained in the case of a real fire in the tunnel as calculated at the design stage (i.e. 50 MW fire at 1050 m from entry portal with a tunnel full of vehicles and an adverse pressure of 15 Pa). The fans activated during the test are shown in the following figure.

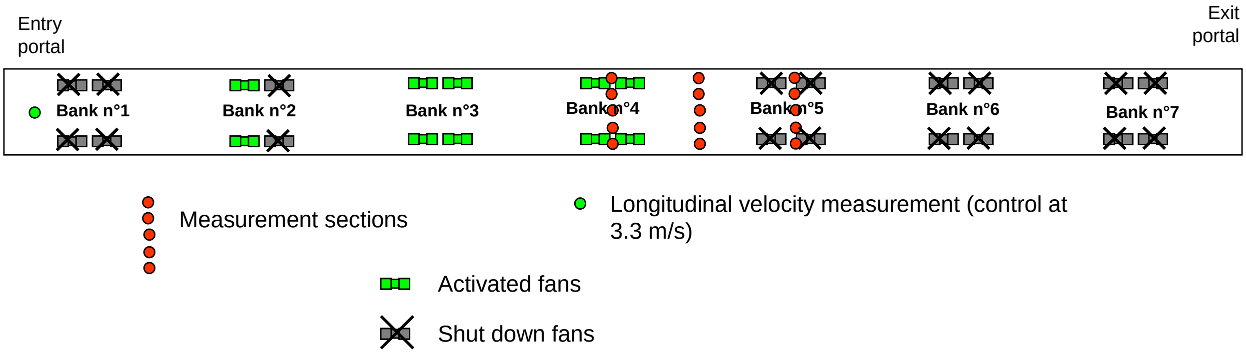

Figure 7: Ventilation rate activated for the measurement of the transverse velocity profiles (emergency mode)

The transverse velocity profile was measured at the following cross-sections:

- Cross-section located at 80 m downstream of an active bank of fans (i.e. midway between bank 4 & 5).
- Cross-section corresponding to the first non active bank downstream an active one (i.e. bank 5).

For each cross section, the measurements have been taken at 1.5 m and 3.5 m above the carriageway and seven measurement points in the transverse direction as shown in **Figure 8** below.

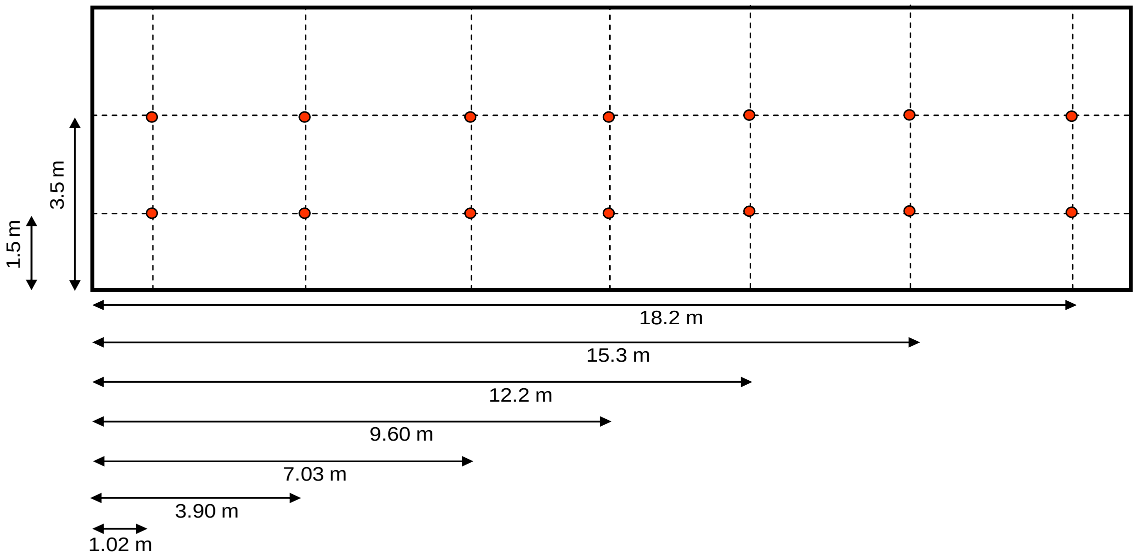

Figure 8: Location of measurement points in the cross section during transverse velocity profile tests

3.2. Test Results and analyses

The following figures represent the longitudinal velocity profiles measured in the two cross sections described above.

The results obtained for the cross section at the non active bank 5 (**Figure 10)** cross sections show that the longitudinal velocity is always higher than the critical velocity of 2m/s for a 50 MW fire. The results also show that the velocity is globally higher than the critical velocity of 2.5 m/s for a 100 MW fire especially at the 3.5 m height which corresponds to the lower smoke layer in the case of a fire. As the measurements show good results at this height, we can finally conclude that backlayering can not occur when the nearest activated bank is at 160 m. At 80 m downstream of the active bank which is midway between bank 4 & 5 (**Figure 9**), the profiles show that the velocity drops below the critical velocity in the middle of the tunnel. This is over a width of about 3 m for a 50 MW fire and 5 m for a 100 MW fire at 3.5 m height. The minimum velocity is 1 m/s (i.e. no backflow).

In conclusion, backlayering can not occur when the fire is located at 160 m downstream of an activated bank.

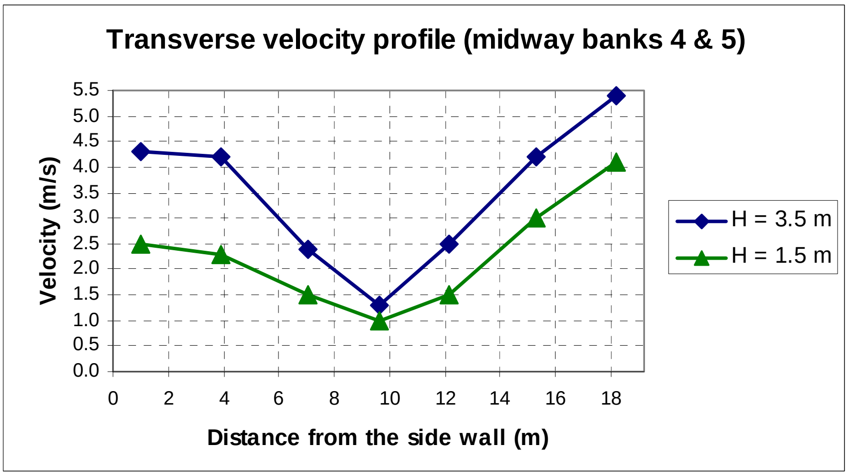

Figure 9 : Transverse velocity profile – Emergency mode (midway bank 4 & 5)

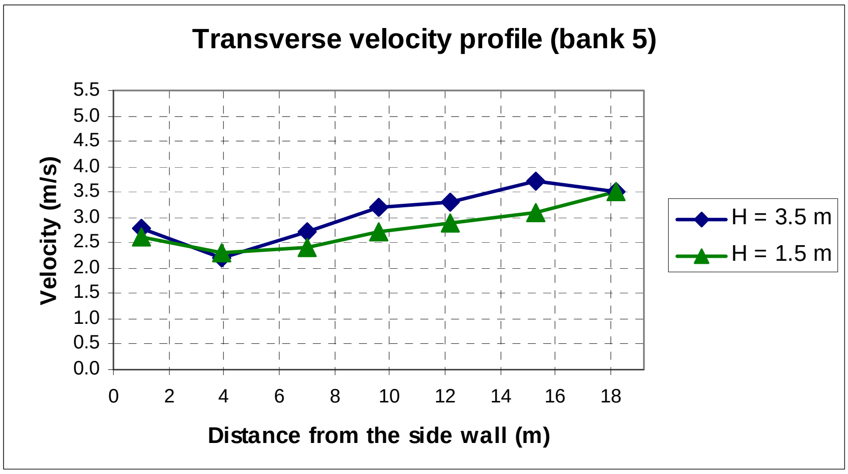

Figure 10: Transverse velocity profile – Emergency mode (bank 5 – non active bank)

4. CONCLUSION

Designing a longitudinal ventilation system in a wide cut and cover tunnel where jet fans can only be installed along the side walls is always a challenge. Indeed, the use of jet fans tends to create in such configuration low velocities in the middle of the cross-section that could lead to significant backlayering when it occurs in the region of fire. The solution that has been proposed by Egis Tunnels and successfully applied in Hatfield Tunnel is to inhibit the nearest bank of fans upstream of the fire. This is facilitated by the use of an accurate linear heat detection system. The design and the test results presented in the paper have shown the benefit of this ventilation strategy to provide a velocity profile which will control smoke propagation.

5. ACKNOWLEDGEMENTS

The authors wish to thank the Highway Agency which has funded the Hatfield tunnel refurbishment project.

The authors would also like to acknowledge Zitron and Deritend companies who provided and installed the fans and measurement equipment for the Site Acceptance Tests.

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CROSSRAIL FIRE SAFETY DESIGNS

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ABSTRACT

The Crossrail project in London, UK, is currently the largest active sub-surface infrastructure project in Europe. It consists of a new heavy rail line spanning London from west to east, and incorporates 22km of new tunnels beneath central London with eight new sub-surface stations. Five of the stations will be mined with individual platforms connected via cross-passages, and three will be cut-and-cover box-type with island platforms. Ultimately the line will run a metro-like service, with a peak service of 24 trains per hour when the system is fully operational. Mott MacDonald has been heavily involved in the project from its inception in the 1990s right through to the current detailed design stage. Construction has now commenced on a number of sites across London.

Mott MacDonald's recent responsibilities in the fire engineering area have included:

- development of the system-wide fire strategy for all of the tunnels;
- fire safety aspects of the proposed open-wide gangway rolling stock for the project, and determination of the design fire size for the tunnel ventilation and platform smoke control systems;
- design of the smoke-control measures for the tunnels and all station platforms and of fire-fighting systems for the tunnels;
- development of the fire strategies and fully-integrated detailed design of the major underground interchange station at Liverpool Street.

This paper will give an overview of the evolving fire safety issues and designs for the Crossrail project, and will highlight several of the challenges faced by the design team.

Keywords: fire strategies, smoke control, tunnel ventilation, design fire size, rolling stock, open-wide gangways, fire safety systems

1. INTRODUCTION

This paper will give an overview of key fire safety designs for the Crossrail project, and highlights several of the more complicated and difficult challenges faced by the design team. The Crossrail project consists of a new heavy rail line spanning London from west to east, and incorporates 22km of new tunnels beneath central London with eight new sub-surface stations, see Figure 1. Mott MacDonald's most recent responsibilities in the fire engineering area have included the system-wide fire strategy for all of the tunnels, the fire strategies for one of the major interchange stations at Liverpool Street, the design of smoke control systems for the tunnel and all station platforms (equipped with full height Platform Screen Doors (PSDs)), the design of fire-fighting systems for the tunnels, the design fire size and fire safety of the proposed Open-Wide Gangway (OWG) rolling stock for the project, and the design of the fire safety systems at Liverpool Street Station.

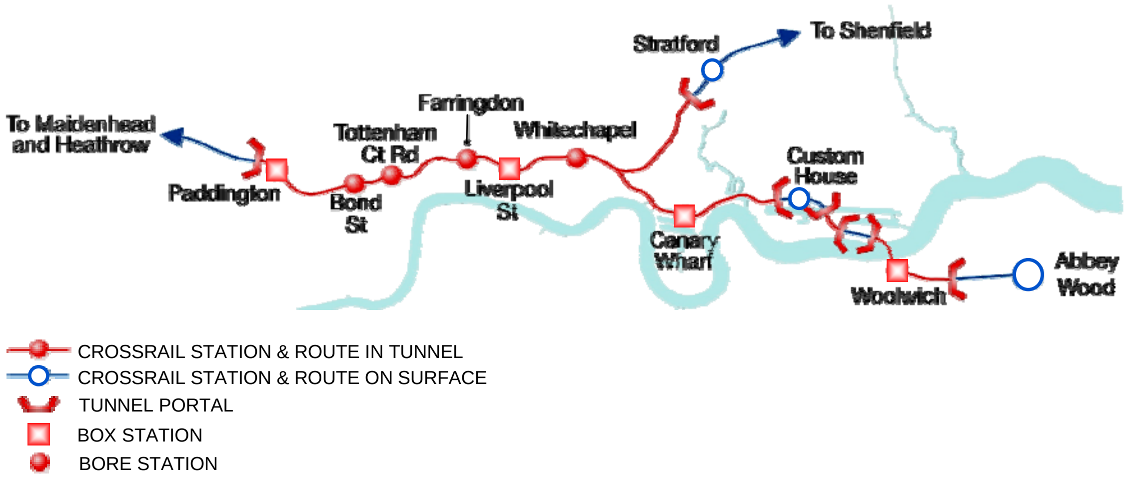

Figure 1: Central area of Crossrail route map through London

2. ROLLING STOCK

Purpose-built rolling stock will operate on the Crossrail network. At present, Crossrail have issued a detailed design brief to manufacturers, with a contract to be awarded in late 2013.

Each train will consist of two five-car sets, with open-wide gangway runs the full length of the ten-car train. In terms of fire safety, the rolling stock design must demonstrate compliance with the *Code of Practice for Fire Precautions in the Design and Construction of Passenger Trains*, BS 6853. All materials used in the rolling stock design must be suitable for use within a Category 1a environment.

However, BS 6853 explicitly excludes trains whose interiors “take the form of a single extended compartment”. Even if the rolling stock design adheres to BS 6853 in terms of materials selection, the inclusion of open-wide gangways means that the rolling stock must be “subject of specific hazard analysis” to gain full compliance.

Hence, to demonstrate that the Crossrail open-wide gangway rolling stock will be able to achieve a similar level of fire safety to a conventional BS 6853-compliant design, it was necessary to conduct investigations of how a reference design of the rolling stock would perform in event of an onboard fire. In lieu of a full train with which to conduct fire tests, the most appropriate method was to carry out three-dimensional simulations using computational fluid dynamics (CFD) techniques.

Mott MacDonald modelled the spread of fire within the train to establish the likely maximum fire size resulting from realistic baggage fires. Simulations of how heat, smoke and Carbon Monoxide propagate throughout the train were also carried out to evaluate tenability on board, in the time between fire ignition and the arrival of the train at a suitable location for passenger detrainment. Mott MacDonald also carried out simulations of evacuation from the rolling stock to estimate detrainment times.

A reference design for the rolling stock was considered in these studies. Each carriage is 20m long and has three sets of double passenger doors, with the exception of the driving vehicles, which have only two. The passenger saloons contain seats, draught screens, overhead luggage racks and passenger information displays. The geometry and layout of these items has been considered in these studies (Figure 2), since their presence will influence the propagation of fire during a fire incident.

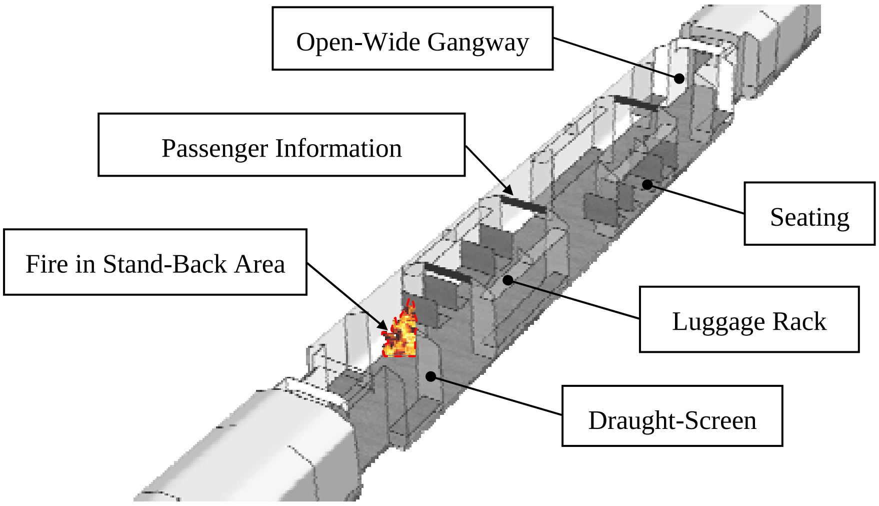

Figure 2: CFD model of a reference Crossrail carriage

2.1. Smoke Spread within Rolling Stock with Open-Wide Gangways

CFD techniques were used to predict the propagation of smoke within a reference design of the Crossrail rolling stock for an onboard fire. The results of this simulation were analysed by reference to suitable tenability conditions, based on the temperatures, visibility levels and carbon monoxide concentrations experienced by passengers, prior to evacuation starting. By this method, the life safety performance of the proposed rolling stock during such a fire incident was assessed.

The realistic size for an in-cabin fire was debated extensively over the life of the project. Ultimately, the considered fuel source consisted of two luggage cases, complying with airline carry on hand luggage constraints, filled with clothing items that would typically be carried by the public. The combined weight of the two luggage items was 16 kg. A furniture calorimeter was used to measure the heat release rate, which reached a peak value of 284 kW at approximately 6 minutes (Figure 3). While the test case burned for a total of 30 minutes, the simulation time in this study only considered the first 5 minutes after ignition due to the maximum journey time between stations. It is assumed that the fire starts immediately after the train leaves the station and that the train proceeds to the next available station, where evacuation of the train would occur.

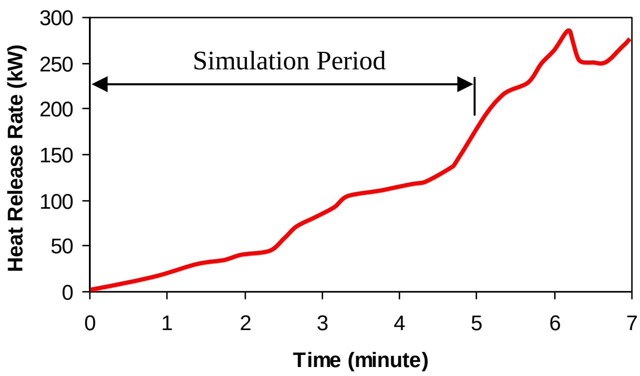

Figure 3: Fire HHR curves from baggage fire test

Transient simulations of the resulting smoke propagation inside the rolling stock were carried out using the multipurpose CFD software ANSYS CFX. The fire was represented as a source of heat and smoke. Smoke is dispersed within the train by the buoyancy driven flow. The simulations calculate the relative smoke concentration, air temperatures, airflow velocities and all other relevant flow variables throughout the modelled domain and at discrete moments in time, thereby providing the basis of the assessment. Figure 4 shows the envelope (iso-surface) of 4m local visibility distance within carriages, for a 284 kW fire. Here, the 4m distance was chosen because in the Crossrail rolling stock design the passenger is never further than 4m from train doors.

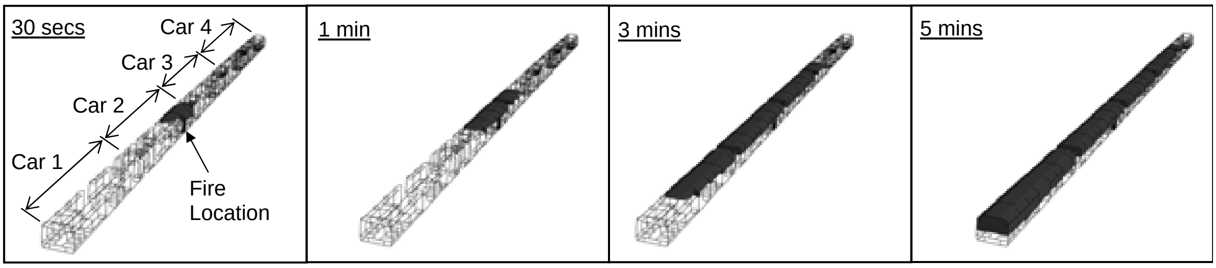

Figure 4: 3-D iso-surface of local-visibility (dark regions indicate visibility less than 4m)

The internal design features of the train (bulkheads, passenger information displays, etc) have some effect as barriers to the longitudinal dispersal of the smoke layer and thus delay the spread of smoke to adjacent cars.

2.2. Fire Spread within Rolling Stock with Open-Wide Gangways

To date, the design of stations, tunnels and smoke control systems have been based upon the assumption that a fire event on a train will lead to the involvement of no more than a single train carriage. Under the assumption that all the materials in one carriage are involved in the fire, a fire size of 8.8 MW is derived. However, due to the provision of open-wide gangways in the rolling stock, a specific fire hazard analysis is required to show that this assumption is conservative, and to gain compliance with BS 6853. To this end, a study was undertaken to quantify the potential fire spread within a reference rolling stock design resulting from an onboard baggage fire.

Fire Dynamics Simulator (FDS) Version 5 was used to carry out computational simulations of fire spread. This tool uses a CFD model to simulate the gas-phase fluid mechanics, combustion and heat transfer, coupled with a solid phase fuel generation model, which describes the thermal decomposition and pyrolysis of the combustible materials. Whilst such an approach is currently the most promising method for modelling flame spread at building scales, validation of the employed methodology against a relevant experimental data set is essential in validating the methodology, particularly with regards to mesh resolution and the methods of material property estimation. Validation was made against the research carried out by Kivimäki and Vaari (2010), which includes free-burn fire tests carried out on a metro carriage set up using well defined materials.

Characterisation of the solid-phase material properties is one of the most challenging aspects of fire spread modelling. In this study, the properties of combustible materials were estimated by a process of calibration against bench-scale cone calorimeter test results. To do so, an FDS model of the cone calorimeter apparatus was created, and the material properties were iterated until close replication of the calorimeter test results were observed. Specific attention was given to the replication of ignition time, peak heat release rate and the total energy released from the sample. Two or three phases of burning were defined for each material considered, in order to achieve close agreement with the test results.

An inventory of materials which are likely to feature in the interior of a Crossrail passenger carriage was compiled specifying typical calorific values for each material, and allowing the relative contribution of each element to the total fire load to be assessed. Such analysis shows that seating and floor materials constitute the most significant portion of the total fire load, with gangway bellows material also representing a significant contribution. Other elements and surfaces are typically constructed from glass or aluminium with a fire resistant powder or paint coating, and so represent a significantly smaller contribution. It is also noted that wall and ceiling materials of typical rolling stock require significantly higher heat fluxes for ignition, as reported by Chiam (2005). These elements have consequently been neglected in the fire spread analysis.

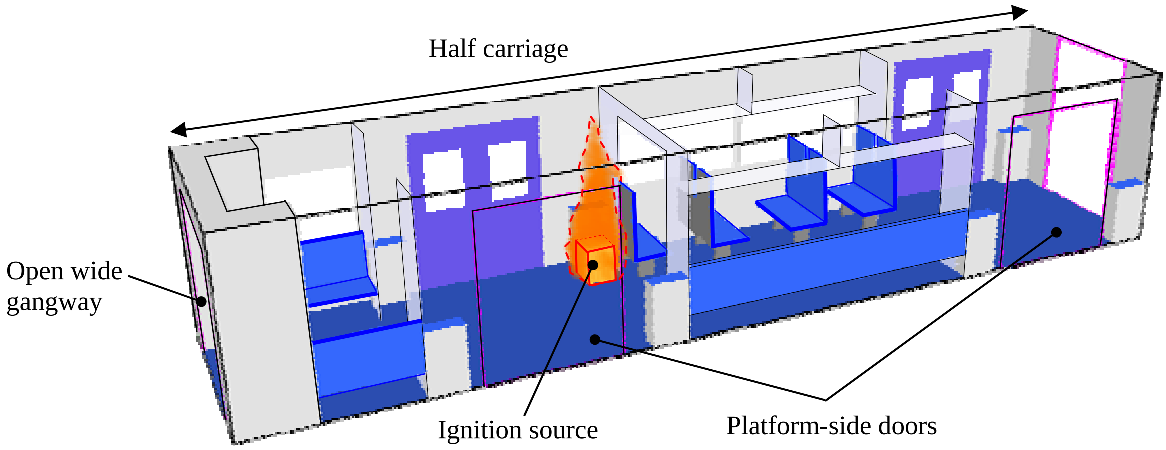

Figure 5: FDS model of Crossrail half-carriage

Simulations of the fire spread within the reference carriage were carried out using the validated modelling approach and the calibrated material properties. An ignition source was located in the stand-back area of the rolling stock, with a peak HRR value of 0.5 MW, representing a baggage fire involving approximately four suitcases. The growth rate of the ignition source was scaled from the heat release data in Figure 3.

The results show the gradual ignition and involvement of nearby seating and floor material in the fire. At the fire's peak, the carriage materials contribute an additional 20% to the heat released from the ignition source. However, the fire is not self-sustaining and extinguishes as the ignition source is exhausted. This confirms that the use of flame retardant, BS6853 Cat1a compliant materials suitably avoids flashover within the cabin and prevents the uncontrolled spread of fire to adjacent carriages.

Tests and studies conducted by Kim *et al.* (2008) in the wake of the Daegu incident corroborate this research supporting the assumption that fires do not cause ignition of train materials when compliant to BS6853. Four litres of paint thinner was used as an ignition source, and test results showed that although the surfaces covered with thinner were locally scorched, the fire did not ignite the car materials and so did not spread beyond the initial fuel source.

3. TUNNELS - FIRE STRATEGY

The central section of Crossrail will provide 21 km of new tunnels, plus a major refurbishment of a 550m existing disused tunnel. The tunnels provide distinct challenges in terms of ensuring fire safety. The main section of twin bore single track tunnels includes a Y-junction at Stepney Green. A separate section of tunnel takes the route underneath the Thames, and the third section of existing tunnel will be completely refurbished for use by Crossrail. The fire strategy was developed to minimise the risks from fire to both life safety and asset protection, and also to minimise the impacts on operational continuity. Stakeholder approval was required for all the tunnel fire strategies, achieved via usage of the BS7974 process. The major stakeholders in the project include Crossrail Limited (Project & Train

Operator), London Underground (Station Infrastructure Manager), Network Rail (Railway Infrastructure Manager), Rail for London (Station Infrastructure Manager), and London Fire Brigade (Fire & Rescue Service), plus other site-specific stakeholders. The primary aim of the tunnels fire strategy will be to extract and control the movement of smoke in the event of fire, and to provide safe evacuation routes for passengers (including Persons of Restricted Mobility) and safe intervention routes for the fire services. Means for fire fighting will be provided along the tunnels. Evacuation routes will use both the incident tunnel and the non-incident tunnel (in the longer inter-station tunnel sections, using cross-passages).

4. TUNNELS - DESIGN

For evacuation and intervention purposes the tunnels include a side walkway along the full length of the tunnels. Tunnel ventilation shafts will be located at each end of each station, containing either two or three reversible axial fans. The tunnel ventilation system will provide longitudinal forced ventilation for the control and extract of smoke from a fire in the tunnels, to maintain tenable conditions in the non-incident tunnel, and to control and extract smoke in the event of fire on a train at a station platform. The presence of full height platform screen doors at the stations requires careful consideration of the interaction between tunnel and station ventilation systems, combined analysis of the tunnel and platform spaces, and the coordinated operation of these systems in the event of an incident.

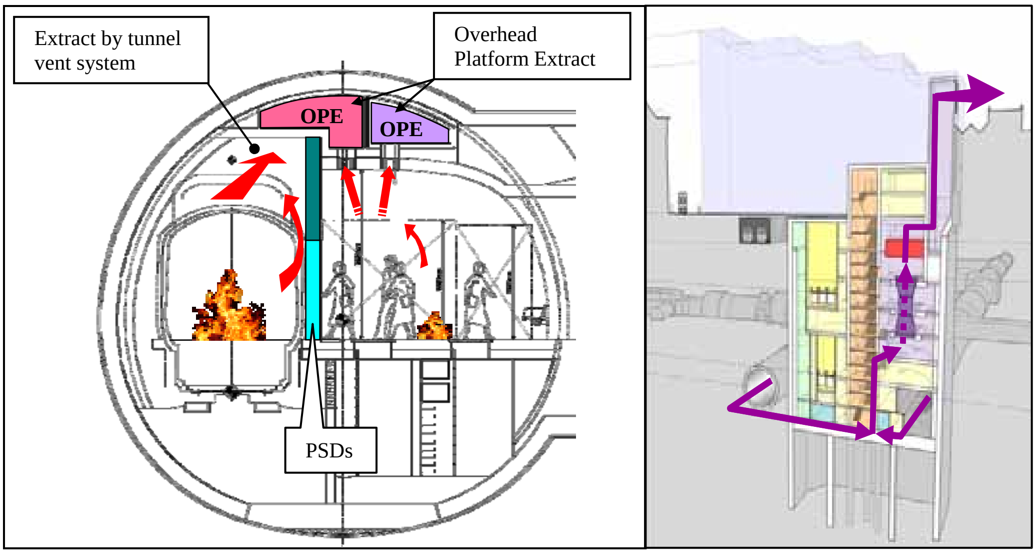

Figure 6: Tunnel smoke extract system for sub-surface station

The tunnel fire-fighting systems for such a large tunnel system are complex, due to the length of the tunnels and the vertical alignment. A large number of various types of tunnels already exist underneath London, and the geology further complicates the tunnel alignment requirements. Furthermore, energy usage optimisation requirements for the rolling stock add more constraints upon the vertical alignment. The consequences are that the Crossrail tunnel vertical alignment has significant gradients, both upwards and downwards. There is a supply main located at each surface access point (one at each end of a station, plus at every intermediate shaft and portal), and independent supplies for each bore. The detailed design of the system was required to maintain flowrate and supply pressure to fire service requirements at all locations within this complex system with over 44 km of fire mains in total.

5. STATIONS - FIRE STRATEGY

Liverpool Street station is a main interchange for the Crossrail project. It links with two London Underground metro stations as well as the heavy-rail Liverpool Street main line terminus. Accordingly, there were numerous challenges in integrating the Crossrail station operations and fire safety provisions with those of the existing infrastructure, without compromising the safety cases for the existing stations. The fire strategy was developed to minimise the risks from fire to both life safety and asset protection, and also to minimise the impacts on operational continuity both during the construction stage and the completed stage. As part of the fire strategies, risk assessments were undertaken to determine the requirements for fire suppression systems in the station. Stakeholder Approval was required for each fire strategy, and was achieved via usage of the BS7974 process.

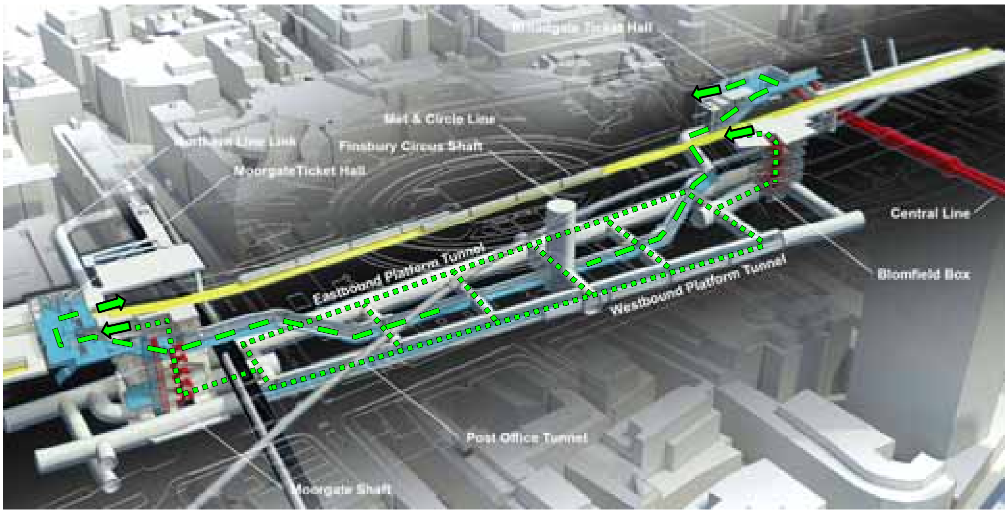

Figure 7: An example of emergency evacuation routes for Crossrail's Liverpool Street station

6. STATIONS - DESIGN

The fire safety measures for the station include means of controlling smoke and allowing persons, including Persons of Restricted Mobility, to evacuate safely from the station, intervention routes for the fire services, fire & smoke detection and alarms, fire suppression systems where deemed necessary, fixed fire-fighting systems, including provisions for the fire services to attend and use the systems, and passive fire protection via compartmentation and materials.

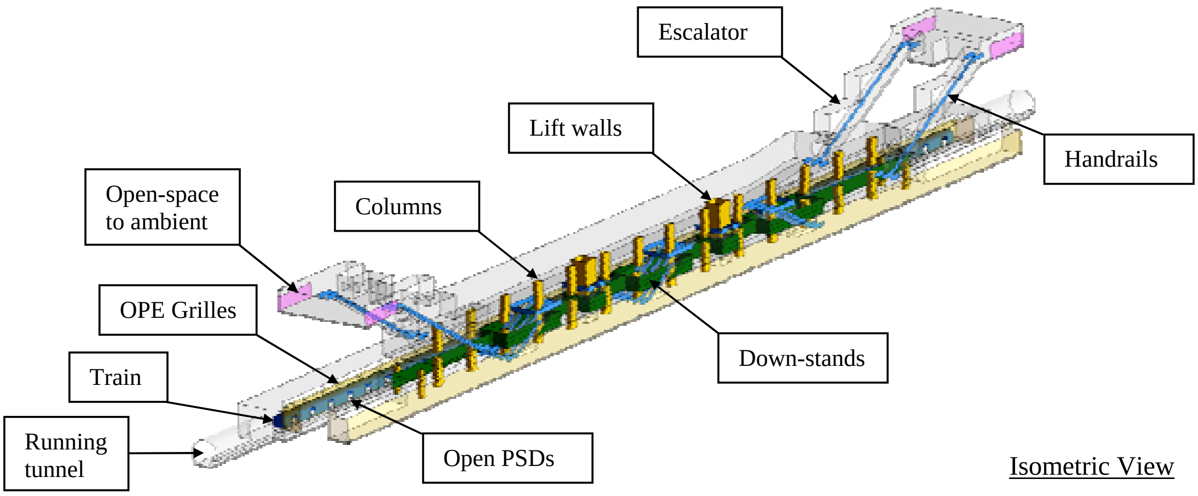

Figure 8: Geometry for sub-surface box station

Mott MacDonald has performed CFD simulations for predicting the time varying behaviour of hot smoke from fire at sub-surface station. The results from the simulations are used to determine the minimum extract flow rate required from the platform smoke extract system, and the down-stand depth required for containing smoke.

Figure 8 shows an example of Crossrail sub-surface station (box-type) with full height platform screen doors. The model includes the whole of the public areas of the station (i.e. promenade concourse, ticket hall, and platform level), as well as the trackside and a short length of running tunnel at both ends of the station, for the incident side. The main portion of down-stand (with a clearance above floor level) runs along the station centreline, separating the eastbound and westbound platforms. The down-stand also surrounds the openings through which each escalator rises, to prevent smoke flowing upwards to the ticket hall.

Figure 9 shows the visibility contours at 2.5m height from platform level, for a 1.1 MW fire.

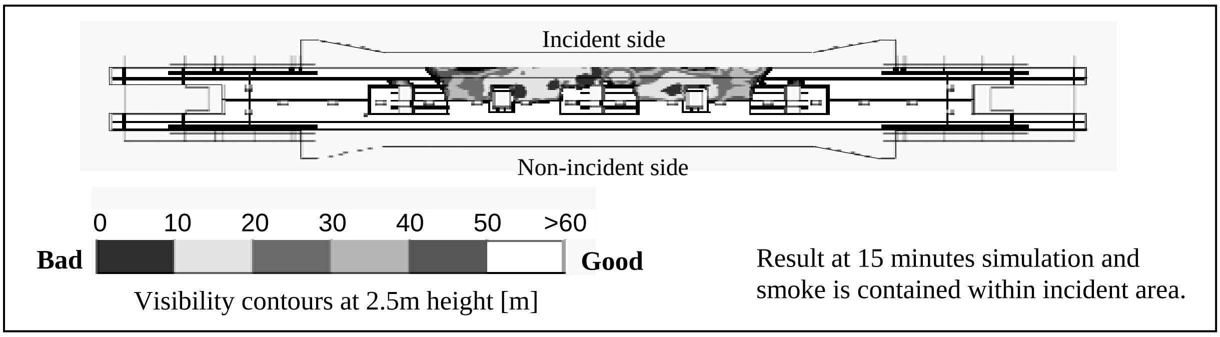

Figure 9: Visibility contours at head-height level for platform fire incident

The results from this study have been used in the planning of the public evacuation and fire intervention procedures in the sub-surface stations.

7. FUTURE PLANS

The project has recently completed the technical designs and specifications. Enabling works have commenced and the next major stage will be preparation of production information in sufficient detail and beyond, and selection of contractors to design-and-build contracts. Project completion is scheduled for 2018.

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USAGE PATTERN OF JET FANS FOR VENTILATION OF RAILWAY TUNNELS

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ABSTRACT
It is noted that if construction of shafts to secure air injection and air removal from tunnels is either impossible or commercially inexpedient, one of the most efficient options is the longitudinal ventilation pattern with jet fans.
Alternates of jet fan distribution in railway tunnels are suggested for both electric and diesel locomotives.
Examples are provided on identification of jet fan parameters and assessment of their efficiency in maintaining the required thermal and humidity conditions in the Lysogorsky tunnel, in decreasing the amount of natural draft in the Baikalsky tunnel and in removal of diesel combustion gases from the traffic section during operation of the Kuznetsovsky tunnel.

Keywords: railway tunnels, ventilation design, longitudinal ventilation, jet fans, diesel – mechanical propulsion, natural draft.

1. INTRODUCTION

The issue of forced ventilation of railway tunnels for electric propulsion engines has been repeatedly discussed in various publications. As a consequence of this it is generally believed that in nominal situations and in the absence of specific requirements for thermodynamic parameters of the air, forced ventilation is required only in cases where the tunnel length exceeds 20 km. Numerous experiments and theoretical studies have demonstrated that railway tunnels of a shorter length will be ventilated due to natural forces and the piston-like action of the trains.

Requirements that determine application of forced ventilation in tunnels in nominal situations can include the need to maintain pre-selected thermal and humidity conditions, normalization of radiation environment in the underground working spaces (Gendler, 2008), minimizing of the ice coating formation (Gendler, 1997), reduction of the amount of air entering the tunnel to minimize power consumption for its heating (Gendler et al. 2011).

The most critical issue is the design of emergency ventilation that in case of a fire must secure save evacuation of people and create favorable fire fighting conditions.

If construction of shafts to secure air injection and air removal from the traffic section of the tunnels is either impossible or commercially inexpedient, the most efficient option that would both meet all the specific requirements for operation in nominal situations and emergency ventilation modes is the longitudinal ventilation with jet fans.

In railway tunnels where diesel–mechanical propulsion are used the permanent ventilation system is to secure cleaning of the traffic section from toxic gasses exhausted by the moving locomotives in the time window between the trains. Applicability of the longitudinal ventilation with jet fans in such conditions is controlled by the length of the tunnel, its cross-section, the impact of natural forces resulting from the meteorological parameters of the atmospheric air at the tunnel portals, as well as the required throughput capacity of the tunnel, the allowed travel speed of the rolling equipment, its length and the type of carriages (locomotive carriages, high-sided wagons, flat wagons, tank-wagons, etc.).

2. ALTERNATES OF JET FAN LOCATION IN RAIWAY TUNNELS

As opposed to highway tunnels, the location of the jet fans at the roofing in the railway tunnels is impeded by the smaller cross-sectional area of the tunnel (34 – 55 m^2) as well as the presence of the overhead trolley line in case of electrically driven engines. Thereby, only jet fans with the diameter below 900 mm can be located directly in the tunnel.

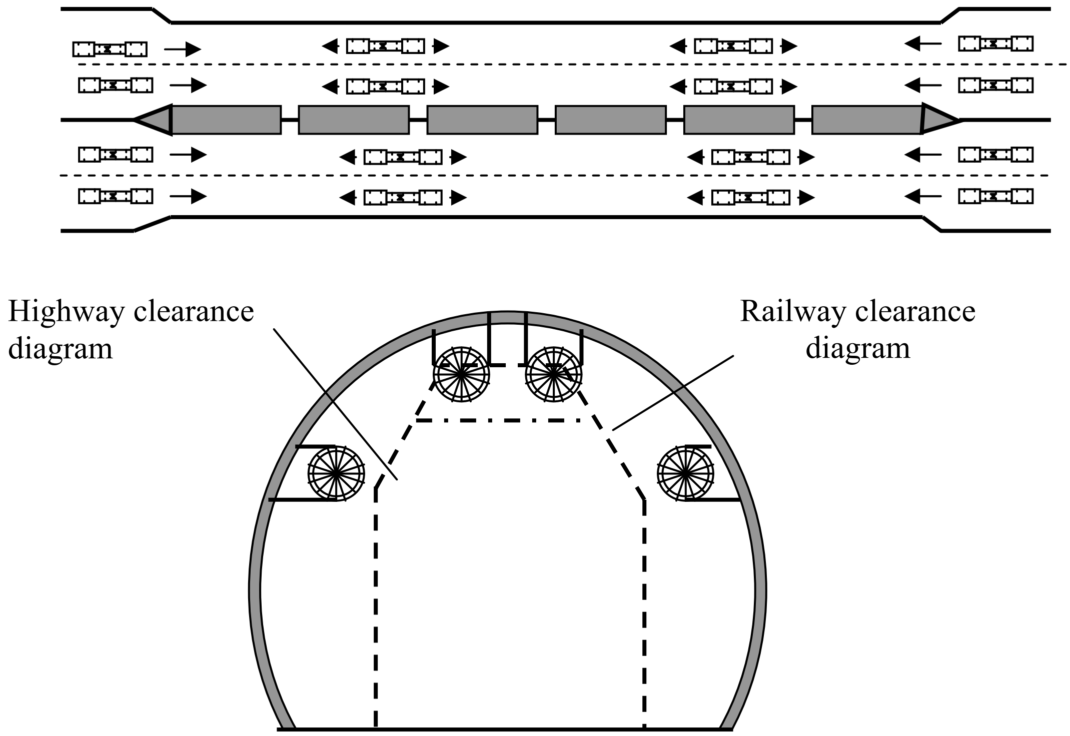

Figure 1: Options of jet fans arrangement in railway tunnels

In railway tunnels where electric propulsion engines are used the safety design margin limits the number of fans that can be installed in the section down to two fans fixed to the tunnel side walls only (**Figure 1**). In railway tunnels that use diesel engines the safety design margin allows installation of up to four fans both at the roofing and on the side walls.

The limited capacity of the traffic sections of the tunnels to locate the required number of jet fans needed to maintain the specified ventilation modes has resulted in attempts to find other design solutions. The options with the jet fan location in niches available or constructed in the side walls of the tunnel (**Figure 2**), in the splayed parts of the tunnel or in special galleries located at the tunnel portals (**Figures 3 and 4**) have been selected as the most rational ones.

In all cases, the choice of jet fan position depends on the engineering possibility to construct either a gallery of the required design at the tunnel portal or a niche inside the tunnel and is eventually controlled by the construction costs.

Dimensions of the niches and the galleries depend on the standard size of the jet fans and should secure the maximum efficiency of their operation. Correlations between the jet fan sizes and the niche dimensions that would ensure the minimal loss of pulse developed by the fans are shown in Figure 1. Moreover, these fans should be installed so as to ensure air injection in opposite directions, i.e. they should be reversible.

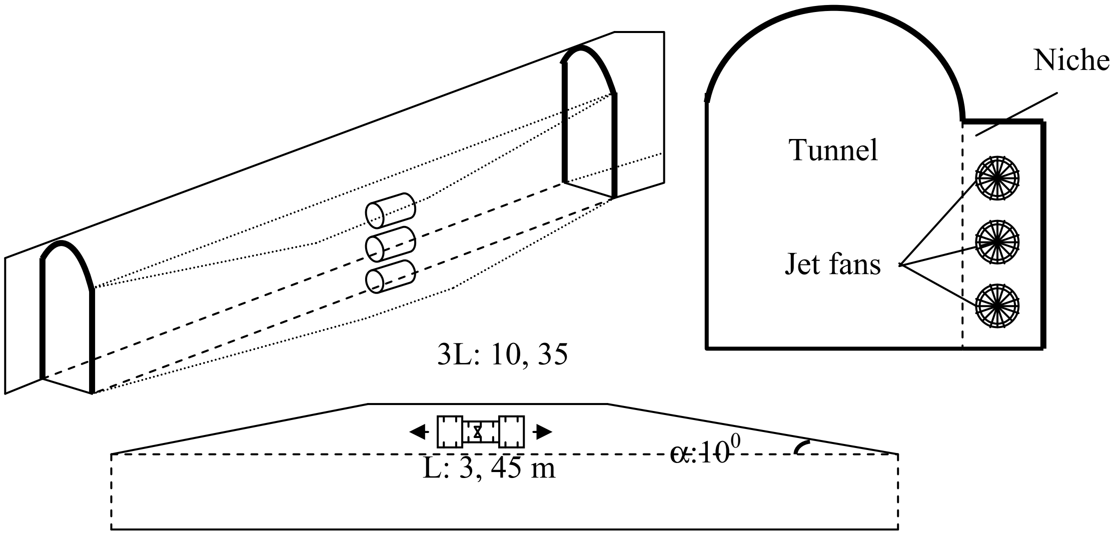

Figure 2: Positions of the jet fans inside the tunnel

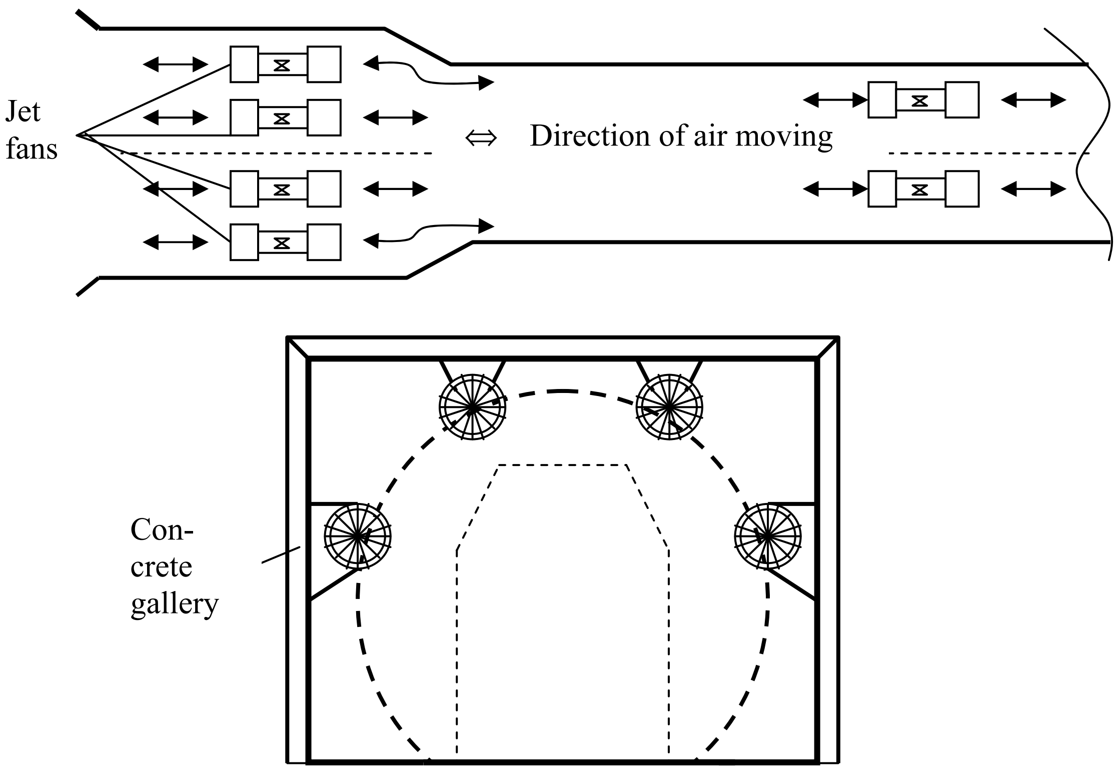

Figure 3: Arrangement of jet fans in the gallery and the tunnel inside the Kuznetsovsky railway tunnel

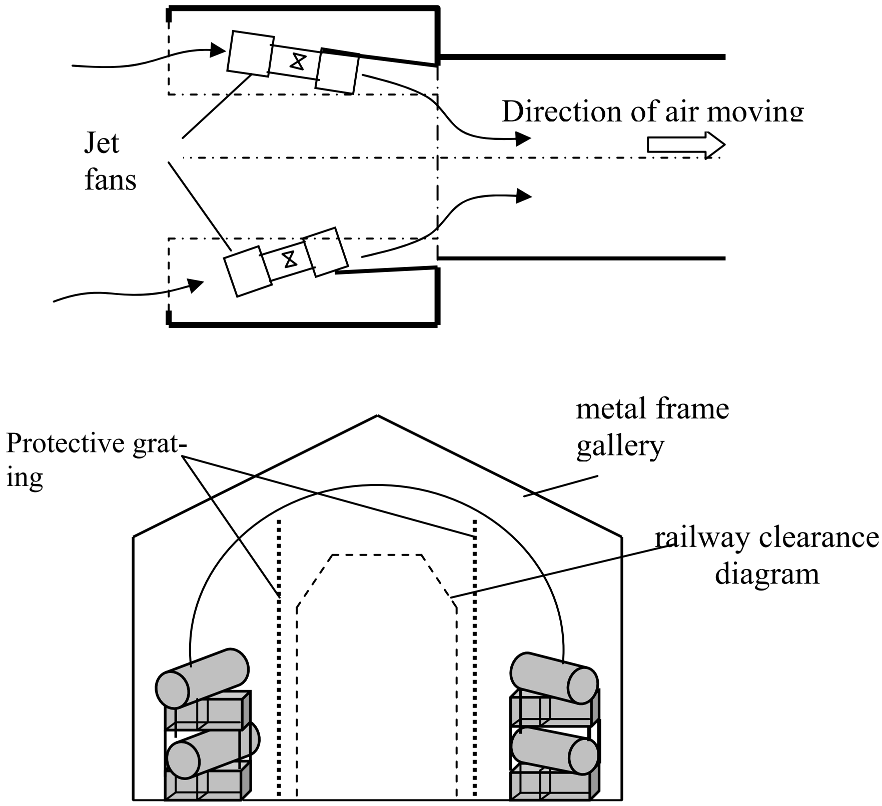

Figure 4: Arrangement jet fans in gallery in the Lysogorsky railway tunnel

3. SELECTION OF JET FAN PARAMETERS FOR VENTILATION OF KUZNETSOVSKY RAILWAY TUNNEL

Construction of the Kuznetsovsky railway tunnel that crosses the Sikhote Alin Rangy is one of the stages to bypass the Kuznetsovsky Passover. The Kuznetsovsky Tunnel is 3890-meter long and the corresponding elevations of the Western and the Eastern portals are 594 m and 558 m. The cross sectional area of the tunnel is 50 m^2. A side drift was constructed along the tunnel with the cross sectional area of 10.3 m^2 which is connected to the tunnel with cross passages spaced every 300 m.

A peculiar feature of this railway section including the tunnel is its diesel operation. Passing the tunnel the diesel locomotives will discharge a significant amount of hazardous substances which can disrupt the normal operation conditions in the tunnel.

The content of pollutants in the tunnel air is dependent not only on their discharge intensity, but also on the amounts of air displaced by the piston effect of the trains, entering the tunnel due to natural draft and injected by the forced ventilation equipment. Therefore, the forced ventilation and the fan capacity should be designed with account of the natural and operational factors.

A forecast assessment of the impact of natural factors on the amount of air in the tunnel was made using atmospheric data typical of the tunnel location area. The most distinctive periods were selected for each season, which were characterized with various time-related and spatial distributions of thermodynamic parameters of the atmospheric air.

Calculations of the natural draft and the amount of air that can enter the tunnel due to this draft were made using these data and methodology described in paper (Gendler et. al. 2003) Analysis of the design data has shown that natural draft can move the air in the tunnel both in eastern and western directions. The air flow rate in the tunnel can reach 200 m^3/s.

The amount of air displaced in the tunnel due to the piston effect of the rolling equipment was calculated using the methodology described in paper (Gendler, 1997) taking into account the scheduled speed of the trains that stands at 33 km/h and 45 km/h in the western and eastern directions respectively.

Calculations have shown that with the above speeds the pressure drop due to the train movement will not exceed 200 Pa. The air flow rate with concurrent direction of the natural draft and the rolling equipment in the tunnel will stand at 306 m^3/s. With conflicting movement of the natural air flow and the equipment the piston-like effect and the natural draft might counterbalance each other. In this case, the air flow rate in the tunnel will tend to zero and the hazardous substances will be distributed along the whole length of the tunnel exceeding the maximum admissible concentrations.

The task of ventilation is to clear the air from the end products of fuel combustion before the next train enters the tunnel, i.e. ventilation schemes should be designed on compensatory principles.

In order to completely remove contaminants from the tunnel it is necessary to inject the amount of air that equals the total volume of the tunnel, i.e. $\Sigma Q = V_T = L \cdot S$ ($V_T = 50 \times 3890 = 194\,500$ m^3) during the time window between two concurrent trains.

With the admissible air flow rate of 6 m/s in the traffic section of the tunnel, the maximal amount of air that can be delivered in the tunnel with the longitudinal ventilation is limited to 300 m^3/s. In this case, complete removal of contaminating agents will take 10.8 min with the pressure drop of 420 Pa created by the jet fans.

Considering these time constraints, the peak traffic intensity which will allow utilization of the longitudinal ventilation in this tunnel is 40 pair's trains per day.

Due to the fact that in the future the Kuznetsovsky tunnel is planned to be converted into electric operation, it was decided to locate the1600-mm jet fans, which are characterized with the maximum jet pulse, in galleries at the tunnel portals as well as to place additional 900-mm jet fans inside the tunnel in order to create the pressure drop that would secure the required air flow rate (see Figure 3). The total number of the 1600-mm jet fans will be eight (four per each gallery), while the number of the 900-mm jet fans will stand at 16. As the natural draft can change its direction, all the jet fans must be reversible.

4. SELECTION OF VENTILATION PATTERN FOR LYSOGORSKY TUNNEL TO ENHANCE ITS OPERATIONAL SAFETY

The Lysogorsky railway tunnel, which major overhaul is planned in the nearest future, is located on the Tuapse-Krasnodar railway line between the Chilipsy and Chinary stations. The tunnel length is 3020 m with the cross sectional area of 44.5m^2. The tunnel passes through one of the offsets of Mt. Lysaya. The offset elevation is 530 m, while the elevation of Mt. Lysaya is 976 m. The respective elevations of the Southern and Northern Portals are 267.03 m and 283.94 m.

The Lysogorky tunnel is characterized with bio-corrosion of engineering structures that lead to destruction of the concrete lining and malfunction of the signaling and communication systems, which impairs the safety of railway traffic.

It was established that the main appearance cause of bio-corrosion is possibly the intense mass-exchange processes taking place during air movement in the tunnel and result in humidity levels rising up to 96-100% as well as to moisture condensation on the surfaces of the tunnel lining. The possibility to prevent the development of these processes lies in maintaining such thermodynamic parameters of the tunnel air masses that would suppress or minimize the mass-exchange processes between the air and the tunnel lining. This can be achieved through a controlled ventilation regime. The air flow rates in the tunnel and its delivery pattern should be selected with account of the intensity of the mass-exchange processes in different seasons and day periods, the influence of the natural draft and the piston-like action of the trains. The key condition in keeping the mass-exchange processes down to the safe level is to maintain the relative air humidity below 90%.

Results of field observations and subsequent calculations helped to establish the annual patterns in natural draft dynamics and the amount of air entering the tunnel. The calculation results demonstrated that in the majority of cases the natural draft will be oriented from the Northern towards the Southern Portals. The air flow rates in winter periods can reach 100-120 m^3/s. During the winter and transition periods the air flow rates decrease down to 40-60 m^3/s. At the same time, as the thermodynamic parameters of the air at the tunnel portals are changing not only due to seasonal changes, but also depending on the time of day, the air flow rate in the tunnel will be changing accordingly and can be falling down to 10-40 m^3/s.

Minimum acceptable air consumption in the tunnel (Q, m^3/s), guaranteeing not excess of relative humidity of air of 90 %, has been calculated for each month under condition of air motion to the Southern portal and the certain initial relative of air humidity at Northern portal (φ_0). For calculation the mathematical model described in paper (Gendler, 1997) has been used. The calculation results are presented in the table below. The data shown in the table proves that in order to maintain the thermal and humidity conditions which can prevent or minimize bio-corrosion it would be necessary to secure the incoming air flow rates of 80-100 m^3/s.

The most rational way to achieve this is to utilize the natural draft, which during most of the operational time is oriented from the Northern towards the Southern Portals, as well as to introduce the forced mechanical ventilation that will be activated when the air flow rate due to the natural draft falls below 60 m^3/s or change its direction.

Table 1: Finite values of relative air humidity, %

month / φ_0 / Q	1 84	2 79	3 75	4 76	5 77	6 76	7 74	8 74	9 80	10 83	11 86	12 81
40	97	95	93	93	94	95	94	92	93	94	93	96
60	95	94	91	91	91	93	92	89	90	91	90	94
80	92	89	87	86	87	89	87	86	88	90	87	90
100	88	86	84	83	85	86	85	83	86	87	86	87

Parameters of the jet fans that we propose to install at the Northern Portal of the tunnel (see Figure 4) were selected to ensure the air delivery flow rates of 80-100 m^3/s in the tunnel in the absence of natural draft or its direction from the Southern towards the Northern Portals. Our assessment proves that to achieve that it will be sufficient to use four 900-mm jet fans with the total rated pulse not exceeding 2,800 N.

5. ASSESSMENT OF EFFICIENCY OF NATURAL AIR FLOW CONTROL IN BAIKALSKY TUNNEL WITH JET FANS

The Baikalsky tunnel crosses the ridge of the same name under the saddle of the Davan mountain pass at the border of Buryatia and the Irkutsk Region 80 km to the West from the city of Nizhneangarsk. The peak elevation of the ridge reaches 1080 m. The Baikal tunnel is 6700 m in length with the cross sectional area of 34 m^2 and the difference in portal elevation of 84 m. The tunnel was designed for unit-directional reverse movement of trains.

Positive temperatures have to be maintained in the Baikalsky tunnel to prevent ice formation. To achieve this outside air is heated in winter time with fan heaters installed in ventilation structures at the tunnel portals (Gendler, 1997). In order to decrease the required power capacity of the fan heaters it is required to maximally decrease the amount of air coming into the tunnel due to the natural draft. In order to decrease the amount of the outside air entering the tunnel due to the natural draft it was suggested to use jet fans.

Assessment of application efficiency of the jet fans was done for three reversible jet fans of located in a niche in the central part of the tunnel and characterized with the following specifications: fan diameter 1,6 m, nominal thrust N_j = 2810 N, jet velocity V_j = 34.9 m/s, air flow Q_j = 70,2 m^3/s. Niche parameters and positioning of the jet fans is shown (see **Figure 2**).

Baikalsky tunnel when the outside air enters the tunnel due to the natural draft and the air is forced against the natural draft by jet fans installed in a niche. The value of the natural draft ($P_{n.d.}$) was ranging from 100 Pa to 700 Pa. Simulation results were produced as distribution of air velocities and the map of air paths within a tunnel section where the niche with the jet fans is located (Gendler et.al. 2011)

Simulation data processed as average air velocities V_a at the tunnel cross-section are given in (**Figure 5,** solid line). The same Figure demonstrates dependencies of the air velocity entering the tunnel due to the natural draft only (dashed line). Comparison of these curves demonstrates that with increasing values of the natural draft the efficiency of jet fans decreases. Starting with the natural draft values of 400 Pa the difference between the air velocities in the tunnel with active and with deactivated jet fans goes below 20%. Analysis of curves in Figure 5 testifies that at values of natural draft exceeding 400 Pa applications of jet fans to decrease the amount of air entering the tunnel becomes inefficient.

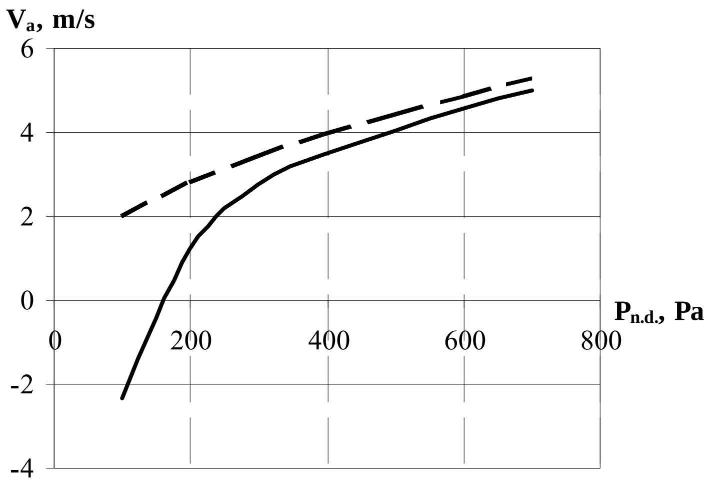

Figure 5: Dependence of the air velocity in the tunnel V_a on the value of the natural draft $P_{n.d.}$.

6. CONCLUSION

Introduction of the longitudinal ventilation with jet fans is practical in railway tunnels with electric propulsion engine for incident ventilation, in order to control the amount of air delivered to the tunnel due to natural draft and to maintain the desirable thermal and humidity conditions.

In railway tunnels with diesel-mechanical propulsion the applicability of the longitudinal ventilation with jet fans is dependent on the required train-handling capacity of the tunnel.

Inside the railway tunnel ventilated using the longitudinal, the jet fans should be located either in galleries at the portals or in the splayed parts which cross sectional area exceeds the cross-sectional area of the tunnel itself. Construction of side niches where jet fans can be located is economically efficient only in rock tunneling.

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DETERMINATION OF AERODYNAMIC BURDEN IN RAIL TUNNELS USING MEASUREMENTS AND SIMULATION

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ABSTRACT

When a train passes through a tunnel, pressure waves at nearly the speed of sound are propagated in the tunnel. If the train is not absolutely pressure-tight, these pressure changes are partly transmitted inside the train and may be uncomfortable for the passengers. The difference between the pressure outside and the pressure inside the vehicle puts an alternating load onto the train body. Likewise, the tunnel installations are also exposed to these pressure variations. Mainly high train speed combined with small tunnel cross sections results in pressure variations with high amplitudes and simultaneous heavy air flows. The usual operative situation is the passage of a single train through the tunnel even if the tunnel is designed for double-track use. In this case, the loads resulting from the pressure variations in general represent the construction reference for the endurance limit of the trains and of the built-in components of rail tunnels.

The authorisation of new rolling stock on the "Westbahn" section (e.g. Stadler KISS WESTbahn) or the increase of the sectional speed limit up to 230 km/h (e.g. railjet) in the unrestricted mixed rail-traffic requires analyses and measurements regarding possible pressure loads. In this process, the relevant aerodynamic properties of the rolling stock are determined based on 1:1-tests and compared with the directives of the TSI or the parameters of other, aerodynamically high-quality passenger trains (e.g. ICE 2). They serve as basis for the approval and authorisation of trains and tunnels.

Keywords: TSI, aerodynamic burdens, rail tunnel, pressure wave, measurements

1. INTRODUCTION

When a train passes through a tunnel, pressure waves at nearly the speed of sound are propagated in the tunnel. The compression wave (frontal wave) generated at the moment the train enters the tunnel is reflected at the opposite portal as an expansion wave. When the train tail enters the tunnel, an expansion wave (rear wave) is generated and reflected at the portal as compression wave. Due to the superposition of waves, the pressure amplitude increases, leading to high loads on the tunnel installations in some places. Besides this, the size and the direction of the impact forces change very quickly.

With pressure-tight rolling stock, there are less pressure loads inside the vehicle than with non-pressure-tight rolling stock. Higher pressure loads on pressure-tight trains are registered via the vehicle walls at windows, the doors, the air-conditioning openings etc.

Furthermore, pressure variations are occasionally felt by passengers as being uncomfortable; in extreme cases, they can even cause permanent health damages.

The authorisation of new rolling stock on Austrian railway sections requires e.g. the confirmation of the vehicle aerodynamics evidence pursuant to the directives of the TSI guidelines (cf. [6], [7]) and of the ÖBB Infrastruktur AG (cf. [5]).

With regard to aerodynamics, the vehicles must be constructed in such a way that the required characteristic pressure variations are fulfilled for a given combination (reference case) of train speed and tunnel cross-section. The assumption is that a single train passes through a standard, straight tubular tunnel (without shafts etc.). Since 1:1-measuring of every combination is not possible; calculation results with validated calculation models will be also accepted. The model building / validation will be based on measured pressure curves. The procedure is presented in details below.

2. GUIDELINES

2.1. Requirements of vehicle aerodynamics for the authorisation in the ÖBB railway network

The requirements of vehicle aerodynamics are listed in the catalogue of requirements for trains applying for authorisation in the ÖBB railway network (cf. [5]). Accordingly, the aerodynamic effects, in particular the pressure waves in the tunnel, must not lead to any negative impact on the oncoming or overtaking train. Corresponding evidence must be provided for the speed level v_{tr} > 160 km/h. Alternatively, an expertise based on a comparison with a train already authorised in the ÖBB railway network will be accepted.

2.2. Technical specifications for the interoperability (TSI)

In a series of legal acts, the European Commission has passed technical specifications for the interoperability (TSI) in the trans-European high-speed railway system and in the conventional trans-European railway system and has published them in the respective gazettes of the European communities.

The directive TSI 96/48/EG about the sub-system “Vehicles” applies to class 1 vehicles ($v_{tr} \geq$ 250 km/h) or class 2 vehicles (190 km/h > v_{tr} > 250 km/h) and defines the requirements the vehicles used in railway network of the trans-European high-speed train system must fulfil. The use of the concerned vehicles by a train company on a specific railway section is also subject to compliance with the guidelines 2004/49/EG and 2001/14/EG, modified by the guideline 2004/50/E.G.

3. AERODYNAMIC CRITERION / PRESSURE SIGNATURE

The aerodynamic properties of a train in a tunnel can be determined with the pressure curve. Fig. 1 schematically shows the pressure variations generated when a train enters a tunnel or passes another train in a tunnel. This so-called pressure signature includes:

Δp_N	Pressure rise generated by the frontal wave of the train nose entering the tunnel
Δp_{fr}	Pressure rise generated during the tunnel passage due to the friction
Δp_T	Pressure drop due to rear wave generated by train tail entering the tunnel
Δp_{Hp}	Pressure drop during the passage of the train nose

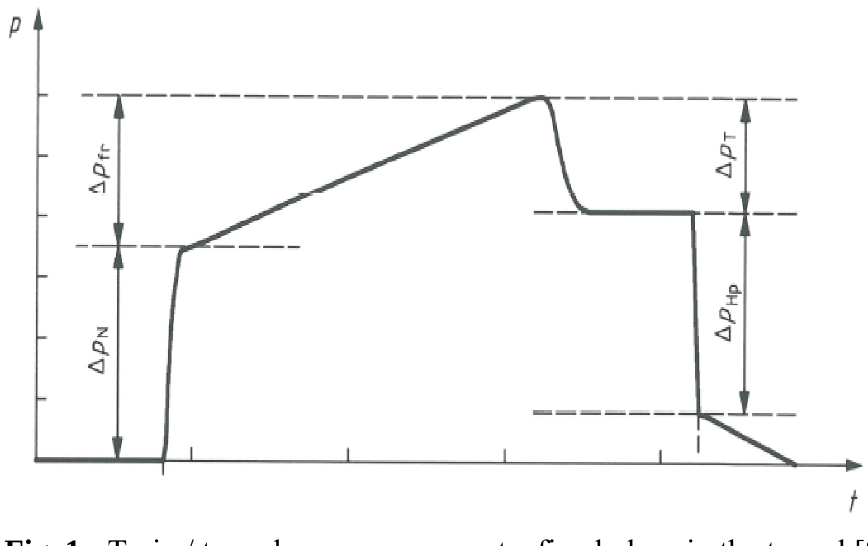

Fig. 1: Train / tunnel pressure curve at a fixed place in the tunnel [8]

The applicable characteristic limits for Δp_N, Δp_{Fr} and Δp_T are compiled in table 1.

Table 1: Requirements for an interoperable train passing through a tunnel tube at a speed of $v_{tr} < 250$ km/h [7]

Train type	Reference case		Criteria of the reference case		
	v_{tr} [km/h]	A_{tu} [m²]	Δp_N [Pa]	$\Delta p_N+\Delta p_{Fr}$ [Pa]	$\Delta p_N+\Delta p_{Fr}+\Delta p_T$ [Pa]
$v_{tr,\,max} < 250$ km/h	200	53,6	≤ 1750	≤ 3000	≤ 3700

Evidence must be provided based on 1:1 tests carried out with the reference speed or a higher speed in a tunnel with a cross-section as close as possible to the reference case. Next, the transfer to the reference requirement must be done with verified simulation software.

4. TEST RUNS

Extended measurements have been carried out in summer 2011 at different places of the "Westbahn" section regarding the authorisation of new rolling stock on this section (Stadler KISS WESTbahn) or regarding the increase of the sectional limit speed to 230 km/h for the railjet of the ÖBB in the unrestricted mixed traffic. Beside measurements on the free section or on a train station platform, aerodynamic measurements were also carried out in a tunnel. The measurement setup and the measurement technique are described below. Next, the measurement results and the subsequent calculations will be presented.

5. MEASUREMENTS

5.1. Measurement Setup

The measurements were carried out on three days at the end of August 2011 in the Melk tunnel. Beside the railjet and the KISS WESTbahn train, regular traffic trains were also analysed. The Melk tunnel on the "Westbahn" section has a length of 1845 m. It is a double-tracked tunnel with concrete pavement and has a cross-section of 78 m² (fig. 2).

Fig. 2: East portal of Melk tunnel and the measurement setup at km 84.4

For the measurement of the train / tunnel pressure curves, ideally a fixed place is selected in the tunnel. Measurements directly on the passing train are also possible; but the values of the pressure signature must then be approximated by the measured values. The test tunnel must have a constant cross-section and no further pressure waves must be generated inside. Ideally, there must be no ground flow in the tunnel.

Under EN 14067-5: 2006 – “Requirements and test procedures for aerodynamics in tunnels” [8], the equation of the distance x_p between the entrance portal and the measurement position is:

$$x_p = \frac{c * L_{tr}}{c - v_{tr}} + \Delta x_1 \qquad \text{formula 1}$$

The extra length Δx_1 (approx. 100 m) ensures a clear time-related separation of the pressure variations over time. The installation of the measurement devices near to the portal is meant to avoid a deadening of the pressure wave. Based on the formula 1, a minimal distance of about 460 m away from the portal is necessary with a train length of 300 m and a maximum speed of v_{tr} = 200 km/h. Finally the measurement position was 550 m from the entrance portal in direction of the traffic. The pressure sensor was placed on the tunnel wall, the speed sensor on the sidewalk at a distance of 2.5 m of the middle of the track (measurement height 1.2 m over the rail top edge).

5.2. Measurement Devices

Strict requirements apply to the measurement technique with regard to the measurement frequency and accuracy (cf. [8]). The minimal scan frequency is determined based on the length of the train nose and the train speed.

Piezoresistive miniature differential pressure gauges were used for the pressure measurement in the tunnel. Table 2 shows the characteristic parameters of the pressure gauges.

Table 2: Parameters of the pressure gauge

Parameters	Value
Measured area	-6895 to +6895 Pa
Maximal error	0.33 % regarding the maximal deflection
Resonance frequency	70 kHz

The pressure gauge is integrated in a plate (150 mm x 150 mm) to protect it against mechanical burdens. The pressure signal reaches the sensor via a perforation (1 mm diameter) and a coupling volume. The transfer properties of this system (amplitude and phase response up to 10 kHz) were taken into account in the installation of the measurement equipment.

The flow speed in the tunnel tube was measured with a 2D supersonic anemometer. The advantages of the supersonic anemometer are the higher accuracy, the absence of inertia in the system and the additional recording of the wind components in x and y directions. The supersonic device has 4 supersonic converters with respectively 2 of them placed at a distance of 135 mm opposite the other. The two measuring paths are vertically opposite each other. The converters function simultaneously as sound sender and sound receiver. Since the sound speed is considerably dependent on the air temperature, the velocity of sound is measured on each of both measuring paths in both directions. Thus, an influence of the temperature-related sound speed on the measurement result can be excluded. The measurement rate depends on the sound speed on the measuring length and amounts to <10 Hz.

In accordance with [8], the measurement of the train speed must have accuracy better than 1%. Supersonic sensors were placed at 2 measurement points with a defined distance from each other and the speed was calculated based on the time difference between both signals resulting from the passing train. An additional speed measurement device was place on the train itself for a GPS determination of the speed. The measurement device is suitable for accurate measurement (measurement error ±0.1 km/h) and detailed data recording of speed, position, longitudinal and cross acceleration.

The data recording was performed with a portable Dewetron data logger. The logger has 8 analogue channels and multiple digital inputs and captures measurement signals at scan rates up to 100 kSamples/s for each canal. The filtering and the averaging are done automatically inside the logger. The logger is configured and operated with specially designed software. The pressure signal and the flow speed were captured at a scan rate of 300 Hz and their analogue low-pass filtering done with a Butterworth low-pass filter.

In order to reduce the data quantity, the captured data were not stored in full demand time for the whole test period. The supersonic sensors were additional used as triggers activating a quick measurement whenever a train passed by. At this moment a measurement run were stored with scan rate of 300 Hz (15 seconds before and 300 seconds after the triggering). Thus the storage covers the whole passage of the train trough the tunnel incl. a lag of several minutes.

5.3. Measurement Results

Fig. 3 shows the pressure signals recorded in the tunnel for the KISS WESTbahn train. The train speed was within the range of 198.9 to 201.6 km/h. Therefore, all curves are similar. Two curves (measurement 4 and measurement 6) are particularly remarkable. At the time of both measurements, there was already a flow speed of about 4 m/s in the tunnel before the train passes. The direction of the flow was in opposite to the driving direction of the train in the tunnel. This resulted in higher pressures. All the remaining measurements were done with speeds of flow lower than 1.2 m/s, which results in a very good matching of the pressure curves.

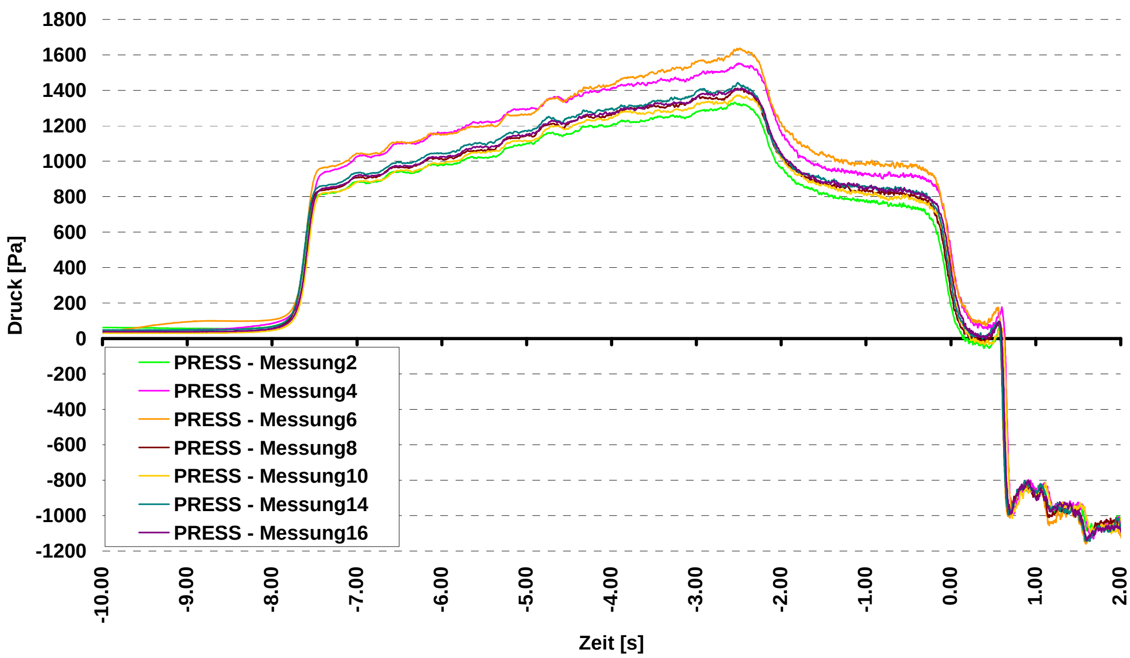

Fig. 3: TSI pressure signal measured for the KISS WESTbahn in the Melk tunnel

6. SIMULATION

6.1. Simulation Program

The measurement results of the Melk tunnel measurement were recalculated with verified software. Some parameters of the analysed train were varied as often as necessary until a good matching with the measurement was reached. Subsequently, the pressure signatures could be calculated with the programme for the in TSI specified tunnel cross-section (A_{Tunnel} = 53.6 m^2).

The software ThermoTun was used for the numerical simulation. ThermoTun is a computer programme accepted worldwide for the simulation of trains in tunnels and of tunnel systems. The correctness is confirmed by extended measurement campaigns (cf. [9], [10]). With the programme, e.g. the following, aerodynamically relevant, unsteady values can be determined:

- Pressure variations of trains passing tunnels and on rolling stocks,
- Traction power reqirements for trains in railway tunnels,
- Averaged air speed in the railway tunnel tube,
- Distribution and concentration of pollutants and smoke in railway tunnels.

6.2. Calculation Results

The measurement run no. 2 (fig. 3) has been chosen for the analysis and for the comparison with the ThermoTun software with respect to the lowest air speed before the train entrance in the tunnel (0.3 m/s). Fig. 4 shows the pressure curve of the measurement (red line) and the corresponding ThermoTun computations. The computated values match well with the measurement. Difference can be seen in the development after the passing of the tail wave at approx. 8 seconds. ThermoTun's ability to reproduce the relatively slow pressure drop is limited. However, the pressure drop due to the tunnel entrance of the train tail is correctly displayed. The pressure drop observable at approx. 10 seconds due to the impacting pressure waves reflected by the exit portal is also reproduced by ThermoTun in a steeper representation.

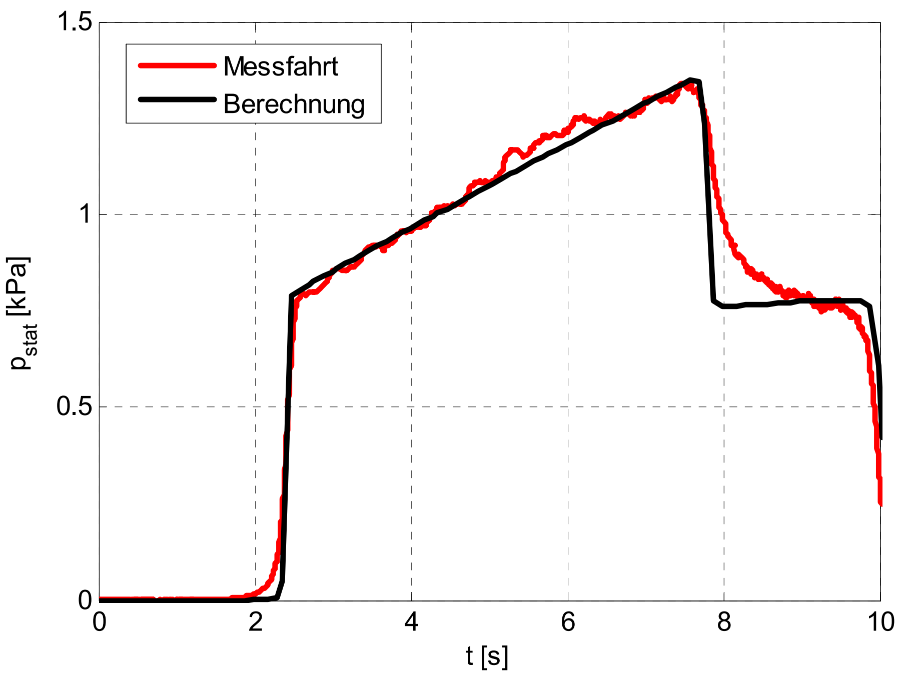

Fig. 4: Comparison of measurement (run 2) with ThermoTun computations

In the following reliable analyses for other tunnel configurations can be done using the input parameters determined by ThermoTun. Fig. 5 shows computations with the input parameters based on the comparison for a tunnel cross-section A_{Tunnel} = 53.6 m^2. The train-related pressure variations due to the train nose and tail pressure waves and due to the longitudinal friction on the train wall are indicated.

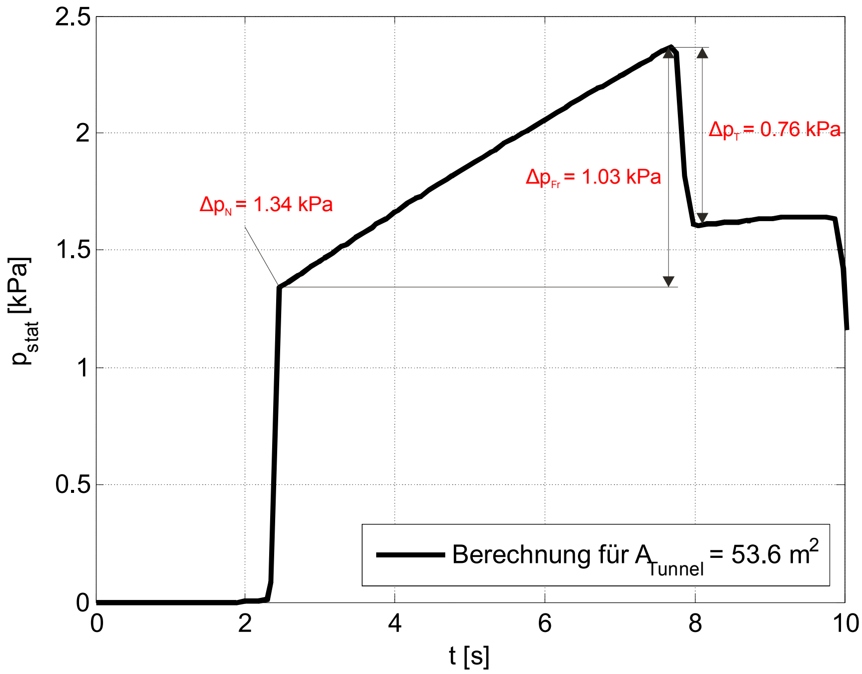

Fig. 5: ThermoTun computation for a tunnel cross-section of A_{Tunnel} = 53.6 m^2

Table 3: Contribution of various causes on the train-related pressure variations

Cause of the pressure variation	**Value**
Frontal pressure generated by the train penetrating the tunnel Δp_N	1.34 kPa
Pressure difference due longitudinal friction Δp_{Fr}	1.03 kPa
Tail pressure wave generated by the train leaving the tunnel Δp_T	0.76 kPa
Total $\Delta p_N + \Delta p_{Fr} + \Delta p_T$	3.13 kPa

7. CONCLUSION

As a requirement for the authorisation of new rolling stock on railway sections e.g. evidence must be produced about the aerodynamics of the train. A new train must be aerodynamically constructed that no damages occur for the train and for the tunnel installations when the train passes through a tunnel or passes by an oncoming train. Besides this, the comfort of the passengers must also be taken into consideration.

This paper describes the authorisation procedure for new trains. It consists in 1:1 measurements being recalculated with verified software and some parameters being varied for a good accordance with the measurements. The measurements were done in the Melk tunnel on the "Westbahn" section in August 2011 and leads to a data set of several train / tunnel pressure curves for the KISS WESTbahn train (v_{tr} = 200 km/h), the railjet train (v_{tr} = 230 km/h) and numerous trains of the regular traffic with different speeds. Subsequently, any other situation in different tunnels now can be calculated from the results using the ThermoTun software.

8. ACKNOWLEDGEMENT

We would like to thank Stadler Altenrhein AG for their kind permission to publish this work.

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SLOVAK ROAD TUNNEL GUIDELINE

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ABSTRACT

The Slovak Republic has 4 existing road tunnels and will build 17 new road tunnels with lengths of 280 m to 7460 m in the next years. In order to harmonize the planning process and to establish uniform requirements for all road tunnels, the Slovak Tunneling Association together with the Slovak Highway Company and external planners has established a new road tunnel guideline.

This guideline follows in particular the requirements of the EU guideline on minimum safety requirements for tunnels in the Trans-European Road Network from 29 April 2004. Further, it pursues consequently the approach to specify functional requirements, i.e. it sets primarily the ventilation aims. These aims represent in turn the safety level required by the Slovak Republic, which exceed the EU requirements.

The specifications of functional requirements accounts for the fact that optimal technical solutions are different for all tunnels, even tunnels which appear similar. Hence, the guideline gives the planner at the time clear guidance about minimal requirements for road tunnels in the Slovak Republic and relies on his expert knowledge with respect to the methods and the ideal technical solution for the specific project.

Keywords: guideline, road tunnel, ventilation design

1. INTRODUCTION

The EU guideline on minimum safety requirements for tunnels in the Trans-European Road Network from 29 April 2004 sets the minimum standard for safety installations in Europe. Ventilation is a small but integral part of this guideline. To meet or exceed the European standard is within the ruling of each EU country and is triggered by the country specific safety level. This has led to different road tunnel standards in most EU countries, the most well-known being the German RABT, the Austrian RVS 09.02.31, the Swiss ASTRA guideline, the French « ANNEXE N° 2 à la circulaire interministérielle n° 2000- 63 du 25 août 2000 relative à la sécurité dans les tunnels du réseau routier national » and the Italian “Linee Guida per la progettazione della sicurezza nelle Gallerie Stradali”.

While it is not unusual that guidelines set not only the ventilation aims but specify also constructional details or methods, the Slovak guideline concentrates on functional requirements and passes on the responsibility to choose state-of-the-art engineering methods and to come up with an ideal project specific solution to the ventilation engineer. Where engineering solutions should be prescribed and for standardized calculation or test procedures or technical standards, technical bulletins are attached to the guideline.

This structure appears most appropriate in order to ensure at the time that the guideline

- remains a stable prescription expressing the fundamental safety requirements of the Slovak Republic and
- provides an opportunity to adapt standardized calculation or test procedures or to add technical standards.

2. GENERAL ASPECTS

2.1. General ventilation aims

The guideline lists the following general ventilation aims for the system choice, the dimensioning, the implementation and the operation of ventilation systems in road tunnels:

- control of heat and smoke in case of an incident with smoke production
- control of exhaust gases and particulate matter during normal operation
- limit the concentration of noxious gases and opacity during maintenance and incident without smoke

The choice and size of the ventilation system shall be governed by the requirements for emergency operation (incident with or without smoke) or normal operation. The ventilation system shall be energy efficient during normal operation. If necessary, temporary operational measures shall be considered for maintenance.

2.2. Deviations from the guideline

The guideline allows deviations if a particular technical solution results in an unbalanced cost / benefit relation. In these cases the regulating authority must authorizes these deviations and the planner must provide:

- a thorough documentation of the motivation, the technical and the financial consequences for the suggested deviation
- a risk analysis if requested by the regulating authority.

2.3. Tunnel categories

The tunnel categories referred to in the Slovak road tunnel guideline in Table 1 are based on the categories in the EU directive 54-2004 and account for the increased risk of longer and more frequented tunnels.

Table 1: Tunnel categories

	A	B	C
traffic volume	< 2000 veh / (d.lane)	> 2000 veh / (d.lane)	> 2000 veh / (d.lane)
	or	and	and
tunnel length	< 1000 m	> 1000 m < 3000 m	> 3000 m

The length of the tunnel is defined as the maximum length from any entrance to any exit portal. Galleries with a roof covering more than half of the road or tunnels less than 200 m away from the tunnel portal are added to the total length.

2.4. Traffic

The guideline requires that traffic data for the year the tunnel opens and 10 years thereafter, whatever triggers the more demanding ventilations requirements, must be considered for the ventilation design.

2.5. Meteorology

The ventilation system must reach the ventilation aims in the presence of the following meteorological conditions:

a) pressure

- the 95-percentile of the barometric pressure difference between tunnel portals Δp or
- the 95-percentile of the maximum wind speed u_W in direction of the tunnel portals, measured 10 m above ground and in approximately 300 m distance from the corresponding tunnel portal,

whatever is higher.

b) temperature (for buoyancy)

- the 5- and the 95-percentile of the ambient temperatures $T_{a,5}$ und $T_{a,95}$
- the (predicted) tunnel temperatures inside the tunnel during winter $T_{i,W}$ and summer $T_{i,S}$.

at the same time.

3. VENTILATION SYSTEM

The guideline requires that the ventilation system covers all possible incident locations. It leaves it up to the planner to define the scenarios required to prove the feasibility of the ventilation concept.

The ventilation installations shall be determined by the requirements of emergency or normal ventilation. If possible, installations for emergency operation shall also be used for normal operation.

In order to account for the impact of seasonal density variations on the power requirement of the ventilation system, the fans have to cover at least the reference density of 1.2 kg/m³ or the density at p_0 and $T_{a,5}$, whichever is bigger.

The guideline also requires that temperature and density variations due to a fire must be considered when the operational points are determined. This obliges the planner to consider the density reduction in the pressure drop calculations as well for the operational points of the fans. The guideline does not refer to a simplified model but requests to perform these calculations in a conservative manner, if needed also unsteady.

The required smoke extraction capacity at the incident location results from the required longitudinal flow velocities in the traffic area and the relevant heat release rate.

3.1. Emergency Ventilation

The emergency ventilation covers incidents with smoke and incidents without smoke.

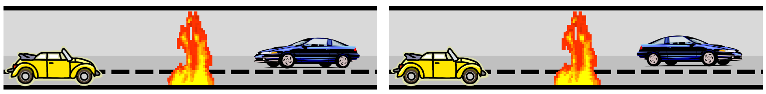
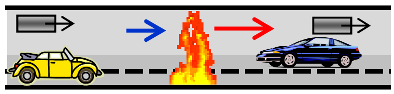
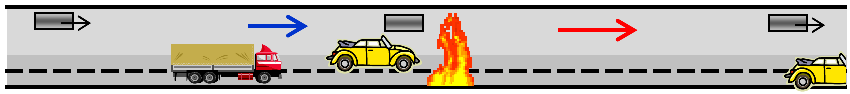
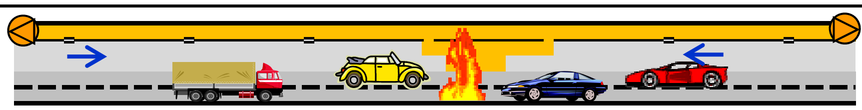
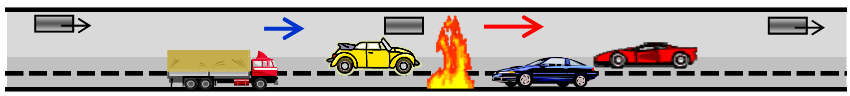
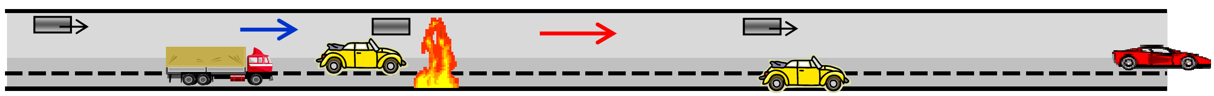
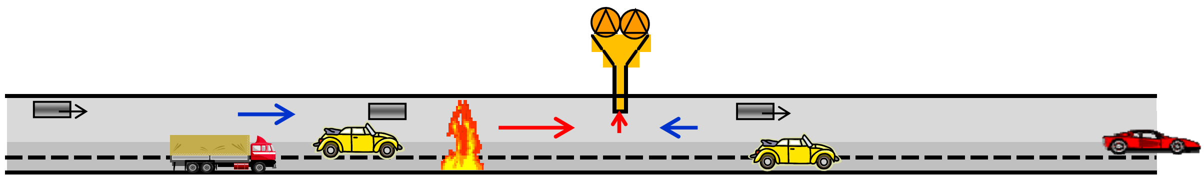
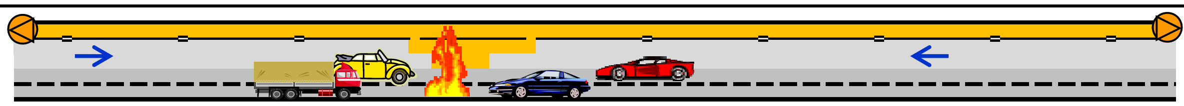
The guideline distinguishes the following tunnel categories which define the emergency ventilation concept as shown in Table 2. If a risk analysis is performed, it may lead to stricter requirements.

A1: <500 m or >500 m with directional traffic: no mechanical ventilation required
A2: >500 m with bi-directional traffic: longitudinal ventilation

B1: directional traffic with no traffic jam: longitudinal ventilation
B2: bi-directional traffic or directional traffic with sporadic or regular traffic jam: longitudinal ventilation only if risk analysis results in acceptable risk, otherwise smoke extraction near incident location

C1: directional traffic with no traffic jam: longitudinal ventilation or longitudinal ventilation with punctual smoke extraction
C2: bi-directional traffic or directional traffic with sporadic or regular traffic jam: smoke extraction near incident location

Table 2: Schematic drawings of possible ventilation systems for the different tunnel categories

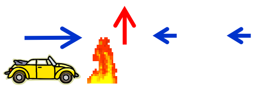
A1	
A2	
B1	
B2	 or, if a risk analysis results in acceptable risk: 
C1	 or 
C2	

3.2. Ventilation aims for emergency ventilation

The determination of the ventilation aims is the central part of the guideline as it contains the main functional requirements which have to be met by the ventilation system.

Under all relevant boundary conditions, the ventilation system must at least be able to achieve the ventilation aims as given in

Table 3: Ventilation aims

	v_{left}		v_{right}
A1	n/a		n/a
A2	1.5 m/s		n/a*
B1	v_{crit}		n/a*
B2	1.5 m/s	extraction:  longitudinal: 	-1.5 m/s n/a*
C1	v_{crit}	 or 	n/a* < 0
C2	1.5 m/s		-1.5 m/s

* In these cases, the velocity downstream of the fire is no ventilation aim. It results in particular from the required velocity upstream of the fire and the heat release rate.

with

v_{left}: longitudinal flow velocity left of incident location towards incident location
v_{right}: longitudinal flow velocity right of incident location away from incident location

In a tunnel with directional traffic the tunnel entrance portal is left and the tunnel exit portal is right. I a tunnel with bi-directional traffic, left and right are chosen for each incident so that

b) the least amount of people are exposed to smoke

c) the initial flow direction is not reversed by the mechanical ventilation

The critical velocity v_{crit} must be calculated as:

$$v_{crit} = C_0 C_3 \sqrt{C_1 C_4} \frac{\sqrt{1+(1-C_2/C_1) C_4 \frac{B^2}{gH}}}{1+C_4 \frac{B^2}{gH}} B \qquad (1)$$

with

$$C_0 = 0.9 \cdot \left(1 + 0.0374 \cdot \max(0;-s)^{0.8}\right) \tag{2}$$

$$C_1 = \frac{1-0.1\frac{H}{W}}{1+0.1\frac{H}{W}}\left[1+0.1\tfrac{H}{W}-0.015\left(\tfrac{H}{W}\right)^2\right] \cong 1-0.1\tfrac{H}{W} \tag{3}$$

$$C_2 = \frac{1-0.1\frac{H}{W}}{1+0.1\frac{H}{W}} 0.574\left[1-0.2\tfrac{H}{W}\right] \tag{4}$$

$$C_3 = 0.613 \tag{5}$$

$$C_4 = 6.13\left(\tfrac{W}{H}\right)^{\frac{2}{3}} \tag{6}$$

$$B = \left(\frac{QgH}{c_p T_a \rho_a A}\right)^{\frac{1}{3}} \tag{7}$$

where

Q	:: heat release rate	[W]
g	:: gravity	[m/s²]
c_p	:: heat capacity of fresh air current	[J/(kg.K)]
H	:: height of the driving tunnel	[m]
W	:: width of the driving tunnel	[m]
A	:: cross-sectional area of the driving tunnel	[m²]
s	:: slope of the driving tunnel (negative when tunnel is falling)	[%]
T_a	:: temperature of fresh air current	[K]
ρ_a	:: density of fresh air current	[kg/m³]

Remark: Eq. (1) corresponds to the formula for the horizontal tunnel in Kunsch (2002) except for the factor C_0. The coefficient C_0 has been introduced by the author of this guideline. It contains the “Kennedy” slope factor according to Fig. 9.3 in SES (1997) and an additional factor of 0.9. This factor gives a good fit to the critical velocity in the horizontal tunnel as measured in small scale models. It is therefore less conservative than the original formula by Kunsch (2002) but a bit higher than the formula in SES (1997).

For all tunnel categories the risk for tunnel users to be exposed to smoke before the start of the automated emergency response shall be minimized.

3.3. Ventilation aims for normal operation

The ventilation system as defined by the requirements for the emergency ventilation (see ch. 3.2) shall be used also for normal operation. If necessary, it has to be enhanced, which ideally creates additional capacities for the emergency case.

The following threshold values for the opacity and the CO-concentration must be met inside the tunnel:

OP_{max} = 5/km

$c_{CO,max}$ = 70 ppm

Until the emission values of the Slovak car fleet has been empirically assessed, base emissions and the calculation procedure for the required flow rate of fresh air have to be calculated according to the Austrian RVS 09.02.32.

3.4. Ventilation aims for emergency exits

The flow velocity through open passenger escape doors as averaged over the open cross-section must be larger than 2 m/s, should be evenly distributed and must be directed towards the traffic area in all points. The flow velocity should not exceed 6 m/s.
The opening force of the escape door must not exceed 100 N.
For times larger than 120 s after the emergency response has been triggered, this ventilation aim must be reached at most 3 s after the escape door is opened.

3.5. Redundancy

In general, the availability of the tunnel has a very high priority. Depending of the consequences of the failure or maintenance of one piece of the ventilation system during normal operation, an additional redundancy for normal operation may be required.

4. EMERGENCY CONTROL STRATEGY

The Slovak guideline applies a similar control logic to the one outlined in ASTRA (2009), where a moving incident and a localized stationary incident are distinguished. A localized stationary incident triggers the alarm, which sets off the emergency operation. The release of fire extinguishers and the opening of escape doors trigger the pre-alarm.

4.1. Moving or stationary incident

An incident is considered moving if

- at least 3 smoke detectors measure an opacity larger than 12/km

An incident is considered stationary if

- at least 1 sensor measures an opacity larger than 30/km
- the smoke propagation speed is similar to the flow velocity in the tunnel

The smoke propagation speed is given by the distance of activated smoke sensors divided by the time lag between their activation.

4.2. Pre-alarm

A pre-alarm is triggered by

- a moving incident or
- the fire detection system.

The ventilation system shows the following reactions:

- the escape path ventilation is turned on (if applicable)
- all smoke exhaust dampers are closed and attached exhaust fans are turned off (if applicable)
- the air supply system is turned off (if applicable)
- the longitudinal flow velocity is reduced to a value below 1.5 m/s

Additionally, the traffic lights at the entrance portal turn red.

4.3. Alarm

An alarm is triggered by

- a stationary incident or
- the fire detection system.

The ventilation system shows the following reaction:

step 1 (automatic)

	system with smoke extraction	*systems without smoke extraction*
bi-directional traffic	smoke exhaust fan is turned on with extraction points open the longitudinal flow velocity is maintained at a value of 1.5 m/s towards the smoke zone on both sides of the smoke zone	the longitudinal flow velocity is maintained at a value close to 0
directional traffic	smoke exhaust fan is turned on with extraction points open the longitudinal flow velocity is maintained at a value of 1.5 m/s upstream and 1 m/s downstream of the smoke zone towards the smoke zone	the longitudinal flow velocity is maintained at a value of no more than 1.5 m/s

step 2 (manual)
The operator or trained rescue personnel decide when to switch from step 1 to step 2. In step 2, the ventilation system is controlled to reach the ventilation aims according to ch. 3.2.

4.4. Ventilation of parallel tunnel

In tunnel systems with 2 parallel tunnels, the non-incident tunnel must be ventilated

- to support the ventilation of the emergency exits
- to avoid recirculation by the portals

Typically, the jet-fans at both ends of the non-incident tunnel are turned on with their thrust to the inside of the tunnel. If smoke escapes from the incident tunnel, the flow at the neighboring portal of the non-incident tunnel must exit with at least 0.5 m/s.

5. CONCLUSION

The new Slovak guideline sets mainly functional requirements to the ventilation systems in all Slovak road tunnels. It describes in particular the ventilation aims and the control strategy. It relies on the planner to apply state-of-the-art methods for his ventilation calculations and to come up with an optimum technical solution for the particular project.

Technical bulletins contain more specific details which may be adapted to reflect actual developments.

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A NEW AUSTRIAN GUIDELINE FOR TUNNEL SAFETY DOCUMENTATIONS

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ABSTRACT

According to the Austrian tunnel safety legislation (STSG) for all tunnels of the national major road network, the tunnel manager has to compile a tunnel safety documentation, which shall describe the preventive and safeguard measures needed to ensure the safety of the users. This documentation is a necessary part of the technical documentation required for the approval by the administrative authority according to STSG §7 (approval of the preliminary design) and §8 (approval of putting into operation of a new tunnel). For this reason in 2006 i.e. immediately after the introduction of the STSG, the administrative authority, the ministry of transport (bmvit), released a guideline for the preparation of the tunnel safety documentation

Due to a revision of the STSG in 2010 and due to new standards, which have been introduced since the preparation of the first guideline in 2006, it has been decided to update the existing guideline. The main objective was to benefit from the experience gained so far, to accelerate the approval process and to simplify it wherever possible.

The paper presents the updated guideline. The emphasis is on the goals, the structure and the contents of the tunnel safety documentation. The annexes to the safety documentation as well as the additional documents needed for an efficient approval process are also described.

Keywords: guideline, tunnel, safety documentation, STSG

1. INTRODUCTION

In the Austrian tunnel safety legislation (STSG) [1], the European Directive on minimum safety requirements for road tunnels [2] is transposed into a national law. According to STSG, just like in the EU Directive, for each tunnel of the primary road network, a tunnel safety documentation must be prepared.

The tunnel safety documentation is the central part of the technical documentation on which the approval by the administrative authority is based. The STSG defines two distinct steps in the approval process:

- Approval of the preliminary design (§7 STSG)
- Approval for putting into operation of a new tunnel (§8 STSG)

For both of these steps, an independent review of the tunnel safety by an expert, specialised in the field of tunnel safety, is required. This expert report is normally based on the safety documentation and a number of additional documents, which are prepared by the project applicant. The quality of the safety documentation is thus of fundamental importance for an efficient approval procedure.

For this reason already in 2006, a first guideline for the elaboration of a tunnel safety documentation was published by the Ministry of Transport (tunnel authority) [3]. Based on this guideline, for each tunnel of the primary road network a safety documentation has been prepared and a large number of approval procedures according to §7 und §8 STSG have been accomplished.

The experience from these approval procedures shows

- that the minimum requirements for the contents of the tunnel documentation, formulated with catchwords, are often misinterpreted which results in incomplete safety documentations,
- that the information in the different documents (safety document, emergency response plan, tunnel-operation manual, maintenance concept, etc.) is often redundant and sometimes contradictory,
- that the safety documentations contain unnecessary ballast, which has been added for example during approval procedures.

This leads to inefficient approval procedures. In addition, a number of changes which influence the safety documentation have occurred since the first introduction of the guideline:

- Amendment of the STSG with new procedural steps (§7a, §10).
- Release of new guidelines (e.g. on tunnel portals and transport of dangerous goods)

An update of the tunnel safety documentation guideline was therefore necessary.

2. OBJECTIVES OF THE NEW GUIDELINE

The tunnel safety documentation is the main document describing the tunnel safety. It shall therefore describe and summarize all aspects which are relevant for tunnel safety in a condensed manner in one, clearly structured, super ordinated documentation. The safety documentation serves as a basis for the following administrative procedures:

- The approval procedures according to §7, §7a and §8 STSG are based on the safety documentation. The tunnel safety documentation shall support these approval procedures of the STSG and shall help to understand the planned structure and the access to it, together with the plans necessary for understanding its design and anticipated operating arrangements.
- As the tunnel safety documentation is also used by the Administrative Authority in the regular inspections (according to §3 Abs. 5 STSG), a quick overview over the tunnel system and the existing deviations from the state of the art shall be possible.

With the actualisation of tunnel safety documentation guideline, the following objectives are pursued:

- Overview: The different bodies responsible for tunnel safety (tunnel manager, safety officer, administrative tunnel authority, independent expert, etc.) shall be able to obtain a quick overview over the relevant aspects of the tunnel safety. Accepted deviations from the state of the art are clearly visible.
- Standardisation: The structure of the safety documentation shall be standardized so that a quick overview is possible and existing deviations from the state of the art can easily be detected.

- Living document: The safety documentation shall be structured in such a manner that an update is easily possible. The quantity of documents must therefore be limited.
- Working instrument: The tunnel safety officer and the tunnel manager dispose over a tool for the coordination between the different documents relevant for tunnel safety. Changes in the tunnel infrastructure or of the equipment which are relevant for safety can be traced.

3. SELECTED APPROACH

3.1. Project team

The guideline has been prepared by a group of specialists from the bmvit (Administrative Authority), ASFINAG (project applicant, tunnel operator) and independent experts for tunnel safety.

3.2. Stepwise development

In a first step, a draft of the guideline has been elaborated by this team and published for provisional use. The draft of the guideline was applied in different projects, where an approval procedure was necessary (pilot projects). Additionally, it was checked that the guideline can also be applied to existing tunnels.

In addition to the guideline, a number of templates for selected documents have been prepared. These templates shall support and guide the writer of a tunnel safety documentation as well as in the production of additional plans and reports, so that all the information which is needed is included in these documents.

In a second step, the experience with the guideline was evaluated. On this basis, the final version of the guideline was prepared. The application of the guideline confirmed the advantage and the need of templates. Another important finding was that special provisions are needed for existing tunnels because in this case the quality of the original documentation can be lower than required today.

The final version of the guideline [4] is now available at www.bmvit.gv.at/verkehr/strasse/tunnel (in German only).

3.3. Structure and contents

The tunnel safety documentation has a modular structure (figure 1) with a master document and a number of annexes. This allows exchanging parts of the documentation easily and opens the possibility to implement running modifications without much effort.

The structure and the contents of the master document are standardised. The 12 chapters of the safety documentation are shown in table 1.

In order to keep the work for changes at the already existing safety documentations as low as possible, the structure and the contents are as far as possible similar to the structure and the contents defined in the previous guideline.

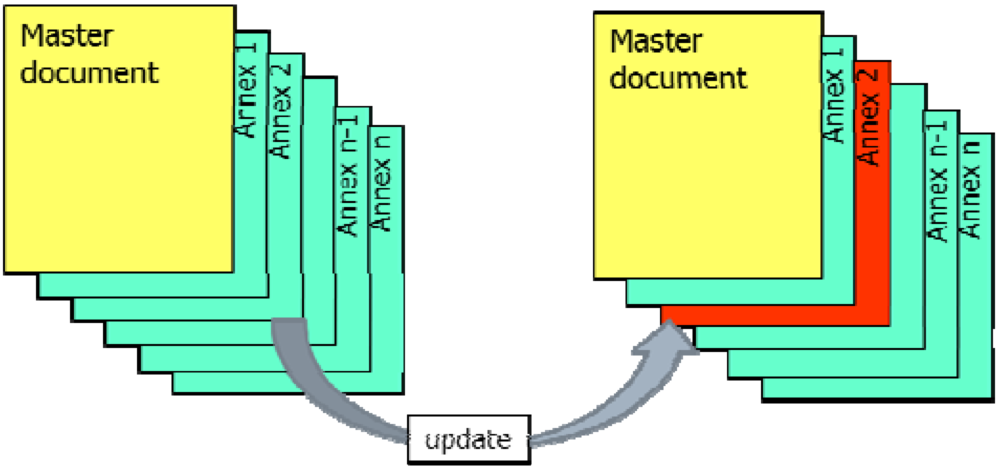

Figure 1: Modular structure of the tunnel safety documentation

The master document contains 12 chapters (see table 1). The first ten chapters summarize in a short form the main characteristics of the tunnel system as well as the technical and organisational measures.

Further details can be found in annexes which are joined to the safety documentation (chapter 11). The annexes needed for the different approval procedures as well as for a tunnel in operation are defined in the guideline. Chapter 12 contains a list of additional documents which are necessary for the approval procedures but which are not part of the safety documentation.

Table 1: Chapters of the main document

Chapter	**Title**	**Modifications**
I	Introduction	
II	Overview over the tunnel system	
III	Description of the structure and the access to the tunnel	
IV	Traffic situation and expected trend	
V	Specific hazard analysis	yes
VI	Organisational and operational procedures	
VII	Incident management	yes
VIII	Continuous improvement process	
IX	Exercises, tests and instructions	
X	Documentation of minor changes	new chapter
XI	Administrative notifications and their control	new chapter
XII	Annexes	
XIII	Additional documents	new chapter

The structure of the safety documentation allows a continuous evolution from the first project phase (planning stage) over the first putting into operation to the operation phase (living document).

3.4. Templates

To facilitate the preparation of a tunnel safety documentation, to minimize possible interpretation errors of the guideline and to guarantee a high degree of standardisation, the development of a template for the master document is in progress.

The template of the master document will be provided on the ASFINAG website.

To reduce the uncertainties, it is planned to provide also templates for selected annexes to the safety documentation. With such standardization, it is much easier to guide the originator of the safety documentation and to minimize misinterpretations of the guideline.

3.5. Additional documents

The most important elements for tunnel safety are documented in the master document and the annexes to the safety document. However in the approval procedures, additional information must be provided to the Administrative Authority and the safety expert in charge. These additional documents have also been defined in the new version of the guideline (chapter 12). However, in order to keep the safety documentation as lean as possible, these additional documents are not part of the tunnel safety documentation.

4. MODIFICATIONS COMPARED TO THE OLD GUIDELINE

Some of the major changes compared to the previous guideline have already been mentioned (list of annex documents and list of additional documents, templates). Some other important modifications are described below.

4.1. Deviations from the state-of-the-art

Existing tunnels often show deviations from the actual state-of-the art. Guidelines normally allow such deviations in existing tunnels as an upgrade is often possible only at excessive costs (principles of proportionality). To make these deviations transparent, a special subchapter is foreseen in the safety documentation.

4.2. Instrument to categorize tunnels with or without special characteristics

When a tunnel has a special characteristic with respect to the parameters mentioned in the annex of the STSG, a risk analysis shall be carried out to establish whether additional safety measures and/or supplementary equipment is necessary in order to ensure a high level of tunnel safety. In the past, the check if a tunnel has special characteristics has often been mixed up with the check if the minimum safety requirements defined in the annex of the STSG are fulfilled. Therefore, a simple instrument has been developed to categorize tunnels with/without a special characteristic. The instrument uses the 16 safety parameters mentioned in the annex of the STSG.

4.3. Periodic update of the safety documentation

According to §4(3) of the STSG, the safety documentation has to be kept permanently up-to-date. In the new guideline, the periods in which an update is necessary have been defined.

4.4. Additional notes

At the end of the guideline, some additional notes can be found:

- Guidance for the case that during a project new guidelines are introduced.
- A chronological sequence for a procedure according to §8 STSG: The sequence shows in an exemplary way the interaction and interdependence between the preparation of the tunnel safety documentation with the corresponding administrative steps and the still on-going finalisation of the construction, the installation and the tests of the electromechanical equipment.

5. CONCLUSIONS

The administrative procedures, especially the procedure to put into operation new or refurbished tunnels, normally have to be accomplished at a tight time schedule. It is therefore crucial that the tunnel safety documentation and the additional documents needed by the Administrative Authority are complete and of good quality. The new guideline for the preparation of the tunnel safety documentation aims at supporting this process and thus helps in speeding up the administrative procedures and making them more efficient. At the same time, it defines the standard for documentation, which can be used by the safety officer and the tunnel management as a tool in the daily work.

The new guideline is available at the website of the bmvit. To facilitate the preparation of tunnel safety documentations and to improve their quality, templates will be produced and made available in the near future for the public.

6. LITERATURE

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COORDINATION WITH EMERGENCY SERVICES / EFFECTIVE EMERGENCY RESPONSE PLAN

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Abstract

"Emergency services" can be defined as all local services, whether public or private, including tunnel and non-tunnel staff, which would intervene in the event of an incident. Safety in tunnels requires effective incident management and training of emergency services.

The safety officer, a formerly missing link between tunnel-management and emergency services, coordinates the safety measures and ensures effective emergency services action and enhancement of communication between all authorities involved .

A modern ERP - Emergency Response Plan, should comprise of a clear concise graphic layout, providing condensed information for each party involved. Respective scenarios and exact positions and locations of the intervention sites must be indicated in a compressed form.

1. INTRODUCTION

For many years, it was believed that tunnel safety depended primarily on the degree of technical equipment. Subsequent catastrophes in Alpine tunnels were strong lessons highlighting many other potential weaknesses in the safety chain.

Tunnel safety includes numerous measures including a modern ERP - Emergency Response Plan, specific tactical concepts and training for emergency services, efficient incident management by the tunnel control centre and emergency services dispatching, improved communication between different emergency services such as the police, fire-brigades and rescue teams and also the provision of relevant information for tunnel users on how best behaviour within tunnels.

Safety measures should enable those involved in incidents to rescue themselves and ensure efficient and effective action from the professional rescue teams and emergency services.

Luxembourg’s tunnels are highly equipped, improvements brought about by the Directive 2004/54/CE relate mainly to the organization of tunnel-management and emergency services.

The following information highlights the importance of coordination between the tunnel-management and emergency services and gives an overview of the new concept of Luxembourgish ERP.

2. BASIC FORMATION FOR FIRE-FIGHTERS

It is essential that fire-fighters receive information about the particular boundary conditions of tunnel fires. The following topics should be included in a education plan: fire load and power, spatial and temporal sequence of a tunnel fire, mission targets and priorities, behaviour of fumes, risks for fire-fighters, critical velocity, back layering, chimney effect, tunnel ventilation performance limits, reaction of tunnel-structure, tactics etc. Other topics may include effective management of accidents in tunnels → with or without traffic jam inside the tunnel!

3. THE SAFETY OFFICER, THE MISSING LINK

The safety officer’s mission is described in article 6 of the directive 2004/54/CE on minimum safety requirements for tunnels in the Trans-European Road Network.

In the past, the cooperation between tunnel-management (TM) and the emergency services (ES) was normally limited to the phase before commissioning a new tunnel.

Today, the Safety officer’s task of tunnel safety organisation includes:

- continuous ensuring of coordination between TM and ES,
- taking part in the preparation of operational schemes (also of emergency services),
- taking part in the planning, implementation and evaluation of emergency operations,
- taking part in the organisation of joint periodic exercises for tunnel staff and ES,
- taking part in initial training for the scenario "fire in tunnel" (tunnel staff and ES).

Training for tunnel staff and ES is a preventive measure, and the Safety officer is the “*coordinator of all preventive and safeguards measures to ensure the safety of users and operational staff*” (→ article 6, Directive 2004/54/CE).

Previously the important task of ES training was omitted; today however the Safety officer has to ensure that appropriate initial and continuous training is carried out, not only for ES but also for tunnel staff.

The Safety officer also has the task of promoting a continuous dialogue between the tunnel-management and the emergency services; he thus becomes the missing link between all those involved in tunnel safety.

The Safety officer acts as a consultant to all parties involved in incident management, helping to create operational schemes and emergency response plans, and constantly improving knowledge and performance of all persons involved in incident management.

4. HOW BEST TO STRUCTURE A MODERN AND EFFICIENT EMERGENCY RESPONSE PLAN?

Traditional emergency response documents were often so long and laborious that they enticed few to study them at the outset. It was also often difficult to identify the general concept and to comprehend the subtle differences between the various scenarios and approaches. This makes it almost impossible for the emergency services to use the plan in preparation for a mission.

In a traditional plan, it was often not possible to source basic instructions with sufficient speed; thus rendering the ERP fairly useless during an emergency. This outdated approach made no distinction between the different tunnel tubes and certainly took no account of the exact location of the incident inside the tunnel. The precise location of an incident is often essential. Example: A traffic jam in front of an accident makes it impossible for the ambulance to get through in order to arrive beside the victims. Due to the local conditions it is also not possible for the ambulance to use the crossover between the two tunnel tubes (in order to arrive from the opposite direction to the accident).

A traditional plan (as described above) is therefore no real help for the emergency services, not to deal with a tunnel disaster and not even to prepare for the worst.

A modern emergency response plan differs not only between the two tunnel tubes but even considers the exact position of an incident in order to consider local conditions like inexistent crossover, height differences between two directions, traffic jam inside the tunnel etc..

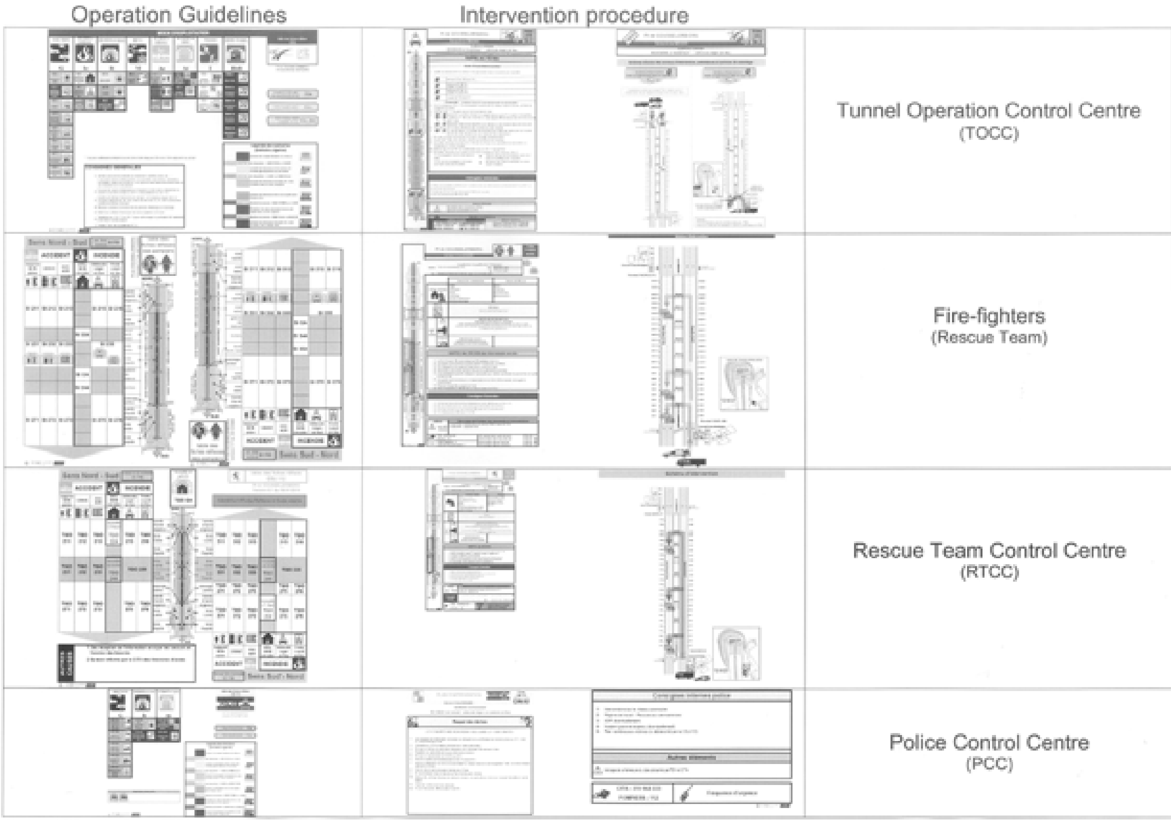
Such a plan provides also different instructions for different groups of interveners.

Examples:

- Fire-fighters instructions depend on whether a fire brigade approaches from one or the other tunnel portals;
- the instructions of the tunnel operators depends on which side the accident has happened.

In a modern emergency response plan, group-oriented “Operation Guidelines” are provided giving an overview of the intervention procedures needed for tunnel operators, fire-fighters, police and emergency service control centre. The procedures are based on an elaborated graphic concept, are visually appealing (see picture 1). and not overloaded with text.

A modern emergency response plan is not only helpful in case of a tunnel disaster but also useful for the different stakeholders in preparing for all type of incidents.



Picture 1

5. OUTLOOK

The most important information within an emergency response plan (ERP), is to explain the best way that the emergency services should intervene.

The key to a successful intervention is speed; to get as early as possible to the incident.

Conclusion: We need a procedure that ensures that the fire-fighters receive detailed information about the best way to intervene, even before they arrived at the tunnel and before they took a look at the ERP.

The rescue teams need before they arrive on site answers to the 3 W-questions:

- What happened? Where it happened?
- Where must I go to do my job?

AN INVESTIGATION OF LONGITUDINAL VENTILATION FOR SHORT ROAD TUNNELS WITH HIGH FIRE HRR

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ABSTRACT

Recent fire tests for tunnels have suggested high fire heat release rates (HRRs), of the order of 100 to 200 MW, may be appropriate under certain conditions. The actual design fire used for a given tunnel will likely be determined from a quantitative risk assessment, an assessment of the maximum HRR expected in the tunnel, or be specified in a project requirement. This paper does not focus on the selection of a design fire HRR, but rather its implications on the ventilation system in short tunnels.

For short road tunnels there are practical limitations to the size of a longitudinal ventilation system, which can include space limitations, portal wind conditions and noise issues. This paper investigates the practical limitations of jet fan longitudinal ventilation for direction of travel smoke management schemes. It identifies that there is a maximum limit to the fire HRR that a jet fan ventilated tunnel of a given length can achieve. Beyond this limit a different smoke control scheme should be investigated or methods to reduce the anticipated design fire size (e.g. risk assessment).

The paper also provides some guidance on the impact of tunnel grade, area and noise criteria on the maximum limit. These results can be used by the designer to establish if a jet fan based longitudinal ventilation system is appropriate for a given tunnel and fire HRR.

Keywords: ventilation design, fire HRR, incident ventilation, short tunnels

1. INTRODUCTION

The design of a longitudinal ventilation system for short road tunnels provides unique challenges compared to longer road tunnels. Due to the length it is likely the design of the ventilation system will be driven primarily by emergency scenarios rather than the need to dilute vehicle emissions.

For short tunnels the dominant impacts on the ventilation system are tunnel area, tunnel grade, tunnel air temperature (as it affects buoyancy and jet fan de-rating), portal wind effects and tunnel acoustic criteria. However, the size of the ventilation system that can be installed is dependent on the length of the tunnel within the bounds of commercially available jet fan sizes. As a result, there exists a limit based on a tunnel's length and characteristics where a longitudinal smoke control system may become impractical. These considerations can become more critical for high fire HRRs.

The purpose of this paper is to investigate the effect of high fire HRR on the size of the ventilation system for short tunnels and identify an indicative limit to the size of the HRR that can be accommodated by a longitudinally ventilated tunnel of a given length. Beyond this limit alternative smoke control or egress strategies may be required or a re-evaluation of the design fire HRR (e.g. risk assessment). The investigation is based on simulating the performance of a tunnel ventilation system for tunnels of various lengths, grades and fire HRRs.

2. MECHANICAL VENTILATION OF SHORT ROAD TUNNELS

2.1. Short road tunnels

The requirement to mechanically ventilate short road tunnels varies around the world. In Australia, the New South Wales requirements are for any tunnels over 360 m in length to be mechanically ventilated (RTA 2006, [4]). Tunnels less than 360 m require a performance assessment. However, there are various examples within Australia of short tunnels being mechanical ventilated ranging from 180 m to 500 m.

In Europe a review of design guidelines suggests that the requirement for mechanical ventilation varies between countries from 250 m long to 500 m long (Fire in Tunnels 2006, [8]). In the United States, NFPA 502 requires mechanical ventilation for tunnels greater than 1000 m in length and should be considered for tunnels greater than 240 m in length (NFPA 502, [3]).

Based on the above it is likely that tunnel lengths from 300 m and longer may require mechanical ventilation. This paper has focussed on tunnel lengths from 300 m to 600 m.

2.2. Fire HRR and smoke management strategies

The fire HRR used for the design of a mechanical ventilation system is heavily dependent on the expected vehicle usage. Typical fire HRRs vary from 5 MW for passenger cars, up to 30 MW for some forms of large vehicles and 100-120 MW for dangerous goods vehicles (PIARC 1999, [6]). Some recent fire tests for tunnels have suggested fire HRRs in the order of 200 MW may be possible under certain conditions. NFPA 502 nominates 70-200 MW for HGV's and 200-300 MW for tankers.

The choice of a design fire HRR will likely be determined from a quantitative risk assessment, an assessment of the maximum HRR expected in the tunnel, or be specified in a project requirement. This paper does not focus on the selection of a design fire HRR, but rather its implications on the ventilation system in short tunnels.

For a longitudinal ventilation system the smoke management strategy has been described in various documents (including PIARC 1999, [6]). The fundamental goal of longitudinal ventilation is to provide airflow in the direction of travel to prevent smoke back-layering upstream of the fire location. This provides tenable conditions for occupants upstream of the fire and an access path for fire service intervention.

2.3. Longitudinal ventilation issues

The momentum equation for a jet fan based longitudinal ventilation system has been developed previously and documented various times (Armstrong et al. 1994 [1], PIARC 1995 [5]). A simplified form is reproduced in equation 1.

$$\sum_{i=1}^{N} \Delta P_{JF,i} = \Delta P_{Tunnel} + \Delta P_{wind} + \Delta P_{Bouyancy} \quad \text{-(1)}$$

Where:

ΔP_{JF}	=	Total pressure rise provided by the jet fans (Pa)
ΔP_{Tunnel}	=	The sum of the pressure loss in the tunnel (e.g. hydraulic losses including tunnel friction, vehicle drag resistance and tunnel losses such as entry contraction losses) (Pa)
ΔP_{wind}	=	Pressure loss from wind forces acting on the portals (Pa)
$\Delta P_{buoyancy}$	=	Buoyancy induced pressure loss due to high temperature smoke (Pa)

For a short tunnel, as distinct from a longer tunnel, the relative contribution of the different pressure terms can vary significantly. In particular, the adverse portal wind pressure (ΔP_{wind}) dominates the contribution from the tunnel resistance (ΔP_{Tunnel}) at shorter tunnel lengths.

At high grades the buoyancy force of the hot smoke is also a considerable driver of the total tunnel thrust requirement (Reiss et al. 2001, [7]). The tunnel air temperature will be significantly hotter in the first 500-1000 m of a fire incident and as a result the buoyancy force for short tunnels will likely be a larger proportion of the total required thrust compared to longer tunnels.

The pressure developed in a tunnel section by the action of a jet fan has been described in several references (Armstrong et al. 1994, [1]) and is shown in equation 2.

$$\Delta \boldsymbol{P}_{\boldsymbol{JF,i}} = \frac{\rho\beta Q_f v_f}{A_T}\left(\mathbf{1} - \frac{v_f}{v_T}\right) \qquad \textbf{-(2)}$$

Where:

Q_f	=	Flow rate through jet fan (m^3/s)
v_f	=	Jet fan discharge velocity (m/s)
v_T	=	Tunnel velocity (m/s)
β	=	Jet fan installation factor (-)
ρ	=	Air density (kg/m^3)
A_T	=	Tunnel cross-sectional area (m^2)

Downstream of a fire incident the tunnel air density ρ and tunnel velocity v_T change with temperature. The effective result is a significant reduction in jet fan thrust downstream of a fire incident. It is also common practice to assume that jet fans located in the vicinity of a fire incident have failed due to the impact of the fire and cannot be relied upon to provide additional tunnel thrust. The combined effect is that for various scenarios it can be difficult to provide sufficient jet fan thrust in a short tunnel.

3. METHODOLOGY

A generic tunnel was analysed to investigate the effect of HRR on the ventilation system performance for a given tunnel length.

The performance of a generic tunnel was simulated for various tunnel lengths, tunnel grades, tunnel areas and fire HRRs to determine the required longitudinal thrust to achieve critical velocity. The simulations were undertaken using SES2000 and the critical velocity was calculated using the critical velocity equation (Kennedy 1996, [2]). The results presented in this paper are based on 144 SES simulations, although numerous iterations were required to estimate the required thrust. A scripted approach was used to generate, run and post-process the models.

A generic tunnel shape was assumed for a 2 and 3 lane tunnel and is shown in **Figure 1**. Other simulation inputs are shown in **Table 1**.

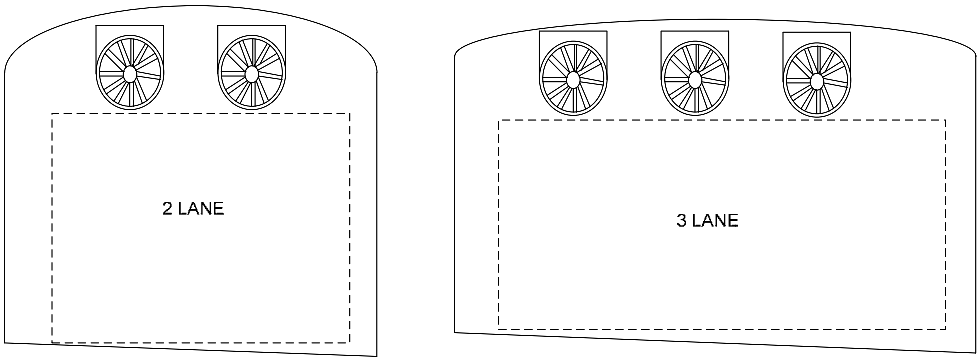


Figure 1: Generic 2 and 3 lane tunnel shape

Table 1: Model Inputs

Parameter	**Value**
Tunnel friction factor	0.035
Tunnel area (2 lane)	66 m^2
Tunnel area (3 lane)	91 m^2
Tunnel grade (constant along length of tunnel)	0 to -5%
Physical limit (max) jet fan catalogue thrust	2500 N (per jet fan)
Acoustic limit jet fan catalogue thrust	1800 N (per jet fan)
Installation factor	0.85
Adverse portal wind velocity (pressure)	5 m/s (15 Pa)

The maximum available (or installed) thrust for a generic tunnel configuration was based on applying best practice for the design of a jet fan based longitudinal ventilation system. This included a separation equivalent to 10 hydraulic diameters between jet fan banks, the loss of one bank of fans in a fire and commonly used installation factors for fan location relative to tunnel ceilings and walls. The maximum jet fan thrust was estimated from manufacturer data assuming no-special high thrust fans (i.e. catalogue available jet fans only).

The size of jet fans that can be installed at a given tunnel location is primarily dependent on the size of the tunnel and the project's acoustic criteria (if any). For a project with no acoustic criteria, a maximum jet fan thrust of 2500 N was assumed. For projects with an acoustic criteria (e.g. 85 dBA at 1.5 m above the walking surface for emergency scenarios) a maximum jet fan thrust of 1800 N was assumed. The selection of 1800 N thrust was based on simple acoustic analysis and verified by recent commissioning experience on a 3 lane 450 m longitudinally ventilated tunnel.

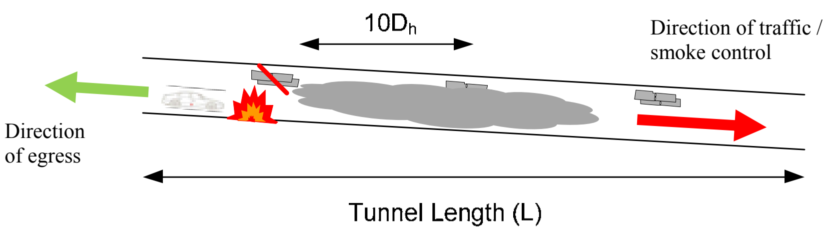


Figure 2: Jet fan installation and fire scenario

It should be noted that this investigation used idealised inputs and best practice installations. It is possible that more jet fans could be installed at a given location, the separation between jet fans relaxed or larger jet fans installed. This would need to be considered on a project specific basis and appropriate analysis undertaken.

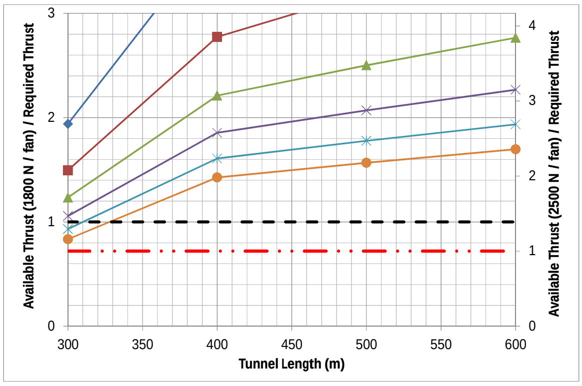
4. RESULTS

The results of this investigation are shown in Figure 3. The results are plotted separately for the different fire HRR's of 30 MW, 50 MW and 100 MW, and for two different tunnel areas. The graphs are normalised by the maximum available jet fan thrust that can be achieved for a given tunnel length with an acoustic criteria (left axis) and without an acoustic criteria (right axis). If a data point sits above the horizontal criteria line (i.e. greater than unity for a given criteria) then the available thrust is sufficient for the given tunnel length, grade and fire HRR. Conversely, if the data point sits below the horizontal criteria line (i.e. less than unity for a given criteria) then the available thrust is insufficient. If a data point sits between the acoustic criteria and physical limit lines then a jet fan based longitudinal ventilation system will only be suitable if there is no acoustic criteria set.

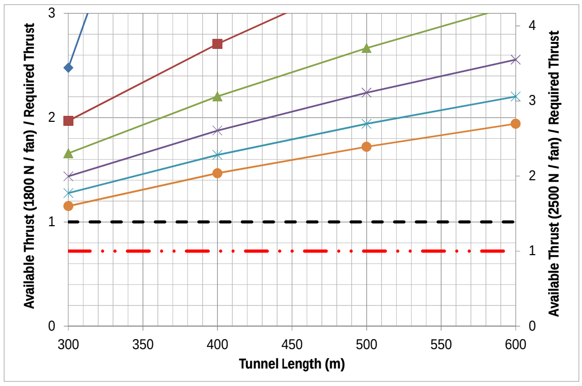
Panels A and B of figure 3 show that, for the tunnel studied, critical velocity can be achieved for a 30 MW fire for the majority of grades and tunnel lengths. However, for the 300 m long, two lane tunnel at high grades (4-5%), there is insufficient thrust to achieve critical velocity for the case with an acoustic limit.

For a 50 MW fire, Panel C shows that, for the two lane tunnel studied, there was insufficient available thrust for a 300 m long tunnel at grades of 3-5%. The inclusion of an acoustic limit made it difficult at 2% grade. Panel D shows that for the 3 lane case there is sufficient available thrust for all cases unless an acoustic limit is applied. In the case of an acoustic limit for a 300m long tunnel and 3-5% there is insufficient available thrust.

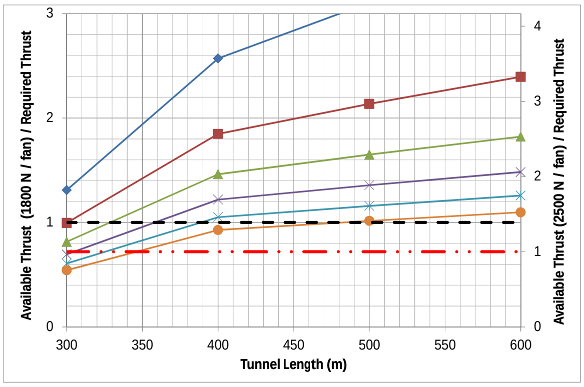
For a 100 MW fire, Panel E shows insufficient available thrust in a two lane tunnel at high grades for all tunnel lengths. For lengths of 400-600 m the results show that critical velocity can be achieved at low (0-1%) grades; however, introducing an acoustic limit results in achieving critical velocity at low grade (0-1%) for tunnels of 500-600 m in length. For the 3 lane tunnel (Panel F) the outcome is improved slightly due to the additional jet fan per bank. However, there is still insufficient thrust for a 300 m tunnel at all grades, albeit 0 and 1% grades can be ventilated without acoustic criteria.



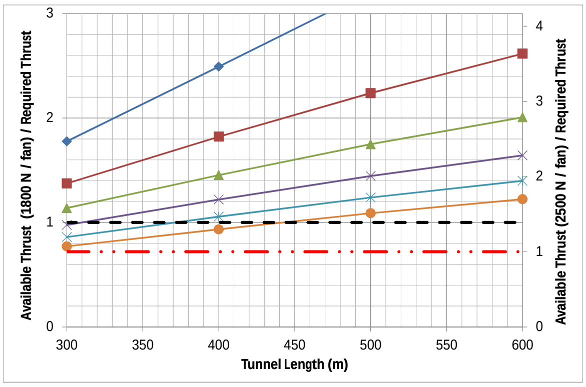
(A) 30 MW design fire, 2 lane tunnel (CSA = 66 m^2)



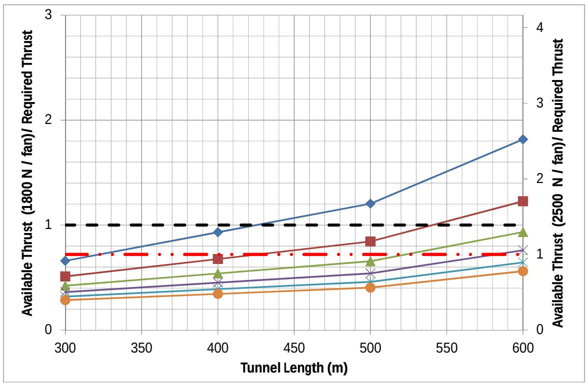
(B) 30 MW design fire, 3 lane tunnel (CSA = 91 m^2)



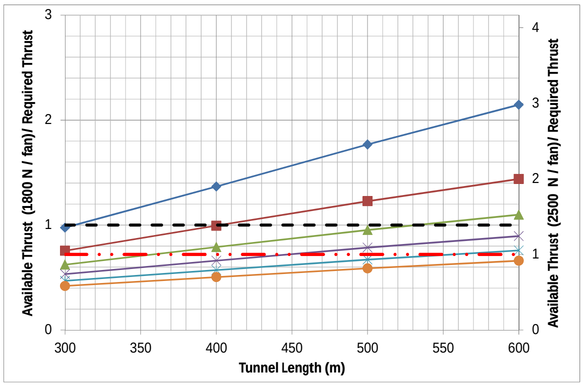
(C) 50 MW design fire, 2 lane tunnel (CSA = 66 m^2)



(D) 50 MW design fire, 3 lane tunnel (CSA = 91 m^2)



(E) 100 MW design fire, 2 lane tunnel (CSA = 66 m^2)



(F) 100 MW design fire, 3 lane tunnel (CSA = 91 m^2)

Key:

Grade = 0% | Grade = 1% | Grade = 2% | Grade = 3%

Grade = 4% | Grade = 5% | Acoustic Limit | Physical Limit

Notes:

1. Acoustic limit jet fans (1800 N) based on achieving 85 dBA at 1.5 m above the walking surface. Refer to left y axis for acoustic limit analysis.
2. Physical limit jet fans (2500 N) based on maximum catalogue fan for the nominal tunnel. Refer to right y axis for physical limit analysis.
3. Best practice jet fans installations at separations of 10 tunnel hydraulic diameters. The first jet fan is at 50 m within the inlet portal.
4. Fire located at 50 m within the inlet portal. First jet fan bank assumed to be destroyed by fire. Downstream fans are temperature de-rated.
5. If the ratio of required thrust to available thrust is greater than unity (for a given y axis) then longitudinal ventilation is suitable.

Figure 3: Investigation results

5. CONCLUSION

Short tunnels provide a unique challenge for smoke management by longitudinal ventilation systems. This is especially the case for tunnels with high fire HRRs. A generic tunnel has been investigated and the required thrust to achieve critical velocity has been simulated for various fire HRRs, tunnel grades, tunnel areas and tunnel lengths. The required thrust has been compared against the maximum available thrust for a given tunnel length with a longitudinal ventilation system designed with “best practice parameters”. The results of this investigation indicate that:

- For short tunnel lengths there is a practical limit to the fire HRR that can be accommodated by a jet fan based longitudinal ventilation system.
- The HRR limit for a jet fan based longitudinal ventilation system for a given tunnel length varies significantly based on tunnel grade and cross sectional area (Likely driven by the increase in space for additional jet fans in a larger cross section)
- The addition of an acoustic limit reduces the available thrust (i.e. lower noise generally equates to lower thrust per fan) and further limits the HRR that can be accommodated.

The ventilation system for a given tunnel should be designed on a case by case basis. However, this paper indicates there is a limit to the HRR that can be longitudinally ventilated. Beyond this limit, alternative smoke management strategies (e.g. Saccardo nozzles), egress strategies (e.g. longitudinal egress passages and / or closer exit door spacing) may need to be adopted or a re-assessment of the design fire HRR.

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MECHANICAL SMOKE EXTRACTION FOR LARGE FIRE LOADS IN THE GOTTHARD BASE TUNNEL

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ABSTRACT

The new Gotthard Base Tunnel will be used by passenger and freight trains, whereby the latter ones may carry heavy good vehicles with large fire loads of up to 250 MW.

As a case study, the impact of these fires was studied with respect to the mechanical smoke extraction, the resulting concrete and air temperatures, and their influence on airflow and subsequent fan operation points. One-dimensional flow simulations combined with a radial shell and a linear layer model for concrete temperature simulation were performed.

The following topics will be addressed in the article:

- Modelling of 40 and 250 MW fires, the smoke extraction system and the entire concrete plenum system.
- Air and concrete temperatures in the smoke exhaust plenums and requirements for the concrete structure and technical equipment, such as doors and exhaust fans.
- Heat fluxes and balances throughout the duration of the fire.
- Impact on the overall pressure loss, volume and mass flows, and operating points of the smoke exhaust fans.
- Simulation of further effects, such as buoyancy and heat penetration into walls of concrete.
- Impact on the design of the smoke exhaust fans and the concrete structure.
- Measures to ensure the function of the smoke exhaust fans.

Keywords: mechanical smoke extraction, large fire loads, modelling of concrete plenum system and smoke extraction system, one dimensional flow simulation

1. INTRODUCTION

The new Gotthard Base Tunnel (GBT) consists of two 57 km long single-track tunnels, which are connected by cross passages. Two multifunction station are placed at 20 and 40 km from the northern portal of the tunnel. Changing lanes and emergency stations as well as technical rooms accommodated for rail operations and ventilation installations are situated in the multifunctional stations. The GBT will be in operation by the end of 2016. Each multifunction station consists of two emergency stations, which can be fully ventilated by air inlet through the escape doors and by smoke extraction. The smoke extraction is designed for a volume flow up to 250 m^3/s.

The fire load of a passenger train is assumed not to exceed 40 MW. When a fire is located on a passenger train, the train in intended to stop in the next emergency station and the exhaust fans are activated.

Beside the passenger trains, the GBT will be primarily used by freight trains and occasionally by trains carrying heavy good vehicles with large fire loads of up to 250 MW. In case of a fire, these trains are not meant to stop in the emergency stations but to get out of the tunnel. In case of the stopping of a freight train at the emergency station, the exhaust fans will not be activated, nor will any damper be opened. Still, as a case study, the impact of a fire with a fire load of 250 MW, combined with the activation of the exhaust ventilation system, was studied.

The impact of these fires was studied with respect to the mechanical smoke extraction, the resulting concrete and air temperatures, and their influence on airflow and subsequent fan operation points.

Various simulations were performed for all emergency stations of which are two at Sedrun and two at Faido. The concept of the smoke exhaust plenums is demonstrated in Figure 1.

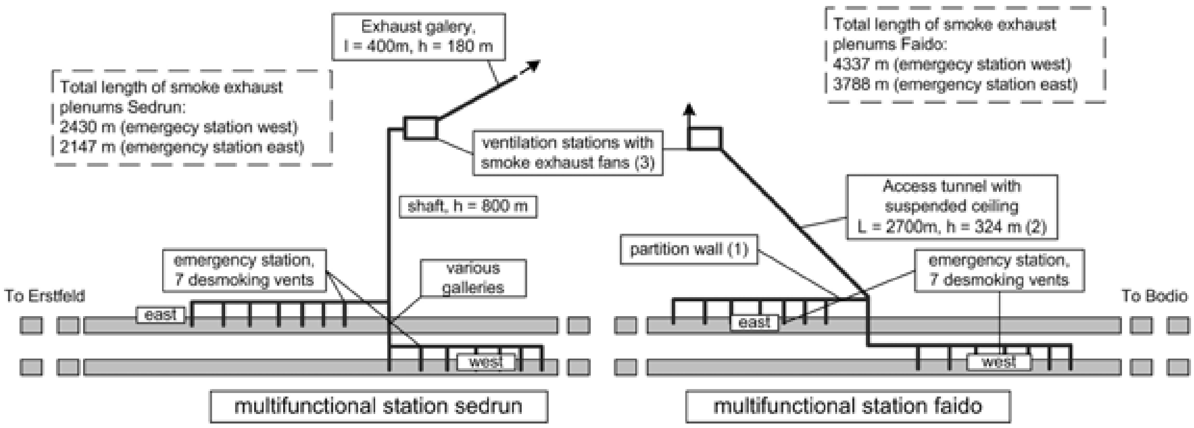

Figure 1: Geometry of the smoke exhaust plenums

2. SIMULATION AND MODELING

2.1. Numerical flow simulation

The impact of the fires was studied with numerical flow simulations, which involved a large number of boundary conditions, dependencies and influences. Therefore, a complex aerodynamic and thermodynamic simulation system was needed. The aerodynamic conditions of the smoke flow had to be linked to the thermodynamic behavior of the smoke and the surrounding concrete structure.

The aerodynamic model used was one dimensional in the direction of the air flow and transient; no branches such as leakages or parallel flow were simulated. Using a conservative approach, it was decided not to simulate any leakages, as they would result in lower gas temperatures in the smoke exhaust plenums. The air volume was discretized in length and time. A typical element length was 20 m, time steps varied between 0.1 and 0.5 s. Due to the high temperature and large altitude difference, the density was variable and calculated by pressure and temperature for each time step and element. An explicit finite volume approach was used to solve the differential equations. Each element was determined by geometrical and physical parameters like altitude difference, pressure drop coefficient, surface area et cetera. Further influences like standing trains in the tunnel, exhaust fans and fire loads were also placed in the simulation model. The thermal condition was calculated for every timestep and every element of the smoke exhaust plenum. Two thermodynamic models for concrete and rock were used to simulate the impact on the surrounding concrete:

- A radial shell model was used for all tunnels, caverns, shafts surrounded by concrete and rock. The rear boundary condition was thereby a constant temperature at a depth of 1 m.

- A linear layer model was used for all partition walls/ceilings that were vented on the rear via the makeup air. The rear boundary condition was a constant air temperature. The heat transfer coefficient between the air and the wall is calculated on the basis of forced or free convection.

The two discretization models were then combined to give a good approach of the real geometry. A typical discretized model of an access tunnel can be found in **Figure 2**.

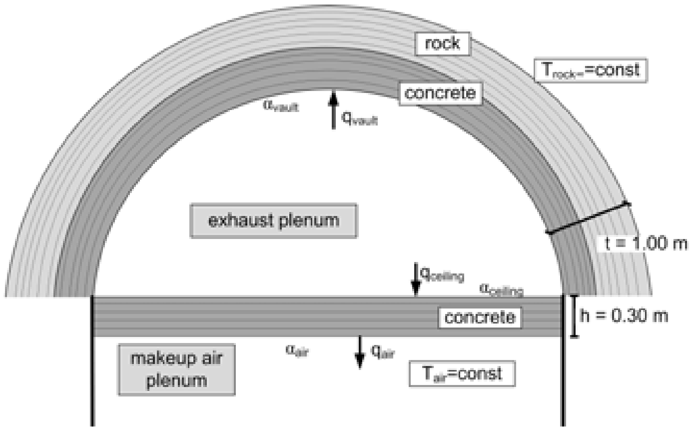

Figure 2: Typical discretized model of the smoke exhaust plenum in an access tunnel showing makeup air below the suspended ceiling.

The heat transfer coefficient α, which describes the convective heat flow from the air/smoke into the concrete surface, is critical parameter for the calculations. The heat transfer coefficient α is calculated, using the following formula (Incropera 2002, [1]):

$$\alpha = 0.027 * \mathrm{Re}^{0.8} * \mathrm{Pr}^{\frac{1}{3}} * \left(\frac{\mu_{LL}}{\mu_{LW}}\right)^{0.14} \frac{\lambda}{d_{hydr}} \tag{1}$$

with

μ_{LL} : Dynamic viscosity of air at air temperature

μ_{LW} : Dynamic viscosity of air at wall temperature

Re: Reynolds number

Pr: Prandtl number

λ: thermal conductivity of air [W/mK]

d_{hydr} = hydraulic diameter

Due to the use of correction factors and temperature dependent values for the calculation of the Reynolds number, this formula is valid for a large temperature range. The heat transfer coefficient for the present simulations is 10-50 W/(m^2/K).

2.2. Modelling of the fire

The simulations were based on two fire load curves for a passenger train (P_{peak} = 40 MW) and a freight train (P_{peak} = 250 MW). The fire load curve of the freight train corresponded to the simultaneous fire of 12 freight trailers.

The fire load of the passenger train rose in its first 70 min to a size of 20 MW from where it further increased to a maximum size of 40 MW after 360 min before it finally stopped after 480 min.

For the freight trains, the fire load at the beginning of the simulation was 180 MW from which it grew after 30 minutes to its peak of 250 MW, where it remained for 150 minutes.

The total heat released by the fire was calculated by the fire load multiplied by a factor of 0.9 for the degree of conversion of the burning material. The heat that the fire emitted by radiation heat transfer was calculated as a fixed percentage amount of the total fire load.

The radiation heat transfer from the hot gases into the smoke exhaust plenums was neglected, resulting in higher exhaust gas temperatures, as the hot gases are significantly warmer than the surrounding walls.

The duration of the simulations covered the entire duration of the fire. Due to the immense amount of heat stored in the concrete exhaust plenums, even after hours, the exhausted air was still relatively hot.

2.3. Modelling the exhaust fans

The smoke exhaust plenums were separated from the tunnel through exhaust dampers. The conservative assumption was that the train would already be burning while entering the emergency station and that the exhaust fans were already operating.

The exhaust fans in Faido are placed at the outer end of the smoke exhaust plenum. At Sedrun, the fans are located at 400 m from the outlet in an underground cavern.

The exhaust fans are equipped with a blade angle control system and frequency converters. In case of an event the exhaust fans run at a constant speed on a characteristic curve with a maximum flow rate. This characteristic was incorporated into the simulation program and served to determine the air flow in the system.

3. RESULTS

Simulations of fires in passenger trains (40 MW) and freight trains, carrying heavy good vehicles (250 MW), in all four emergency stations were examined. The results are illustrated using the example of Faido East emergency station with fire on a freight train. In this case, several effects can be well studied. Where it makes sense, results from other emergency stations are added.

3.1. Exhaust gas temperature

One important variable is the exhaust gas temperature, which strongly depends on the distance from the fire. In Figure 3 these temperatures are shown in relation to the distance to the fire. Due to the large length of the exhaust system (the access tunnel length is 2700 m), the air significantly cools down on the way to the portal. The maximum air temperatures shortly behind the fire area depend on the fire load and the mass flow. The moved mass flow decreases notably after the outbreak of the fire, because the hot air creates a greater resistance to the flow (seen also Section 3.3). Due to the powerful exhaust system, which can extract large amounts of exhaust gas, the maximum exhaust gas temperatures do not exceed 730 °C. The temperature variation over time is shown in **Figure 4**. After 180 minutes the fire diminishes. At this time the maximum air temperatures are reached. An exception is the area near the portal, which has a distance of more than 3000 m to the fire. The gas temperatures in this area continue to rise and reach their maximum after 210 min, due to the enormous amounts of heat, which remain stored in the concrete surrounding.

At Faido the fans are located at the very end of the exhaust duct where the exhaust gas temperature could reach a maximum of 100 °C. At the Sedrun exhaust fan central, much higher smoke temperatures of 240 °C are achieved. The heat resistance requirements for all fixtures and exhaust fans could be derived from the smoke exhaust temperature. Since the temperatures represent mean values, a safety margin had to be added.

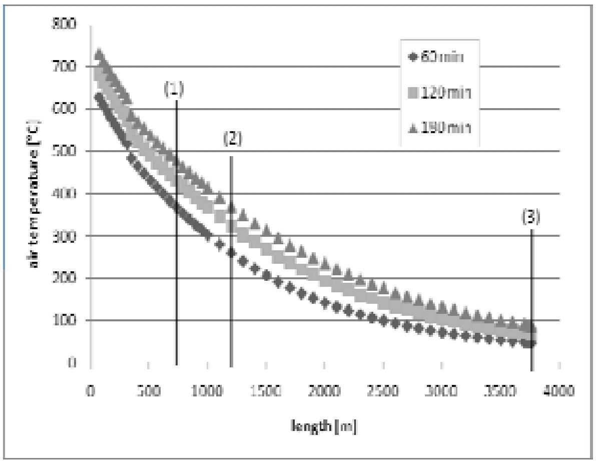

Figure 3: Air temperature in the exhaust duct

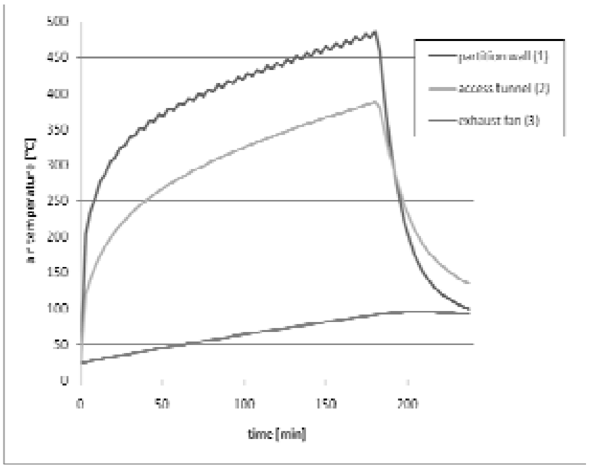

Figure 4: Temperature at points (1), (2) and (3) in relation to time

3.2. Concrete and rock temperature

The concrete temperature is the critical variable for assessing the impact of fire on the concrete, particularly in relation to the explosive spalling of concrete. The most important factors are the concrete temperature (critical from 180°C to 250°C an higher), the temperature gradient in the concrete depth (critical from 5 K/mm) and the heating rate (critical from 2.5 K /min). All values can be extracted from the simulation results. A typical temperature profile for the vault and the concrete partition wall at the beginning of the partition wall (Pos. 1 in **Figure 1**) is shown in Figure 5 and Figure 6. While the exhaust gas runs in the first few hundred meters in special excavated galleries where the supply air and exhaust air plenums are separated by a partition wall. The escape routes follow the supply air side. This would result in high security requirements on that wall.

The comparison of Figure 5 and Figure 6 shows that due to the short fire duration of 180 min, only a very small fraction of the heat arrives at a depth of 30 cm. It is found that the use of different models (radial shell and linear layer model) leads to almost identical results. This distinction is important in geometry for simulations with much larger observation periods, such as climate calculations, or case of geometries implying small dimensions.

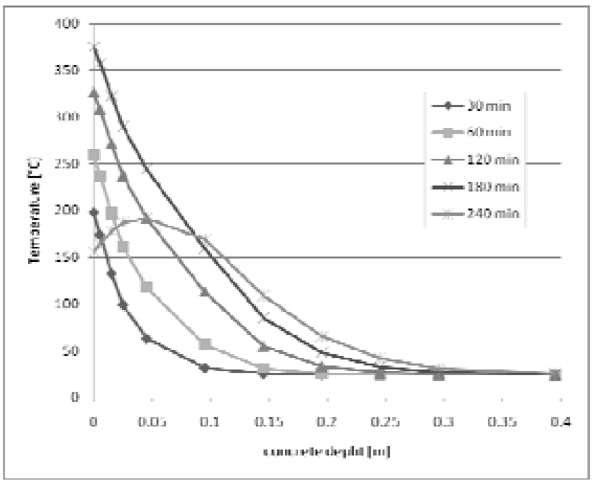

Figure 5: Temperature in the vault at the beginning of the partition wall (Pos. 3 in Figure 1)

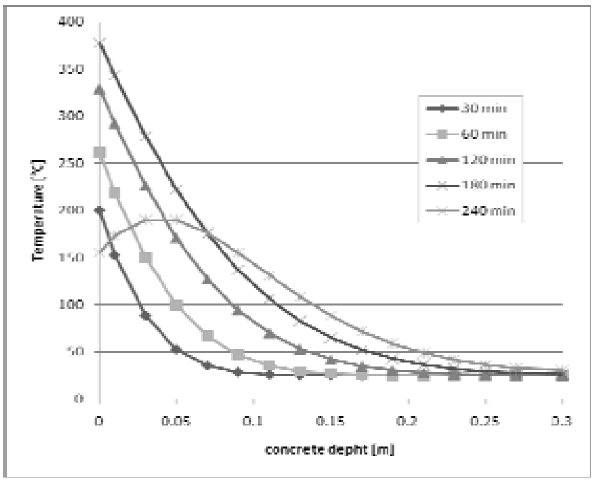

Figure 6: Temperature in the wall at the beginning of the partition wall. (Pos. 3 in Figure 1)

3.3. Mass and volume flow and exhaust fan operating point

As the air temperature increases rapidly, the air density in the exhaust system decreases. After 30 min, the density along the first half of the exhaust plenum is less than 0.8 kg/m^3, close to the fire it is significantly lower. At the fan station, the air density is > 1.0 kg/m^3. According to the mass conservation, a very large flow volume is achieved near the fire. This particular density leads to a higher system pressure loss, so that the fan runs on the characteristic curve in an area with higher pressures. The fans would need aerodynamic (distance to stall point) and engine power capacity to absorb these fluctuations of the operating point. This effect is partially compensated by buoyancy, which takes values in Faido of up to 1670 Pa. At Sedrun the situation is even better, as buoyancy pressures can reach up to 5000 Pa due to the 800 m high shaft.

By neglecting the buoyancy, the operating point of the exhaust fan Faido would rise within 30 min to a total pressure of 7870 Pa compared to 6800 Pa without fire load. At that time, the first part of the channel is dominated by high air temperatures. Far from the fire, especially at the position of the fan, still low temperatures are found. At the GBT the influence of buoyancy due to the differences in height between the fan and the central tunnel would be sufficient to ensure the proper function of the exhaust system even in such a scenario.

In case of the 40 MW fire load, the operation point of the exhaust fan Faido would rise to 7000 Pa, which is only 3 % more than without fire load.

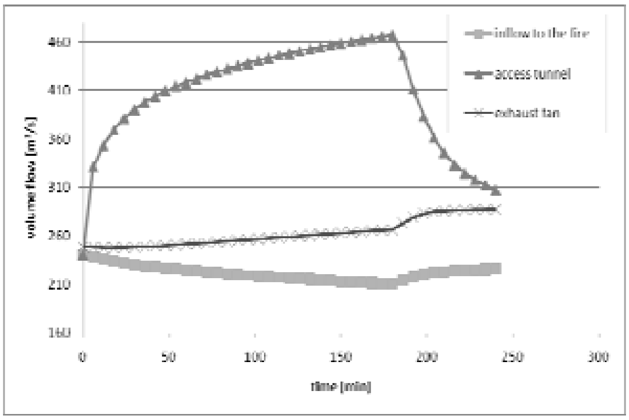

Figure 7: Volume flow in the exhaust duct

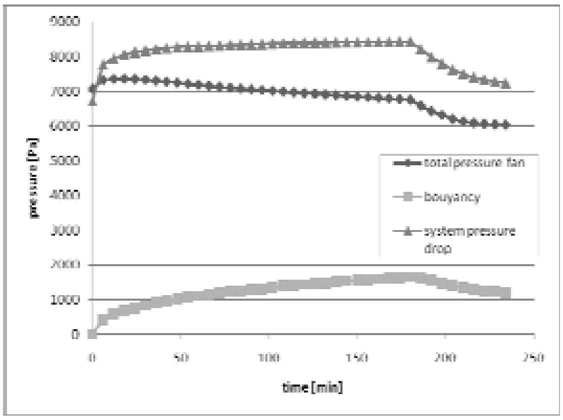

Figure 8: Pressure drop, fan pressure, buoyancy

3.4. Heat flow

In Figure 9 the released heat and the large heat flux into the concrete wall are shown. Accordingly, it takes a long time before the vault temperature has decreased. This effect was investigated in long-term simulations whereby even 5 hours after the fire had stopped, a heat flux of 12 MW was transmitted from the walls to the air.

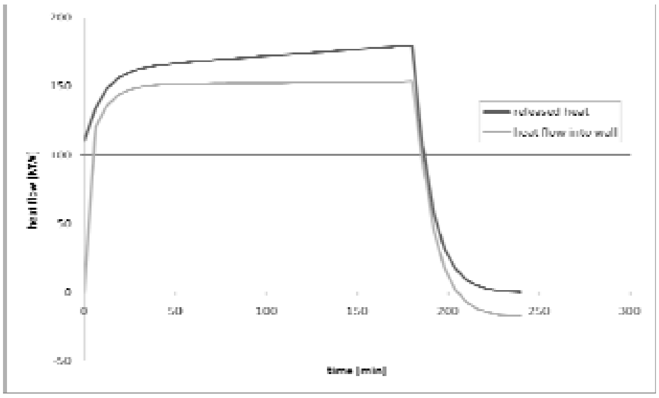

Figure 9: Heat flow into the wall and released heat

4. MEASURES

The exhaust system was designed for the 40 MW fire load according to a passenger train. Based on the current results for the 40 MW fire load and further studies, various measures have been designed and implemented to protect passengers and infrastructure. Polypropylene Fiber Concrete was used in some parts of the exhaust duct. Where necessary, the concrete structure was protected by an insulation acting as a fire protection layer. However, when set up in large areas, this method prevents less heat from flowing into the concrete, resulting in higher smoke temperatures.

All components of the ventilation system (dampers, fans) were designed so that they could fulfill 100 % of their capacity at the given temperatures. The fans have the necessary reserves of aerodynamic and engine power capacity to absorb the fluctuations of the operating point described above.

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MODELLING FIRE IN TUNNELS: A LARGE SCALE VALIDATED TWO STEPS MODELLING METHOD

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ABSTRACT

Fire is a quite common phenomenon in tunnel and being able to model its consequences with a good precision is crucial to design adapted safety measures. Modelling the fire behaviour in tunnel is quite challenging. Managing large scale experiment for all the possible configurations is however economically unrealistic. This paper presents an experimental real scale fire test that was used not only for demonstrating the fire behaviour but also for evaluating the capabilities of the FDS fire code to model fire consequences too. It enables highlighting the importance of wall and inlet boundary condition treatment.

Keeping in mind that predicting fire development using a CFD code is quite impossible, a two levels approach is discussed with an analytical model to predict the fire curve and a CFD model for predicting smoke propagation, temperature and toxic gases distribution inside the tunnel.

The comparisons show a good agreement between experimental fire test and CFD modelling but also let appear requirements when using CFD.

Keywords: CFD modelling, real fire experiment

1. INTRODUCTION

Fire in tunnels can generate dramatic consequences as shown in the past. Following the "Mont Blanc" fire in 1999, a new regulation was created in France with different prescriptions for safety measures. Those measures are of course hardly applicable to existing tunnel and must be adapted to the real risk.

The "tunnel du Roux", in Ardeche, a region in the middle of France, is a typical case where a compromise has to be found. This tunnel is located in a mountainous region invaded by snow during long periods in winter. This tunnel is then crucial for the local inhabitants. This tunnel is however not provided with safety equipment and the question of consequences in case of fire was asked. To demonstrate the smoke propagation and fire consequences inside the tunnel in case of a car fire, a real test was managed with different measures.

Then, to explore the different possibilities in terms of fire, and considering that it was unrealistic to manage several fire tests, for obvious economic reasons a coupled approach was validated on the experiments and then used for predicting consequences in other cases. This coupled approach includes a CFD model for predicting fire consequences associated with an algebraic model to predict the fire curve.

This paper presents the result of the experimental test and the comparison with numerical predictions.

2. TWO STEP MODELLING STRATEGY

Fire consequences modelling in tunnels requires predicting temperature raise inside the tunnel, smoke behaviour and toxic gases distribution inside the infrastructure. One of the key points in such a modelling consists in the definition of the evolution of the fire heat release rate with time used as an input in the 3D model. Regarding car fire, several tests were realised

(Okamoto et al. 2009) [1] or (Lönnermark et al. 2006) [2] and lead to normalized fire curve for such vehicles (CETU 2003) [3]. Such a curve does not however enable to predict real car fire considering these curve give just an estimation of the maximum power and duration linked with linear curve. Furthermore those curves are only provided for one "small vehicle" and one "large vehicle" while there is differences between vehicles. To make a better prediction of the heat release rate from a vehicle fire, a specific model was developed. The fire curve predicted using analytical model was then introduced in the FDS CFD fire code to evaluate the ability of this code to predict the fire consequences. Having validated the numerical approach, it was then used to model some other scenarios.

2.1. Mathematical modelling of a car fire

Considering total heat release rate for a vehicle is governed by the heat release of the different components, this tool enables to compute the fire curve by summing the individual heat release, considering also a propagation time. The car is split into 5 parts, namely: wheels, engine block, interior, trunk and fuel tank. The average combustion velocity and heat of combustion is then computed for each part considering the distribution between following materials.

Material	**ΔH_c (MJ/kg)**	**v (g/m²/s)**
1- Polymers	35.0	20.0
2- Elastomers	35.0	20.0
3- Oil	40.0	30.0
5- battery	35.0	25.0
6- Tires	30.0	20.0
7- Fuel	42.0	55.0

Following relation is used for averaging:

$$\bar{\varphi} = \frac{\sum_i m_i \varphi_i}{\sum_i m_i}$$

m_i is the mass of i^{th} combustible and ϕ the interested quantity.

The non-combustible materials are considered as energy well. Each component fire curve follows three phases: the fire growth, a steady state and a linear decrease phase. The contribution of each element is then summed.

2.2. CFD fire modelling

As mentioned previously, the temperature and smoke distribution along the tunnel was modelled with a CFD code. The FDS fire code (McGrattan et al. 2008) [4] was used. It is clear that predicting the fire growth and evolution with a CFD code is quite difficult (Sanchez 2009) [5] but this code was largely validated for smoke propagation prediction in tunnel (Truchot et al. 2009) [6] or (Hwang 2005) [7], this paper provides a validation for a real car fire in naturally ventilated tunnel. It also highlights the importance of the boundary conditions. It was then chosen for the present modelling. This code enables solving the fluid mechanics equations, continuity, momentum and energy in the computational domain. It also permits to manage largely parallel computations with an acceptable speed-up.

One important point to be mentioned is that turbulence modelling is based on an LES approach. This of course influences the mesh generation because of the constraints imposed by such a modelling approach. For such an LES modelling approach, the cutting scale, defined by the cell size, must be placed in the inertial zone of the turbulence spectrum. This will be highlighted in the numerical description of the paper. It is also important to have in mind when using an LES approach for smoke propagation in tunnel with natural ventilation that the turbulent fluctuations due to external wind perturbations must be considered. The turbulence intensity has to be modelled through velocity fluctuations on tunnel portal. This was done using a sinusoidal variation along time with measurement based frequencies.

It was also demonstrated that predicting the correct smoke behaviour, including the backlayering phenomena requires to model tunnel walls characteristics with a great precision (Truchot et al. 2009) [6]. This is to have a good prediction of the energy transfer from the smoke to the walls. This energy transfer is also crucial when considering the stratification of the smoke. This stratification results from the equilibrium between density gradient due to thermal effect that generates stratification and turbulent mixing due to the flow that destroys the stratification (Boehm et al. 2010) [7].

3. DESCRIPTION OF THE EXPERIMENTAL CAMPAIGN

3.1. Tunnel description

The “Tunnel du Roux”, is a 3 325 m long French tunnel located in Ardeche, in the middle of France, at 950 m of altitude. The tunnel section is about 41 m², **Figure 1**, and it has the particularity to be strictly linear. Safety measures in this tunnel are limited and it is not equipped with ventilation system. Consequently, smoke propagation in the tunnel is governed by pressure difference between tunnel portals, except in winter when one of the two portals is closed to prevent ice formation; there is then no flow inside. However, this closing door is equipped with an automatic system to let vehicle go through the tunnel.

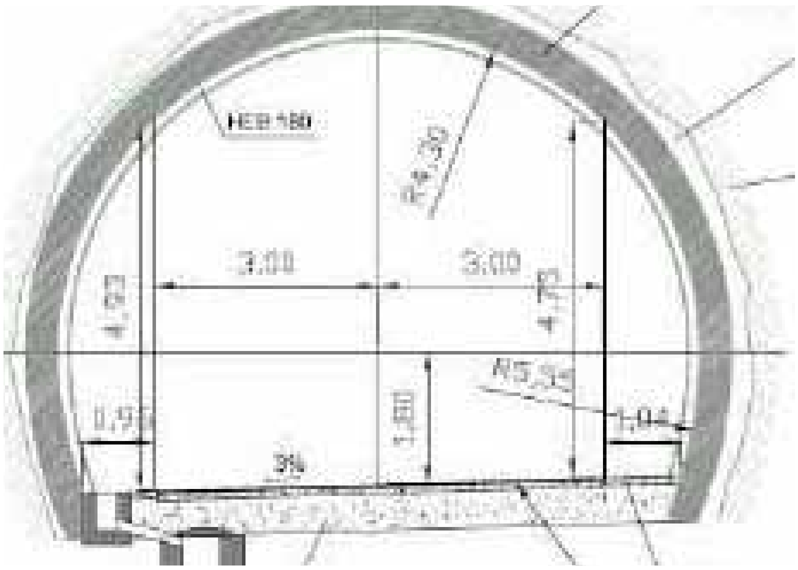


Figure 1: Section of the "tunnel du Roux".

3.2. Introduction of the fire source

The fire in the tunnel was produced using a real car, a Ford Fiesta, from which the main polluting materials as battery and oil were removed, **Figure 2**. The fuel tank was filled with 10 l of gas-oil and the fire was ignited on the passenger seat after having made a cut in its envelope to uncover the foam, several centilitres of heptanes were used for ignition.

Figure 2: Images of car used for the experiment.

Because of the natural ventilation of the tunnel and of the complex wind profile in the surrounding, it was impossible to predict the flow direction for the morning of the test. It was decided to locate the car at 275 m of the South portal of the tunnel.

The tunnel was protected from thermal effects along about 20 m with mineral wool to avoid damages during the test. Such a protection is of course to be considered when modeling the fire because it has an influence on thermal exchanges between smoke and tunnel walls.

3.3. Metrology

Several sensors were distributed along the tunnel to measure temperature, velocity and carbon dioxide concentration.

First of all, velocity (Mac Caffrey probes) and temperature were measured along the cross-section on each side of the fire. This enables to measure the convective power produced by the fire. This quantity is of course crucial for comparison between numerical modelling and experimental measurements. Then thermocouples were positioned in the fire area to follow the temperature evolution all along the fire near the tunnel roof, **Figure 3**.

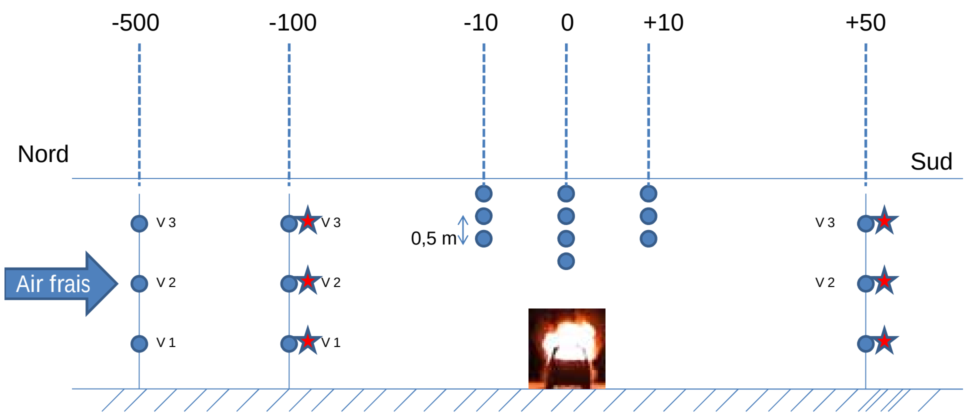


Figure 3: Position of sensors: thermocouples (circles) and Mac Caffrey probes (stars).

On top of those measurements, gas analysers were distributed along the tunnel with, mainly, one located 100 m downstream the fire.

4. MAIN EXPERIMENTAL RESULTS

It first must be notice that the wind was from North to South when fire test was made. The velocity of the air flow in the tunnel before the fire ignition was around 2.5 m/s, this means a natural air flow rate of 102.5 m^3/s.

4.1. Evaluation of the power release

The fire curve developed by the ignited car was computed from the experimental data based on the energy balance between fresh air and smoke. This consists in applying the first principle of thermodynamics on an open system.

Considering ϕ is an energy flux, the conservation of energy is then written:

$$\phi_{s1} + \phi_{s2} + \phi_{\chi} = 0$$

This means that outflow energy flux, ϕ_{s2}, equals the sum of entrance energy, ϕ_{s1}, and the energy produced by the fire, ϕ_{χ}. The power release by the fire was obtained considering both chemical, kinetic and sensible energy, **Figure 4**. This yields the convective heat release rate. The total heat release rate was then obtained assuming a radiative fraction of 0.3 [CETU 2003].

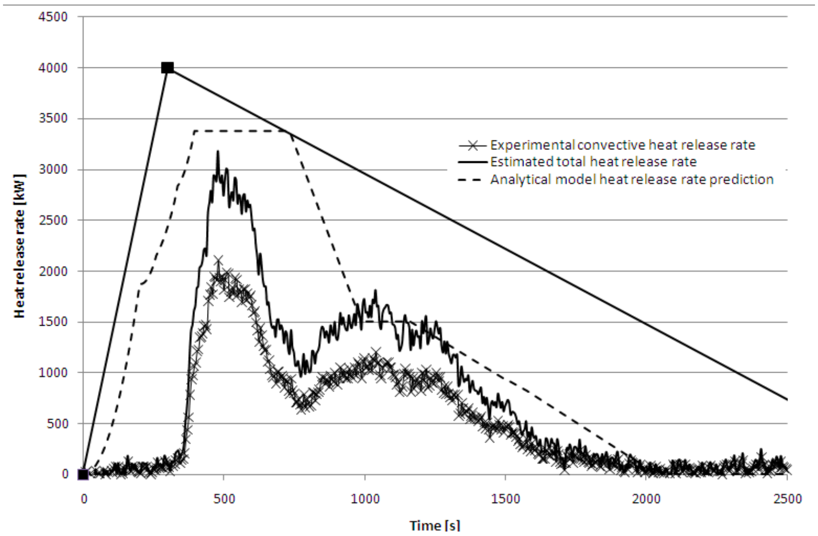


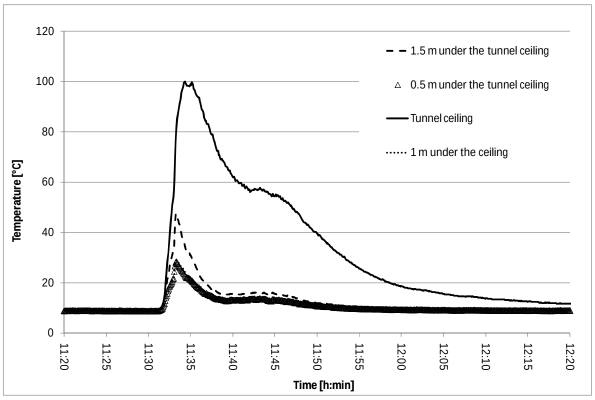
Figure 4: Fire curve determined using energy balance.

This curve shows a slow inflammation phase during the first minutes after ignition, then a quick increase of heat release rate due to the inflammation of all the combustible materials inside the car and finally a quite steady state before extinction. The maximum heat release rate reached by this fire is around 3 MW, 10 minutes after ignition.

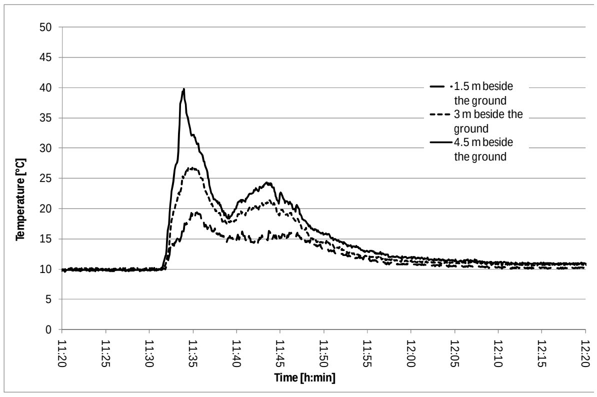
This curve also shows the ability of the analytical model to predict the car fire curve including both the maximum heat release and the combustion duration. Both those values are over estimated using the standard fire curves. One improvement in this model should be the consideration of the incubation time to improve the fire growth prediction.

4.2. Temperature distribution

Because of the low power developed by the fire in relation with the air flow, no backlayering was observed, the maximum temperature 10 m upstream the fire on tunnel ceiling was not modified from ambient, and fire influenced temperatures are located in the fire area and downstream the fire. The maximum temperature reached under ceiling in the fire zone is about 100°C. This is also the case for temperatures measured 50 m downstream the fire, **Figure 5**.



Evolution of temperature in the fire zone.



Temperatures 50 m downstream the fire.

Figure 5: Experimentally measured temperatures on fire zone and 50 m downstream the fire.

4.3. Visibility

Visibility measures inside the tunnel were done using a video camera and a calibrated source. One of the main results is the quick diminution of this visibility and the important smoke cloud generated by the fire.

5. COMPARISON BETWEEN NUMERICAL MODELLING AND EXPERIMENTS

5.1. Requirements for modelling

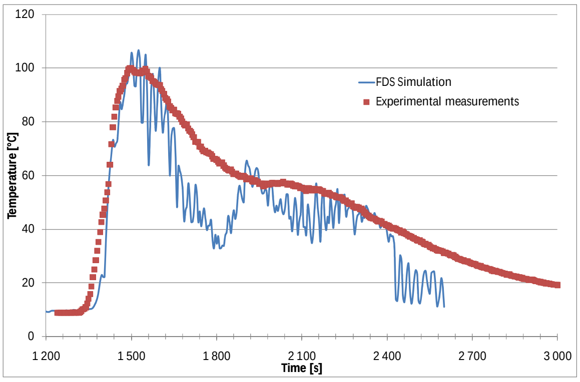
Following constraints mentioned in the FDS specific description, the mesh was built putting a minimum of 20 cells to capture the integral scale. For the validation part, a 1 300 m long part of the tunnel was modelled including the entire tunnel downstream the fire and around 1 000 m upstream to ensure an inlet independent flow. The total number of cells used for that case is 1 900 800 cells with a characteristic size of 20 cm in the fire zone.

The fire was modelled using the fire curve measured during the test considering a ramp based on the measurement. The fire was started 1200 s, 2.5 convective times, after the beginning of the simulation to let time for the flow to be established. To take into account the wind velocity fluctuations that occur outside and of course generate turbulence inside the tunnel, a sinusoidal signal was used [Mouilleau 2009] [8]. This enables to introduce some turbulence inside the domain as in the real configuration. These fluctuations were constructed on the basis of velocity measurement inside the tunnel.

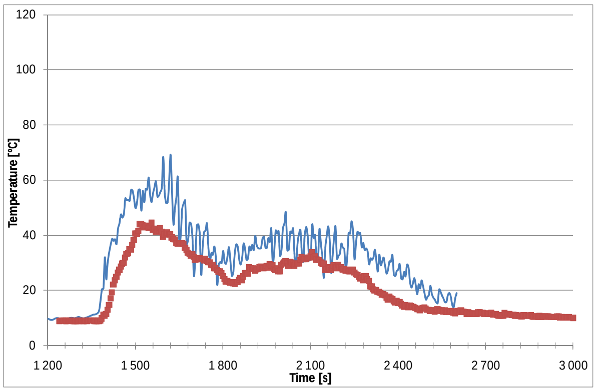
Finally, the tunnel walls were considered as rock with a thickness of 2 m with a conductivity of 3.5 W/m/K, a density of 2 600 kg/m3 and a specific heat of 1 000 kJ/kg/K. In the fire region, the product used for the tunnel thermal protection was modelled with its real characteristics including the evolution of the conductivity with temperature.

5.2. Comparisons

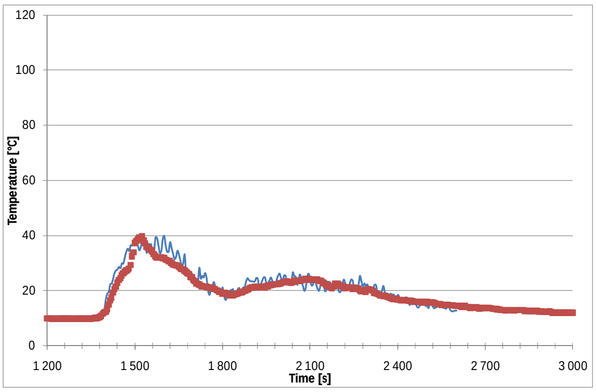
Numerically computed temperatures were first compared with experiment and show a good agreement, **Figure 6.** The fluctuations on the numerical curves are the consequences of the LES turbulence model used.



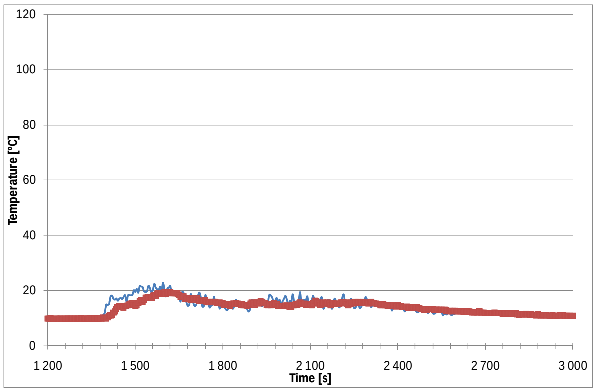
Temperature under ceiling beside the fire.



Temperature under ceiling, 10 m downstream the fire.



Temperature 4.5 m above ground,
50 m downstream the fire.



Temperature 1.5 m above ground,
50 m downstream the fire.

Figure 6: Temperature comparisons, legend is identical for all graphs.

Carbon monoxide concentration 100 m downstream the fire 1.5 m above ground were also compared between experiment and numerical simulation and confirm the ability of the CFD code to give a quite good overview of the fire consequences, **Figure 7**.

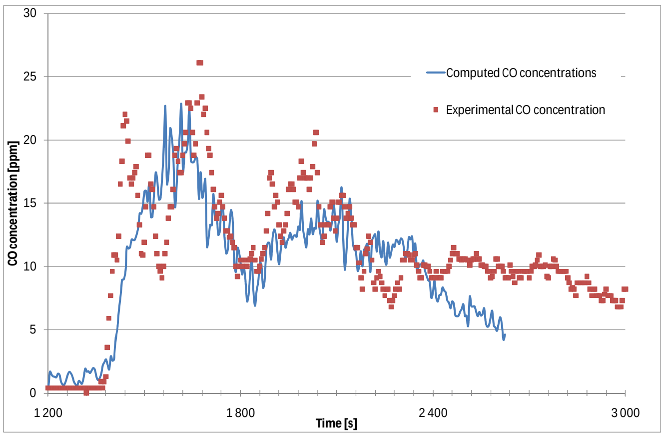


Figure 7: CO concentration comparisons.

These comparisons show the good agreement that can be obtained between experiments and simulations on some important parameters: the energy exchanges between smoke and walls and correct turbulence introduction in the numerical domain. This first simulation case was used to validate the numerical approach and the use of CFD to reproduce other configurations such as more powerful fires or other wind directions considering that all cases cannot be explored experimentally.

6. CONCLUSIONS

The aim of this paper was to present the experimental results and comparisons between experiments and numerical simulation. This paper shows that the analytical model developed for predicting the heat release by a fire of vehicle is able to predict the fire curve with quite a good precision including mainly the maximum value for heat release rate and the combustion duration. This is useful considering CFD codes encountered difficulties in such a prediction.

This paper also showed that, when using correct hypothesis, a CFD code is able to give good predictions of temperature, toxic gas concentration and visibility, i.e. all fire consequences, in the tunnel. The different simulations achieved in this study let appear 2 major elements that have to be accounted for to obtain quite a good prediction. The first is the turbulence in the entrance of the domain, if this is quite simple with a RANS approach, using LES introduces a difficulty and the velocity fluctuation must be considered. The second crucial point is the thermal effect of walls. The exchange between cold walls and hot smokes is fundamental for smoke behaviour modelling and mainly stratification that is based on the thermal gradient. In the present case, the various wall properties were considered.

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NEW TRENDS FOR USING LTHD IN ROAD AND TRAIN TUNNELS FOR FIRE DETECTION

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ABSTRACT

Line type heat detectors (LTHD) are used since many years in road tunnels for reliable fire detection. Today various systems as semiconductor sensor cables, fiber-optic sensor cables, and pneumatic copper tube systems are in use.

In addition, after first pilot installations done in the last years, the demand for applications of LTHD in railroad and metro tunnels as well as in underground stations is increasing. Today LTHD are installed in high-speed train tunnels in Spain, in train and metro tunnels in the Netherlands, and planned in metro networks in Singapore and Moscow. What can be learned from the road tunnel experience and what is new in rail tunnels?

In parallel, the request for systems with high availability and reliability is growing as well. Due to the increased safety requirements system failures are no longer tolerated. MTBF values and maximum false alarm rates are frequently discussed. Several guidelines as German RABT or Swiss tunnel fire detection guideline define some specifications for the availability of LTHD. The requirements in different countries are compared and discussed, resulting in a proposal for a uniform specification.

Keywords: tunnel fire detection, LTHD, linear heat detector, availability

1. LINE TYPE HEAT DETECTORS (LTHD)

In road tunnels, today line type heat detectors (LTHD) are most widely used for automatic fire detection. They are resistant to the aggressive environment in the tunnel with aggressive off gases, dust, humidity, salt mist, etc. and give a very reliable detection even of smaller car fires of few MW. In some countries, visibility monitors, special smoke detectors, or CCTV systems are added for early fire detection. However this should not be the focus of this paper. A more general overview on road tunnel fire detection systems can be found in (Rogner 2009, [7]).

The LTHD typically consists of a linear sensing element like an electrical cable or an optical fiber with a length of several 10 up to several 1000 meters, a central control unit, and some functional units as connectors, filters, terminators, etc. (see Figure 1). The output of the control unit (as alarms, errors, localization, and temperature profile) is usually given to a control and indication equipment like a fire alarm control panel or a process control system. Although LTHD are in use since more than 40 years, so far there has been no standard on these products in Europe for the fire detection application. During the last years a new European standard prEN 54-22 has been developed to cover this type of products. This standard should get effective within the next years. It should guaranty the quality and adequate alarm detection of such system.

Today various types of LTHD are available on the market with a range from very simple and cheap systems just indicating an alarm at a given temperature up to high-performance fiber optic or semiconductor systems reacting on absolute temperature value or rate-of-rise and giving exact temperature and localization information. Table 1 gives an overview on existing technologies and their specifications. The most used systems in European road tunnels today are semiconductor sensor cables and fiber optic sensor cables. Details on these two technologies are given below.

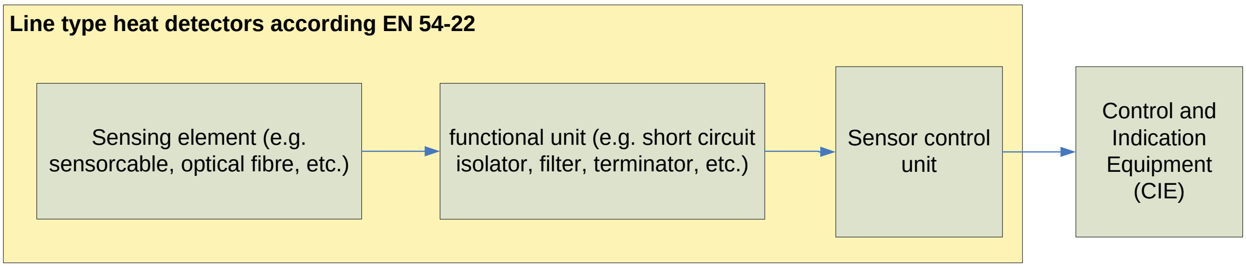

Figure 1: Elements of LTHD according to prEN 54-22 (Meer et al. 2009, [5])

Table 1: Overview on LTHD technologies

System	Measuring principle	Rate-of-rise detection	Typical sensor distance	Maximum system length	Temperature profile	Local resolution
Semiconductor sensor cable	Band-gap effect	yes	7 m…10 m	2500 m	yes	2 m…10 m
Fiber optic sensor cable	Raman scattering	yes	cont.	8000 m	yes	1 m…2 m
Fiber optic Bragg cable	Bragg grating	yes	3 m…5 m	300 m	yes	1 m…10 m
Pneumatic system	Gas expansion	yes	cont.	100 m	no	100 m
Analogue cable	Resistance	optional	cont.	300 m	no	300 m
Non-resettable cable	Melting polymer	no	cont.	250 m	no	250 m

In general it can be said that only systems with the possibility of rate-of-rise detection should be used. Only these systems can detect smaller car fires with 5 MW or less in reasonable time. A comparison of the result of different systems can be found in (FGSV 2005, [2]).

1.1. Semiconductor sensor cable

The temperature sensor cable usually consists of an electrical cable with integrated discrete semiconductor sensors in defined distances, usually between 4 and 10 m. The maximum length can be up to 2000 m. The measuring principle uses the band gap effect, i.e. the temperature dependence of the base-emitter voltage of a bipolar transistor. The information from the single sensors is transferred to a central control unit at the end of the cable. The information can be used to trigger alarms by absolute temperature thresholds or by temperature gradient thresholds. The reaction speed is middle (~ 60 sec for 5 MW fire) to high (~ 30 sec for 5 MW fire) depending on the different systems on the market and on the selected sensitivity. The temperature profile can be visualized and the different sensor can be configured with different sensitivities. The fault alarm rate is negligible, as there is not much interference with other events than fires.

1.2. Fibre optic sensor cable

The fibre optic sensor cables use OFDR (optical frequency domain reflectometry) or OTDR (optical time domain reflectometry). Both principles use Raman backscattering of a laser pulse as a basic effect, which is influenced by the heat induced grid oscillations of the glass fibre. In the OFDR the light pulse is frequency modulated to increase sensitivity. In the control unit, the temperature distribution is calculated from the backscattered light signals. The result is always a compromise between fibre length, temperature resolution, spatial resolution, and detection speed. The higher the desired accuracy and the longer the length of the fibre, the longer is the calculation time and thus the reaction time. The maximum length of the fibre optic systems is up to 10000 m. For the typical length and required resolution in road tunnels, the reaction speed is middle. The information can be used to trigger alarms by absolute temperature thresholds or by temperature gradient thresholds. The temperature profile can be visualized. The fault alarm rate is negligible, as there is not much interference with other events than fires.

2. RAILROAD AND METRO TUNNELS

Whereas the use of LTHD in road tunnels today is standard in most European countries, railroad and metro tunnels are in most cases not equipped with any kind of fire detection system. The detection is usually in the train engines and cars itself and in case of a fire the train should try to leave the tunnel or drive to the next station in case of underground systems.

However there might be specific situations with increased risks demanding the need for fire detection, fighting and escape installations compared to road tunnels. Using some typical examples the advantage of LTHD for such installations is shown.

2.1. Long train tunnels

During the last two decades, the construction of national and European high-speed train networks have started. Usually this results in completely new tracks involving long tunnels to optimize distance and allow high-speed tracks without many curves. In such long tunnels of several km to several 10 km length it might be difficult for the train to exit the tunnel in case of a fire. This means that the tunnel infrastructure has to include the possibility to detect and localize a fire, extract smoke and provide escape possibilities or shelters for the passengers. A fast detection and exact localization of such fires is of course essential for all subsequent activities, as we know from road tunnels. Actually ADIF in Spain is installing in its high-speed train network tunnels such kind of equipment in the tunnels, including fire detection by LTHD.

Taking the 28 km long Guadarrama tunnel of the Madrid-Valladolid line as an example, it has interconnection passages located every 250 m. In the middle of the tunnel is an emergency room between the two tubes. It will be 500 m long, with room for 1,200 people. The emergency room is equipped with its own ventilation system, which guarantees fresh air for 48 hours in case of fire. The tunnels will be monitored by a control center that will check the ventilation, gallery and emergency room air supply, energy, light, signaling, communications and fire extinguishing systems. It is using LTHD supported by visibility and CCTV for fire detection.

But also in Austria research is going on in this subject. The TUSI 2 project has investigated the possibilities to use LTHD for fire detection in train tunnels to increase the safety level. Results can be found in (Maly et al. 2009, [4]).

2.2. Train tunnels entering underground stations

Another application for LTHD can be train tunnels entering underground stations. The detection of a fire in an approaching train can be used to initiate the evacuation of the station and to trigger ventilation to prohibit smoke entering the station. We find such application again in Spain, in the Malaga central station. The 1600 m long access tunnel of the high-speed train entry is monitored by LTHD. Besides fire detection, the temperature profile option can be used to detect overheating events on entering trains and optimizing the ventilation system.

2.3. Cargo train tunnels with high risk

In Holland in 2007 the Betuweroute was opened. This is a 160 km long railway line connecting Rotterdam with Zevenaar close to the German border. It contains 6 tunnels, which have a combined length of approximately 15 km. The longest tunnel is 6 km in length. The intensive use of the line for transporting all types of freight, including hazardous substances, as well as the tunnel fires that occurred in Europe in the mid-90s, was the reason for tightening the requirements of the civil engineering design process for the tunnels. In the Betuweroute tunnels fire detection by LTHD as well as sprinkler systems for fire suppression are used (Jonker 2006, [3]).

2.4. Metro tunnels

Generally for metros today similar approaches than for train tunnels are used. The cars are equipped with a fire detection system and in case of a fire the train should go to the next station for firefighting. Also in the stations we find a good mix of temperature and smoke based fire detection systems and of course also ventilation and suppression systems. However there might be two reasons to install a detection system in the tunnel:

- If the tunnel between two stations is rather long and during the operation more than 1 train might be in this tunnel, a fast detection by LTHD might make sense. Subsequent trains can immediately be stopped to avoid getting them into the dangerous zone.
- In many metro tunnels electrical power and communication cables are installed being a continuous risk for fire. A fire detection system can identify any fire or overheating and stop traffic in the tunnel.

2.5. Similarities and differences to road tunnels

Although the environment of train and road tunnels might be similar on a first view, there are few points to pay attention in train tunnel fire detection:

- The train engines itself are a significant heat source. In case of slow driving trains or trains stopping in the tunnel, the heat of the engine should not create false alarms. Generally the thresholds have to be higher than in road tunnels or an intelligent reaction as multi-detector criteria have to be used.

- In high-speed train tunnels with a profile not much bigger than the train itself, the pressure waves in front and behind the train might induce significant mechanical stress onto the LTHD. Only mechanical robust systems are suitable in this environment.
- The high-voltage power supply for trains or high current power supply for metros might cause electromagnetic interference (EMI) with electrical measuring systems. Only systems with a sufficient protection can be used. The systems shall be tested according to EN 50121-4.

On the other side, as in road tunnels, the systems should provide the following most important features:

- fast detection of a train fire (detection of 5 MW pool fire in 60 seconds)
- Detection by absolute temperature or rate-of-rise
- Suitable for harsh environment
- Maintenance free (or maintenance restricted to once per year)
- Possibility to show a temperature profile

In summary we can see that there might be a good reason to use LTHD for fire detection also in train and metro tunnels with a high risk for the users. Although their installation is not yet widespread today, we see an increasing demand and several new installations. The same technologies as for road tunnels can be used; however the special requirements for train tunnels have to be taken into consideration for selection of the products.

3. AVAILABILITY REQUIREMENTS FOR LTHD SYSTEMS FOR TUNNEL APPLICATIONS

The best fire detection system does not fulfill its job, when it is not available all the time. In building fire detection systems ring lines and redundant control panels are standard. But what about LTHD for road tunnels? The most simple system consisting of a control unit and a temperature sensing element as shown in Figure 1 might easily fail, if the cable is interrupted or shows a short-circuit. As the systems in case of a damage or defect generally are not accessible, an increased resistance to failure or increased availability might be required.

Let us first have a look into different European guidelines for road tunnel safety equipment:

- German RABT (RABT 2006, [6]) says: *Line type heat detectors have to be divided into several sections. With destruction of one sector, the other sectors must remain functional.* However there is no clear hint, how large such sector might be. In addition to the LTHD, visibility monitors are used for early fire warning by smoke detection, giving a certain redundancy.
- Austrian RVS (RVS 2008, [8]) says: *The system has to be set up in a way that in appearance of a single defect (e.g. cable interrupt, failure of a control unit) maximum 1.000 m of the monitoring length can fail.* Do we really want to lose 1000 m of monitoring?
- The Swiss ASTRA guideline (ASTRA 2007, [1]) itself does not give any restriction. However the more detailed worksheets recommend using loop systems with control units at both sides of the LTHD resulting in continued operation in case of interrupt or alternatively LTHD and smoke detectors in parallel. In addition, a maximum of 1 false alarm per year and 2 km is fixed.

If we investigate the installations in European tunnels, we find the following solutions:

- Installations of digital, non-resettable systems reacting at a fixed temperature. The problem of these systems is that with a normal car fire of 3 to 5 MW and a wind velocity of several m/sec the temperature at the ceiling will not reach the values to trigger the alarm (Rogner 2009, [7]). So this type of cable can only detect heavy fires of trucks or other high loads of more than 10 MW. In consequence it is not in compliance with most actual directives and should not be used in road tunnels.
- Stub line systems with a control unit on one side only (Figure 2a). These systems definitely will fail completely or at least in part, when the cable is damaged.
- Stub line systems as above with additional smoke detection by visibility monitors or CCTV detection. This can be an option to ensure fire detection even in case of non-availability of the LTHD system. However it generally will mean increased attention of the control room, as smoke detection usually has to be confirmed manually to avoid false alarms.
- Loop systems, where the end of the cable is looped back to the control unit. This will help to avoid loss of the system in case of cable damage, as the sensing element is accessible from both sides. But what happens, if the control unit is having a failure? Moreover, in fiber optic systems very often the fiber is running back in the same cable. This might lead to loss of a part of the installation, if the cable is interrupted.

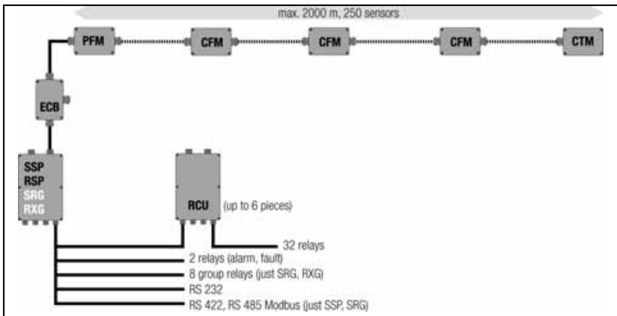

Figure 2a: Stub line installation

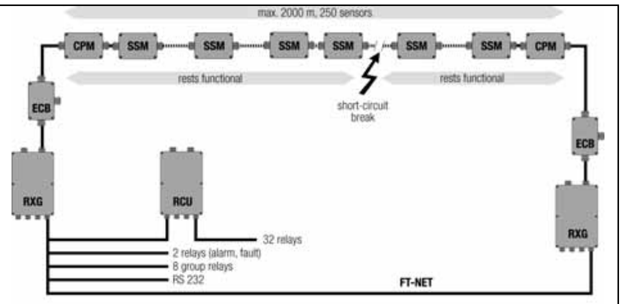

Figure 2b: Loop installation with 2 control units

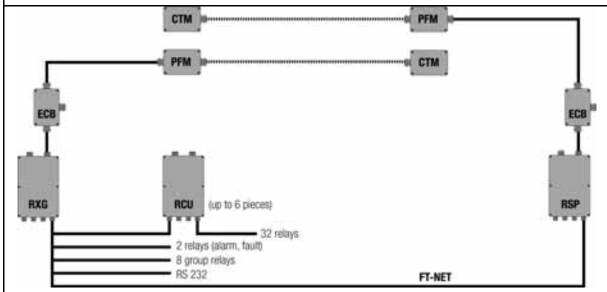

Figure 2c: Redundant installation

- Loop systems with two independent control units at each end of the cable (Figure 2b). Finally this is the only configuration ensuring continuation of the monitoring even in case of interrupt or damage of the cable or a control unit.
- Redundant installation of two stub line system (Figure 2c). Of course this is the best fallback position to have a completely redundant installation of two independent systems.

To ensure a high availability of LTHD in tunnel applications the following minimum requirements are recommended:

- Use state-of-the-art systems with absolute temperature and rate-of-rise alarm possibility to ensure reaction even for small fires at high wind speed.
- Readout of the sensing element (sensor cable) from both ends using two independent control units. In case of damage, interrupt or short-circuit of the sensing element or defect of a control unit only the defect section should get lost. This is the general approach used in Germany today. The maximum length of the not available section should be clearly defined. Depending on the installation this can be a ventilation section, a fire section, a fire suppression section or any other preferred distance.
- Option 1 is to use two independent LTHD systems such creating redundancy. This will even increase the safety. However the two sensing elements have to be installed with sufficient distance in the tunnel to avoid parallel damage.
- Option 2 is to use a stub line system and smoke detectors for redundancy. The maximum distance of the smoke detectors in this case should not exceed 100m. This allows even at a low wind speed of 1.5 m/s detection within 60 seconds. In case of loss of the LTHD, automatic alarming of the smoke detection system or an increased attention in case of manual alarming is required.
- The connections from the control units to the fire alarm control panel (FACP) should also be realized in a redundant way. This is e.g. possible by using the section alarm information and general alarm information.
- The FACP (or the process control system, if no FACP is used) should also be constructed in a redundant way. The damage of a single component should not reduce the availability.

Taking into account all these requirements will lead to a highly available system and in consequence to a reliable detection of any tunnel fires.

4. CONCLUSIONS

Today a variety of LTHD for tunnel fire detection monitoring is available. But only modern systems with the possibility of rate-of-rise detection and exact localization are really suitable to detect even smaller car fires in a reasonable time. The systems should be designed and installed in a way that damage or defect of a single component should not result in the loss of the complete system. Loop systems and redundant installations can satisfy such requirements.

Besides road tunnels the application is also possible in train and metro tunnels. In these objects, increased risks like long tunnels or severe consequences in case of damage of the tunnel might require fire detection and subsequent passenger evacuation and / or fire suppression as well.

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SENSOR FAILURE DETECTION IN ROAD TUNNEL VENTILATION

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ABSTRACT

Tunnel sensors measuring traffic flow, air velocity, visibility index, carbon monoxide and nitrogen dioxide are widely installed and used in road tunnels for ventilation control. If a sensor malfunctions, it can compromise reliability, especially in cases of *automatic* control. This paper proposes a method of detecting sensor failure by comparing measured and predicted values of air velocities and pollution concentrations in longitudinally ventilated tunnels. The detection method uses statistical comparisons of actual measurements and theoretical estimates of air velocities and pollution concentrations based on the evolving traffic conditions and assumed vehicle emission characteristics. The proposed method is illustrated using data collected in an actual tunnel.

Key words: sensor failure detection, longitudinal ventilation

NOMENCLATURE

A_{TL}, A_{TS}	: effective resistance area of large(small) vehicles	[m^2]
A_R	: cross section of tunnel	[m^2]
C_k	: pollution concentration in calculation box k	[g/kg-air]
$\dot{C}_k$	: rate of change of C_k	[g/kg-air/sec]
$F_J(t)$	: fan thrust at time t	[N]
$F_P(t)$	: natural ventilation force at time t	[N]
$F_R(t)$	: tunnel resistance force at time t	[N]
$F_T(t)$	: piston ventilation force at time t	[N]
N_{UL},N_{US}	: number of large(small) vehicles, up-bound lane	[veh./km]
N_{DL},N_{DS}	: number of large(small) vehicles, down-bound lane	[veh./km]
$V_R(t)$	: longitudinal air velocity at time t	[m/s]
$V_T(t,i)$	: i-th vehicle speed at time t	[m/s]
$\dot{V}_T(t,i)$	: i-th vehicle acceleration at time t	[m/s^2]
k	: calculation box number	
L	: tunnel length	[m]
t	: time coordinate	[s]
t_d	: total response delay time combining driver and vehicle	[s]
x	: distance coordinate (longitudinal)	[m]
α	: constant sensitivity factor	
μ_L, μ_S	: pollution gas emission by large(small) vehicles	[g/veh]
$\mu_k(t)$	: local pollution source rate in box k at time t	[m.g/kg-air/sec]
ρ	: air density	[kg/m^3]
σ	: standard deviation	

1. INTRODUCTION

Most road tunnels in Japan are single tube and two-way traffic. Longitudinal ventilation using jet-fans is the standard ventilation scheme in these tunnels, more than three hundred (300) of which are longer than 1,000m. Air velocity ("AV"), visibility index ("VI"), carbon monoxide ("CO") and nitrogen dioxide ("NO_2") sensors are installed as standard and data from them (especially VI sensors) are used in the automatic control of jet-fans. Clearly, the effectiveness of the control is strongly dependent upon the information received from the sensors and yet there will be occasions when this information is inaccurate. It is therefore desirable to have a reliable method of detecting sensor malfunction.

The authors have recently developed a new automatic control method called Feed-forward Cascaded feedback Ventilation Control ("FCVC") (Nakahori *et al*, 2010, 2011). This system requires the measurement of traffic volumes ("TC") in addition to air velocity and pollution and, in addition to greatly improving the reliability of control, it has the spin-off benefit of enabling a powerful method of detecting sensor failure. In a nutshell, the method works by continually assessing the self-consistency of the information received from the various types of sensor (traffic, air-velocity, pollution). The process is described in detail in the following sections and its effectiveness is then confirmed by the use of data from an actual tunnel. It includes the following fundamental steps:

(1) Using data from the traffic counter(s) ("TC") together with expected values of resistance parameters and exhaust emission rates, calculate theoretical estimates of the air velocity and pollution concentrations at the locations of the relevant sensors;

(2) Calculate the differences between the theoretical estimates and actual measurements obtained from the sensors;

(3) Use statistical analysis to compare the differences with reference-value differences obtained during commissioning of the system.

The failure-detection process is undertaken independently of the ventilation control process itself. In this respect, the method differs from that used in the more comprehensive ventilation control process MPVC (e.g. Azuma *et al*, 2011) in which sensor-error can be detected during unsteady-flow conditions, even in long tunnels or in tunnel networks. The latter are much less common than single-tube tunnels, but they exist in many countries (e.g. Maeda *et al*, 2003).

2. SOURCES OF ERROR IN SENSOR MEASUREMENTS

2.1. Traffic Flow

Traffic counters, typically installed at tunnel portals, can measure the type of vehicle (large or small), the time of passing, and the velocity at the time of passing. Using these measurements, it is possible to estimate the location and velocity of all vehicles in a tunnel at any instant (see Eq.1 below). The estimation methods can range from simple extrapolation to complex traffic simulators, but all depend upon the raw data from the traffic sensors themselves. Several types of traffic counters are available – e.g. conventional loop detectors, laser traffic counters and video – and each has advantages and disadvantages. For example, video traffic counters perform less well in poor weather conditions such as heavy rain or snow than they do in good conditions. For all types, appropriate maintenance is necessary.

2.2. Longitudinal Air Flow Rate

The longitudinal air flow rate along a tunnel cannot be measured directly in a manner that is practicable during routine operation. Instead, air velocities are measured and are used to estimate mean velocities and hence flow rates. The accuracy of the inferred flow rates depends upon (i) the accuracy of the actual velocity measurements and (ii) the accuracy of the assumed relationship between these measurements and the flow rate.

Longitudinal AV meters are usually installed at locations where the longitudinal AV is relatively uniform. Often, ultrasonic sensors are used and there are two basic types, in both of which the device has two components mounted some distance apart. With small sized AV meters, both components are mounted on the same wall of the tunnel a few 100’s mm apart and a small distance from the wall. With large sized AV meters, the components are typically about 10m apart and on opposite walls of the tunnel, often above the main traffic space.

It is well known that AV measurement errors can become large when a single, small sized AV meter is used in a two-way traffic tunnel - because the longitudinal AV differs significantly on inbound and outbound lanes. Also, even when AV meters are installed in the best possible locations, they are inevitably affected by the air flow disturbances due to vehicle movements. As a consequence, air velocity measurements are usually averaged before being used for control purposes.

In addition to the above difficulties in estimating air flows, the accuracy of measurements from the sensors can deteriorate when material accumulates on their transmitters and receivers so appropriate maintenance is always necessary.

2.3. Pollution Density

In reasonably steady conditions, pollution concentrations in tunnels increase in the direction of air flow. Accordingly, pollution sensors are usually installed a small distance from tunnel portals. In one-way tunnels, only one portal need be instrumented, but in two-way tunnels, sensors are needed at both portals. Ideally, there should be sensors on both walls, but this is not as important as it is for the measurement of air velocity.

VI, CO and NO_2 meters are widely used. Until relatively recently, VI was by far the most important of these (in Japan), but reductions in emissions from large vehicles are causing more attention to be paid to the measurement of CO and NO_2. Quite strong spatial variations in pollution concentrations can exist and these cause readings to vary in time. Therefore, in common with velocity sensors, the measured data are averaged before use in control.

VI meters measure optical transmittance. There are several methods of doing so, but in all cases, the window used in the sensor can be affected by dust and other contaminants, so regular maintenance is needed (especially cleaning). CO and NO_2 meters use electro-chemical sensors, which deteriorate slowly and need calibration or replacement, perhaps once or more each year. All meters that use sampling methods need special care to avoid clogged filters or pump malfunction.

3. LONGITUDINAL VENTILATION MODELS

3.1. Traffic Flow

Traffic flow in the tunnel is the primary cause of longitudinal air velocities and of pollution. In principle, the error-detection process could utilize any reasonable traffic prediction model – e.g. simple extrapolation of measurements from a single TC sensor or even the use of historical traffic data. However, greater accuracy may be expected with models that include algorithms that mimic real behavior. The model used herein is called a

"Car Following Model" because the assumed acceleration of any particular vehicle at any instant is determined from instantaneous values of (i) its speed and (ii) the speed of the vehicle in front. This behavior is represented by the equation:

$$\dot{V}_T(t + t_d, i - 1) = \alpha\{V_T(t, i) - V_T(t, i - 1)\} \tag{1}$$

in which V_T and $\dot{V}_T$ denote speed and acceleration, i denotes a particular vehicle, t is time, t_d is a delay time and α is a parameter that controls the rate at which the distance between the vehicles evolves. With this model, the speed of each vehicle is influenced by the speeds of all vehicles in front of it. The model does not take explicit account of the distance between individual vehicles, but its input is real data from the traffic sensors so the initial distances will be realistic and appropriate choices of α can ensure that this remains true throughout the journey through the tunnel.

3.2. Longitudinal Air Velocity

The average air velocity over a cross section of longitudinal tunnel, referred to simply as longitudinal AV, is determined by (i) natural ventilation caused by air pressure difference between the two exit portals, (ii) vehicle drag, (iii) jet fans and other fans and (iv) tunnel resistance. The longitudinal AV in single tube tunnel is uniform along the tunnel (assuming incompressible flow). Using Newton's second law of motion, the longitudinal acceleration of the air at any instant, $\dot{V}_R(t)$, satisfies:

$$\rho A_R L \dot{V}_R(t) = F_N(t) + F_T(t) + F_J(t) - F_R(t) \tag{2}$$

where $F_N(t)$ is the natural ventilation force, $F_T(t)$ is the piston ventilation force, $F_J(t)$ is the fan thrust, $F_R(t)$ is the tunnel resistance force, ρ is the air density and L is the tunnel length. The evaluation of the various forces is undertaken in the usual manner and need not be written in detail here. However, for completeness, it is emphasized that the piston force must be evaluated separately for (a) small and large vehicles and (b) traffic in opposite directions. Thus the overall piston force is

$$\begin{aligned} F_T(t) = {} & \frac{\rho}{2} A_{TL} \left\{ \sum_{i=1}^{N_{UL}} \big(V_T(t,i) - V_R(t)\big)^2 - \sum_{i=1}^{N_{DL}} \big(V_T(t,i) - V_R(t)\big)^2 \right\} \\ & + \frac{\rho}{2} A_{TS} \left\{ \sum_{i=1}^{N_{US}} \big(V_T(t,i) - V_R(t)\big)^2 - \sum_{i=1}^{N_{DS}} \big(V_T(t,i) - V_R(t)\big)^2 \right\} \end{aligned} \tag{3}$$

Strictly, Eq.3 is written for the usual case where all vehicles experience a headwind. Within the software itself, the expressions $(V_T\text{-}V_R)^2$ are replaced by $(V_T\text{-}V_R)\,|V_T\text{-}V_R|$ to allow for cases where vehicles experience a tailwind.

3.3. Pollution Concentrations

Vehicle exhaust emissions and road dust are the primary sources of air pollution in tunnels. It is assumed herein that the pollution is transported at air speed and that diffusion may be neglected. This is an acceptable approximation for present purposes. It simplifies the analysis without introducing errors as large as those arising from other approximations (e.g. quasi-steady flow). In this case, the only equation needed to express pollution transport is the continuity equation. For this purpose, the tunnel is regarded as a series of control volumes, each of length Δx, and the rate of change of concentration $\dot{C}_k(t)$ in any particular volume (box) k satisfies:

$$\Delta x \dot{C}_k(t) = V_R \left(C_{k\text{-}1}(t)\text{-}C_k(t) \right) + \mu_k(t) \quad (4)$$

where $C_{k\text{-}1}(t)$ and $C_k(t)$ denote concentrations at inflow and outflow to/from the box and $\mu_k(t)$ describes the local pollution source rate (exhaust emissions, road dust, etc).

Equation 4 is used independently for each pollution type (CO, NO_2, etc) and the pollution source rates are sums of values from all sources. For example, the contributions from vehicle exhausts are expressed as

$$\mu_k(t) = \mu_L\big(N_{UL}(t,k) + N_{DL}(t,k)\big) + \mu_S\big(N_{US}(t,k) + N_{DS}(t,k)\big) \quad (5)$$

in which μ_L and μ_S denote average rates from all large vehicles and all small vehicles in the box respectively. In the software, values are deduced independently for each individual vehicle.

4. DETECTION OF SENSOR FAILURE

4.1. Calibration of the Base Data

Notwithstanding the slow rate of change of base data, it is inevitable that some tunnel-specific dependence will exist overall – e.g. the assumed characteristics of the tunnel, the fan performance and, perhaps also the particular vehicle types within the broad categories of "small" and "large" considered above. Accordingly, when the failure-detection system is first installed (and, ideally, every few years thereafter – perhaps 5 to 10) the self-consistency of the data should be assessed. For this purpose, a two-stage assessment is required. First, the predicted air speeds are compared with measured speeds during different periods of traffic operation – morning, evening, night, weekday, weekend, etc. The base data are then adjusted to give the overall best-fit. Then, predictions of pollution concentrations are compared with measured values and are used to deduce best-fit values of the vehicle-emission parameters.

This process can be undertaken in many different ways, but all reasonable ones should yield similar results. Thereafter, the data can be used with confidence in the failure-detection system.

As an aside, it is interesting to note that even new sensors in good working order are not 100% perfect. Strictly speaking, therefore, if differences detected in the calibration process are minimized exclusively by adjusting input data for the prediction tool, the adjustments will include bias to compensate for sensor inaccuracy. At first sight, this might seem illogical or, at best, a deficiency of the failure-detection methodology. In fact, however, it can be considered to be a significant benefit. This is because the real need is to detect significant *change* in the performance of sensors. Any gross malfunction in their initial behavior should be readily detected during the calibration process. Thereafter, it would be unhelpful to have a permanent bias that has existed from the outset.

4.2. Estimation and Use of "Normal" Differences

The calibration process described in Section 4.1 utilizes measured data over a long period. During this time, the ventilation control system is active, but the failure-detection methodology has not yet been activated. This avoids the risk of an initial period of sub-standard detection leading to false alarms or undetected malfunctions. Either of these outcomes would reduce operator confidence in the process after calibration.

The first purpose of the calibration period is to assess the most suitable values of the base data. To determine these, use is made of measured data over a long period. In principle, the method used to deduce the optimum base data involves assessing many trial sets of base values and then choosing the particular set that gives the minimum statistical variations from the measured values.

An automatic consequence of the above process is the identification of the particular set of statistical data that is applicable for the chosen values of base data to be used in actual operation. That is, the statistical performance of each sensor is known for typical traffic conditions in the tunnel.

When the failure-detection algorithms are implemented in the real tunnel, statistical data describing ongoing differences between measured and predicted values are continually revised and updated. If all is well, the statistical data obtained over sufficiently long periods should be a fairly close match with the corresponding values obtained during calibration. Accordingly, alarms should be raised only when the actual values differ substantially from the calibration values.

It is suggested that the allowable margin should initially be set at a relatively large value and that this should be reduced slowly over a period of months until the smallest value is found that causes no false alarms (or an acceptably small number thereof). This should be done independently for each velocity and pollution sensor.

Let σ_0 denote the standard deviation in the optimum calibration case at a particular sensor and σ_1 denote the evolving standard deviation during actual operation. Then small values of the ratio σ_1/σ_0 will be indicative of a valid sensor and large values will be indication that the sensor is probably faulty. It is provisionally recommended that a value of about 3 is appropriate for defining the boundary between "probably satisfactory" and "probably malfunctioning". However, this value will not be universally suitable; the most appropriate choice will depend upon factors such as (i) the variability of traffic conditions, (ii) the frequency of changes to external atmospheric conditions and (iii) the frequency with which the control system adjusts fan settings. All of these factors influence the validity of the assumption of quasi-steady conditions that underlies the particular methodology described herein.

4.3. Illustrative Example

Figure 1 shows scatter charts for measured and predicted values of air velocity and visibility index in the Kawasaki Koro Tunnel. The measured values were used to deduce optimum values of the base data used in the theoretical predictions. Thus, the variations shown in the figure are indicative of "normal" scatter. We note in passing that the VI sensor appears to have an offset (a best-fit straight line would not pass through the origin). This was not detected before undertaking the present work.

Figure 2 shows evolving differences between measured and predicted values of AV and VI. The figure includes a time when sensor malfunction occurred. This particular incident is pronounced and so it is easily detected visually. However, visual detection is possible only when the data are inspected by a human being – perhaps weeks or months after the event itself. A valuable benefit of the automatic detection process is that failure can be detected quickly, typically within hours or even within minutes in the case of serious failure. This particular malfunction occurred during cleaning of the tunnel by washing its walls. As a consequence, the malfunction occurred simultaneously in the AV and VI sensors. More commonly, failure of one sensor will not be accompanied by the failure of other sensors.

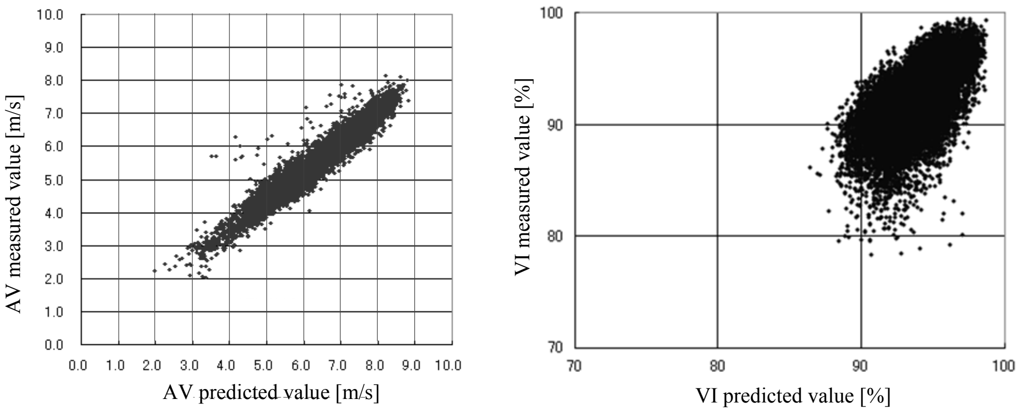
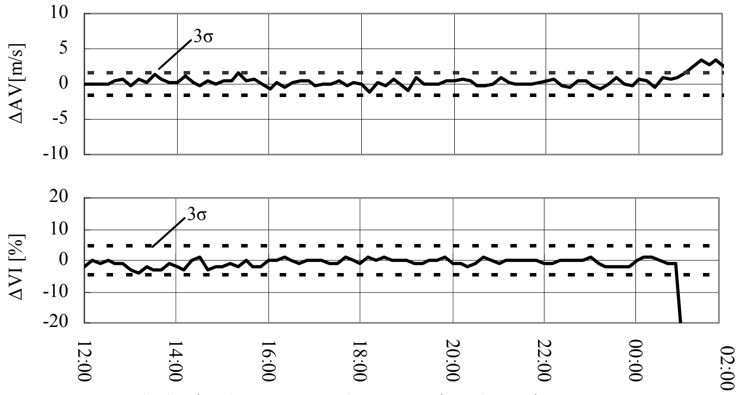


Figure 1: Comparison of predicted and measured values of AV and VI



$\Delta AV(=AV_{measured}\text{-}AV_{predicted})$; $\Delta VI\ (=VI_{measured}\text{-}VI_{predicted})$

Figure 2: Sensor failure at approximately 01:00 hours

4.4. Cascade failures

So far, it has been assumed that unusually large differences detected at any particular sensor will be indicative of problems with that sensor. However, this is not necessarily so. Consider, for instance, the consequences of malfunction in the traffic sensors. This will result in false data being processed in the air speed module of the prediction tool so the predicted air speed will necessarily differ from the measured value. As a consequence, the pollution module will be supplied with false data for air speeds as well as for traffic flows. Therefore all sensors will appear to fail simultaneously. Since this outcome is most unlikely to occur as a consequence of faults in each individual sensor, the post-processing software should not treat it as such. Instead, it should trigger a warning that a wider problem exists and that the malfunction of a TC sensor is one possible cause.

Another example of false alarms with pollution sensors can arise when the true malfunction is at an air speed sensor. This will be possible if the value of the air speed passed to the pollution module is a weighted average of the predicted and measured air speeds. Such averaging can have significant benefits when the AV sensors are performing well so its use should not be discounted without careful thought. How can we allow for the possibility of cascade failures such as this? One possibility is to have two independent predictions for pollution concentrations, namely one based exclusively on the predicted air speed and one based on a weighted average of the predicted and measured values. If both models indicate pollution sensor error, the prediction is probably correct. If only the second of the models indicates pollution sensor error, it will be more likely that the problem lies with the AV sensor.

5. CONCLUSIONS

This paper has presented a failure detection method for TC, AV, VI, and CO meters in routine tunnel operation. The method makes statistical comparisons between measured values and values predicted by air speed and pollution models based on quasi-steady approximations to air flows. The following statements summarise the key messages of the paper:

(1) Measurements of traffic data at tunnel portals can be used to predict evolving air velocities and pollutions concentrations throughout a tunnel;

(2) By analyzing measured data over sufficiently long periods, it is possible to infer realistic approximations for values of base data describing tunnel and vehicle characteristics;

(3) As a by-product of the method of determining optimal values for the base data, quantifiable statistical data are obtained about expected deviations between measured and predicted values at any particular sensor;

(4) By monitoring statistical variations at sensors during actual tunnel operation and comparing them with the expected variations, it is possible to detect significant variations from normal behavior and hence to identify instances of probable sensor malfunctions.

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ACOUSTICAL GUIDANCE IN ROAD TUNNELS

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ABSTRACT

This study supports that acoustical guidance in road tunnels improves self evacuation in emergencies. An analysis of flight behaviours of people enclosed in a smoke-filled tunnel shows that over 91% of the people can be guided to the nearest emergency exit with the help of acoustic signals. Without acoustical guidance, only 59% of the people evacuate towards the optimal emergency exit. Evacuees are willing to overcome their reluctance to escape forward into the unknown, if clear information about the location of the nearest emergency exit can be provided. Additionally it was made clear that people evacuating unknowingly along the wrong side wall, can be encouraged to cross the smoke-filled tunnel if sound beacons signal an escape possibility on the other side.

Keywords: acoustical guidance, road tunnel, evacuation time, human behaviour

1. INTRODUCTION

High severity accidents in road tunnels have shown the importance of efficient self evacuations. Because of limited means for rescue interventions in road tunnels, self evacuation needs to be facilitated as much as possible (see van Linn & Welte, 2006, [11]). National guidelines of the federal roads office (FEDRO) in Switzerland provide that safety equipment is to be identified by optical signals such as flashing lights, light beacons and information plaques (FEDRO, 2011, [4]). It is obvious that these guidance methods, aiming solely at the visual senses, tend to lose their effectiveness when visibility is severely limited because of e.g. smoke.

Research projects in the Netherlands (see Boer, 2002, [1]) and more recently Germany (see Färber & Färber, 2010, [3]) have shown that the localisation of escape routes in smoke-filled tunnels can be enhanced when acoustical signals mark the position of emergency exits. From a Swiss point of view, where road tunnels are only equipped with visual guidance methods, these findings have lead to several questions regarding standard Swiss safety installations:

- Is acoustical guidance really suitable to lead evacuees to the next escape route?
- Does it increase the rate of successful evacuations?
- Should the present guidance methods be enhanced by installing sound beacons above the emergency exits?

With these questions, the focus is deliberately placed upon the *guidance* of people and not upon their *warning*. It is not to be ascertained how motorists can be informed about a danger in a tunnel or whether they can be persuaded to leave their car as quick as possible. Hence, this study does not aim to shorten pre-evacuation time (PEAT) (see Kobes *et al*., 2010, [5]; Shields, 2005, [10]) but works on the assumption that people already have left their vehicle and are on their way through the smoke-filled tunnel seeking shelter. This means that the acoustical signal must either be a sound or spoken message which is audible, self-explanatory, attractive and which allows a good localization of its source (Boer, 2002, [1]; Woodson *et al*., 1992, [12]).

In this sense, this study aims at providing a better understanding of human behaviour in complex situations and the potential possibilities to improve tunnel safety.

2. EXPERIMENT

To verify the raised questions, an experiment with human probands was planned and executed in the Uetlibergtunnel. Being one of the latest road tunnels in Switzerland, it is equipped with all the required safety installations as specified by FEDRO. The two-tube tunnel has a length of 4.42 km with an average incline of 1.6%.

The experiment provided the statistical foundation for the following findings in chapter 3 and in itself was built on two main pillars. On the one hand, the observation and measurement of the test persons' flight behaviour in a smoke-filled environment delivered data on the effectiveness of loudspeakers in tunnels. On the other hand, a questionnaire at the end of the experiment was to examine the probands' subjective experience of the situation.

The original intention was to conduct four scenarios to test different kinds of acoustical guidance: a signal tone, a spoken message, a combination of the two, as well as a control group. However, tightness of this evening's time schedule allowed only three tests, whereas one consisted of a control group and one was repeated (see **Table 1**).

Table 1: Tested scenarios

	Signal Tone	**No Signal Tone**
Speech Transmission	Group A / Group C	
No Speech Transmission		Group B

2.1. Sample

In total over 100 probands were recruited for the experiment. While the test persons were told in advance that they would have to evacuate out of a room filled with harmless smoke, they were not informed on the intended purpose of the test. Finally, 80 probands took part in the experiment. The three groups were identical in their formation, meaning that they neither featured any statistical dependencies on the number of probands, nor on their gender (χ^2 = 0.676; df = 2; p = 0.713)[1] or their average age ($F_{(2,77)}$ = 0.616, p = 0.542)[2] (see **Figure 1**).

It is to be emphasized that all groups also included probands not holding a driving licence at the time of the experiment, who thus could not be assumed to know the situation in tunnels as intimately as car drivers. They were included because in real life there will always be tunnel users who do not know how to behave in case of an emergency and how to make use of the available safety equipment. In short, emergency guiding methods must be aimed at all potential users, be they experienced or inexperienced.

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[1] To establish whether the two variables "group" and "gender" were dependent on each other, a chi-square analysis was conducted (χ^2: chi-square distribution; df: degrees of freedom; p: probability)

[2] To establish whether the two variables "group" and "average age" were dependent on each other, a F-test (analysis of variance) was conducted ($F_{(V1,V2)}$: F distribution for v_1 numerator degrees of freedom and v_2 denominator degrees of freedom; p: probability)

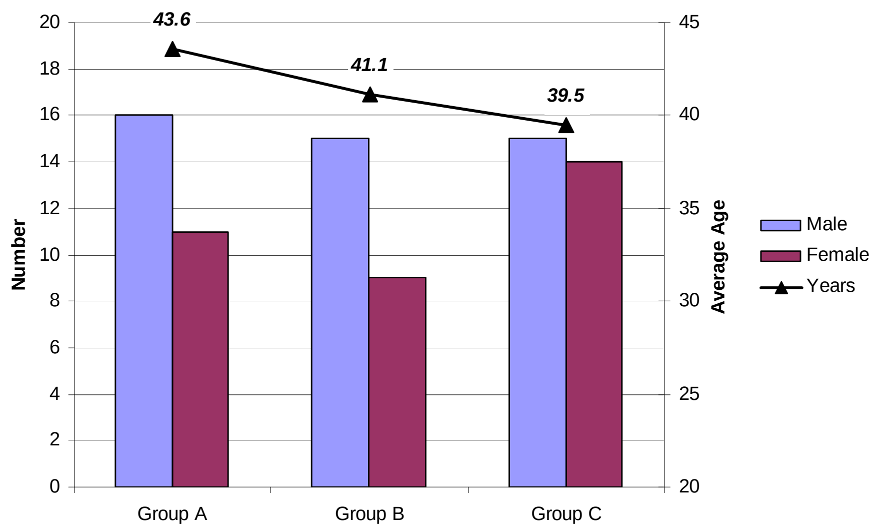

Figure 1: Gender and average age of probands

2.2. Test Area and Installations

The test area had two emergency exits that were 290 m apart; the crossways behind the exit doors leading into the adjoining parallel tunnel tube. The exit doors swinging in direction of escape were operated by applying pressure on the handlebar.

Since statistical reasons dictated the existence of an optimal emergency exit, the starting point for the evacuation experiment could not lie evenly between the two emergency exits, but had to be defined closer to one of them. In accordance with comparable studies (see Boer & van Wijngaarden, 2004, [2]), the starting point was therefore determined to divide the distance between the two exits with a ratio of 0.36:0.64 (see **Figure 2**).

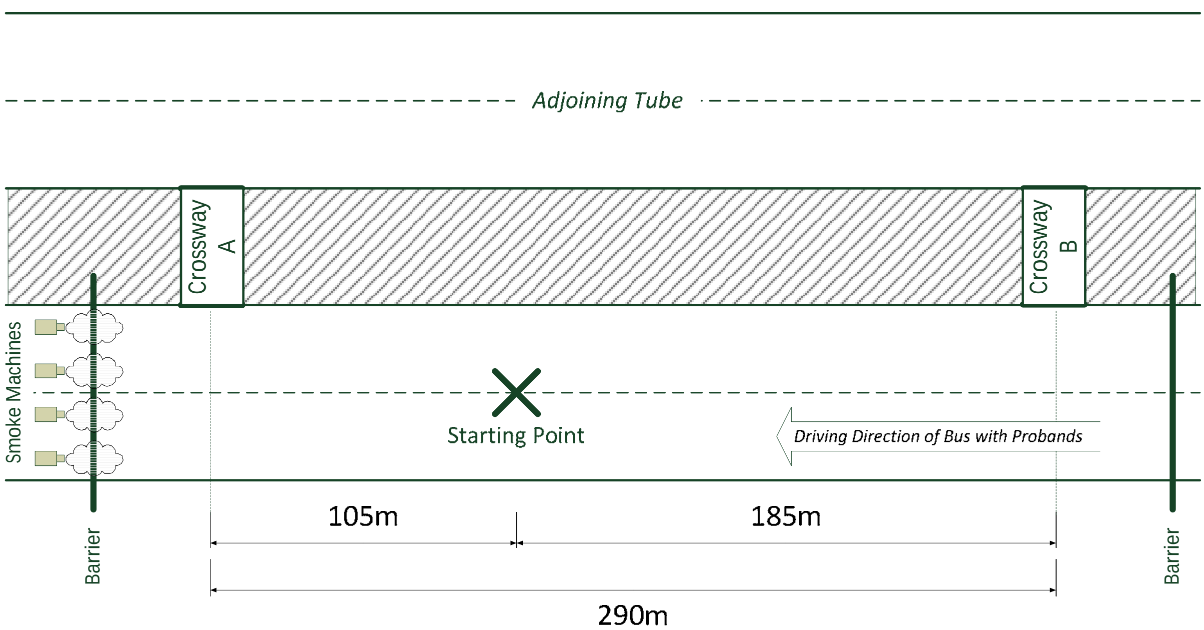

Figure 2: Test area

Above the two exits loudspeaker systems were installed, emitting the acoustic signals in both directions of the tunnel tube. In order to overcome the rather complex acoustical preconditions in a tunnel, a loudspeaker system was constructed of five horn loudspeakers aligned vertically above each other (see **Figure 4**). With this line array the emitted sound waves could be directed along the tunnel walls, eliminating disturbing reflections as much as possible.

The actual acoustical guidance consisted of a succession of two attractive signal tones followed by the speech announcement "Exit Here" in German, English and French. The two signal tones were synthetically created and comprised the two-tones C-E and E-G. Detailed information about the sequential arrangement is illustrated in **Figure 3**.

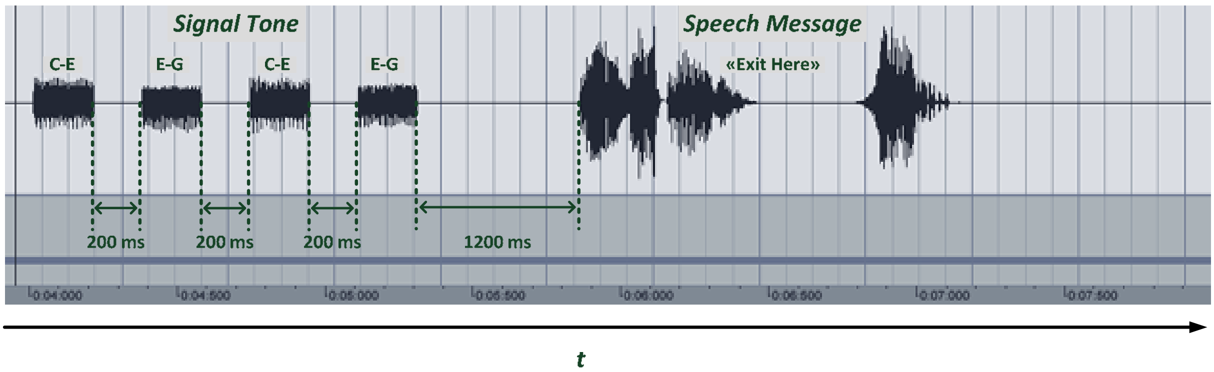

Figure 3: Acoustical signal

The average sound level of the acoustic signals peaked at 87-90 dB at 1 m distance to the sound source, and diminished to 83-86 dB at 100 m distance. Measurements of speech transmission quality resulted in a speech transmission index (STI) of 0.48 in 25 m respectively 0.42 in 105 m (starting point) distance.

After the two emergency exits, plastic ribbons were spanned across the roadway limiting the test area, thus hindering the test persons from straying too far during the experiment. To prevent the barriers from providing visual assistance to the evacuees, they were installed about 40 m away from the emergency exits (see **Figure 2**).

Upwind, behind the barrier after the emergency exit A, four smoke machines were positioned. They produced an artificial white smoke that was non-toxic to the human eye and respiratory system. Due to changing winds, it was difficult to sustain a constantly dense smoke column in the tunnel. By activating the axial ventilators at the portals a steady wind speed could be attained so that the smoke was floating homogenously through the test area with about 0.5 m/s. Visibility was reduced to a constant range between 0.5-1.5 m throughout the whole test area.

2.3. Procedure

On the evening of May 19th 2011 all participants were gathered in the central ventilation station located directly above the tunnel tube. Each proband was assigned a distinct test number written on the person's hand and allowing correct future statistical analysis. For personal safety, face masks were distributed to probands for voluntarily wearing. After this preparation the participants were assembled at the predefined group locations where they were informed about the basics of the forthcoming actions. At scheduled time intervals each group was brought down into the tunnel with an elevator where a bus was ready for transporting them into the test area.

In the tunnel all prevailing safety installations were activated according to standard emergency plans. This means that the ceiling lights were turned to 100% and guidance lights along the tunnel walls as well as the light beacons around the exit doors were switched on. In order to maintain a constant smoke density the ventilation valves in the suspended ceiling were manually closed.

After being driven into the smoke-filled test area, the participants were released separately every 30 seconds and told to evacuate through the next possible emergency exit. They were neither instructed on how to behave nor were they informed about the available safety equipment. The individual test number and the time of every single proband were noted upon leaving the bus at the staring point and upon arriving at one of the emergency exits. Participants that strayed too far were picked up at the barriers marking the end of the test area; their number and time was noted too. Five minutes after the last person had left the bus, the scenario was stopped and the probands were assembled and brought back to the central ventilation station.

3. RESULTS

This study establishes that the direction of evacuation is significantly dependent on the provision of acoustical guidance (χ^2 = 7.378; df = 1; p = 0.007). A more efficient self evacuation can be achieved by combining the conventional safety equipment installed in road tunnels with sound beacons above the emergency exit doors. 92% of the people could be guided to the nearest emergency exit with the help of acoustic signals. Without acoustical guidance, only 59% of the people evacuated towards the optimal emergency exit. The usual guidance methods such as light beacons and information plaques at the walls, aiming solely at the visual senses, proved to be effective only with a certain remaining, yet often severely limited visibility.

3.1. Flight behaviour

People trapped in a fire emergency with heavy smoke present will be attracted towards familiar places (Nilsson *et al.*, 2009, [8]). In terms of road tunnels this implies that people rather evacuate in the direction they have come from, even if information plaques at the tunnel wall indicate the next emergency exit in a forward direction. People usually prefer a longer escape backwards to a shorter flight into the unknown. The availability of unmistakable position signals of safety installation plays a crucial role. This study has made it clear that acoustical guidance is suited to deal with people's tendency to evacuate towards familiar places. Evacuees are willing to overcome their reluctance to escape forward into the unknown, if clear information about the location of the nearest emergency exit can be provided. Without acoustical guidance over 41% of the probands chose the longer way backwards; with acoustical guidance above the emergency exits this percentage can be reduced to almost 8% (see **Figure 4** and **Figure 5**).

Although the participants were released separately at intervals, group formation could be monitored; social influence was found to be an important additional factor when it came to choosing flight direction.

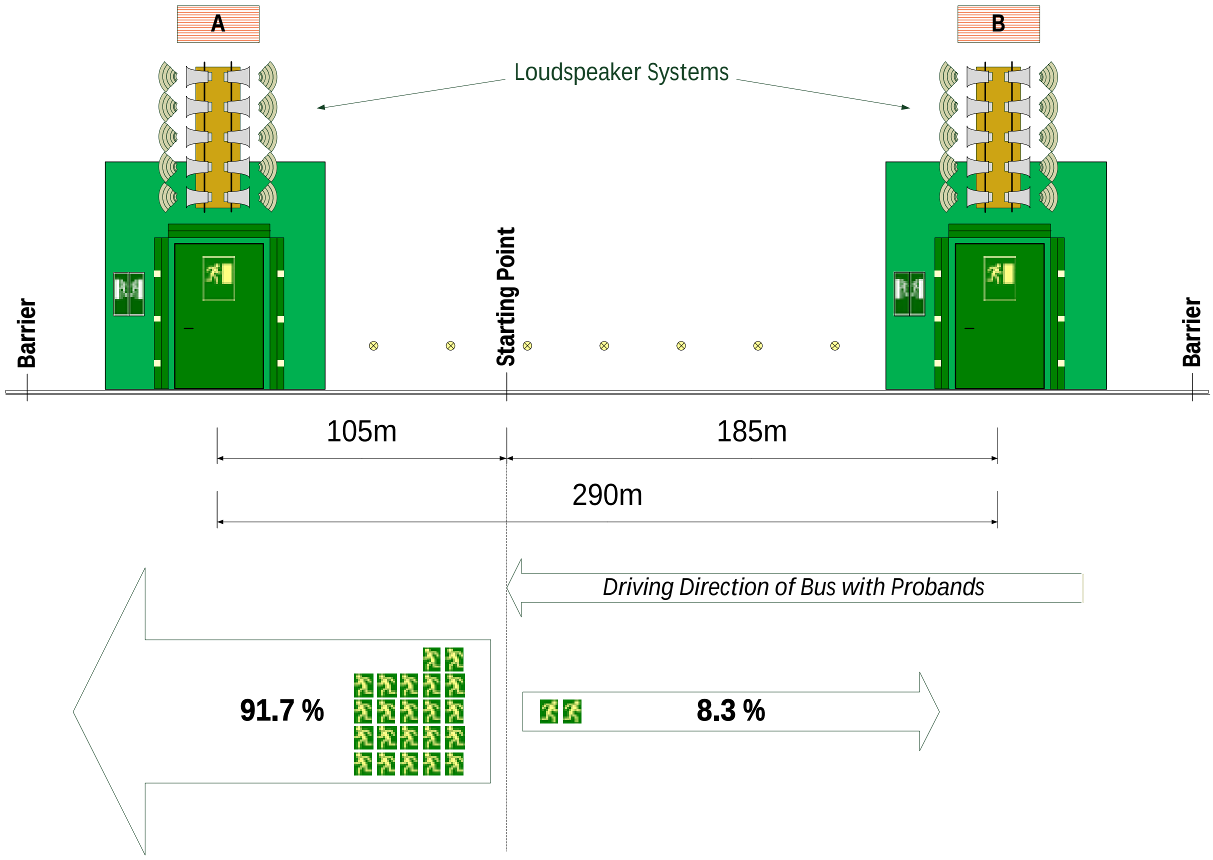

Figure 4: Flight direction with acoustical guidance

It was observed that the participants were moving towards the alleged safety of the wall as soon as they were finding themselves in the smoke-filled environment. The subsequent questioning made clear that during the escape many participants were avoiding to leave the tunnel wall, assuming that this kind of moving would ultimately lead them to an emergency exit. During an incident with bad visibility, this assumption may lead to severe consequences as emergency exits are only installed on one side of a tunnel. If evacuees are escaping along the wrong side they will not find refuge. This experiment illustrated that people evacuating unknowingly along the wrong side wall of the tunnel, can be encouraged to cross the smoke filled tunnel if sound beacons identify the other wall as the correct one. Acoustical guidance provides security, and is therefore capable of influencing human response in complex situations.

All of the participants stated afterwards that during the evacuation they were always relying on a combination of safety installations, and never on one exclusively. It may therefore be concluded that acoustical guidance does not substitute the already existing equipment, but rather complements conventional safety installations aiming at the visual senses, like light beacons and information plaques at the walls.

3.2. Emergency exits

As an additional benefit of this study, weaknesses in the design of the applied emergency exit doors were detected. Almost 30% of the probands complained about problems with the push mechanism of the exit doors. Hyperbaric pressure in the safety rooms prevented an easy opening.

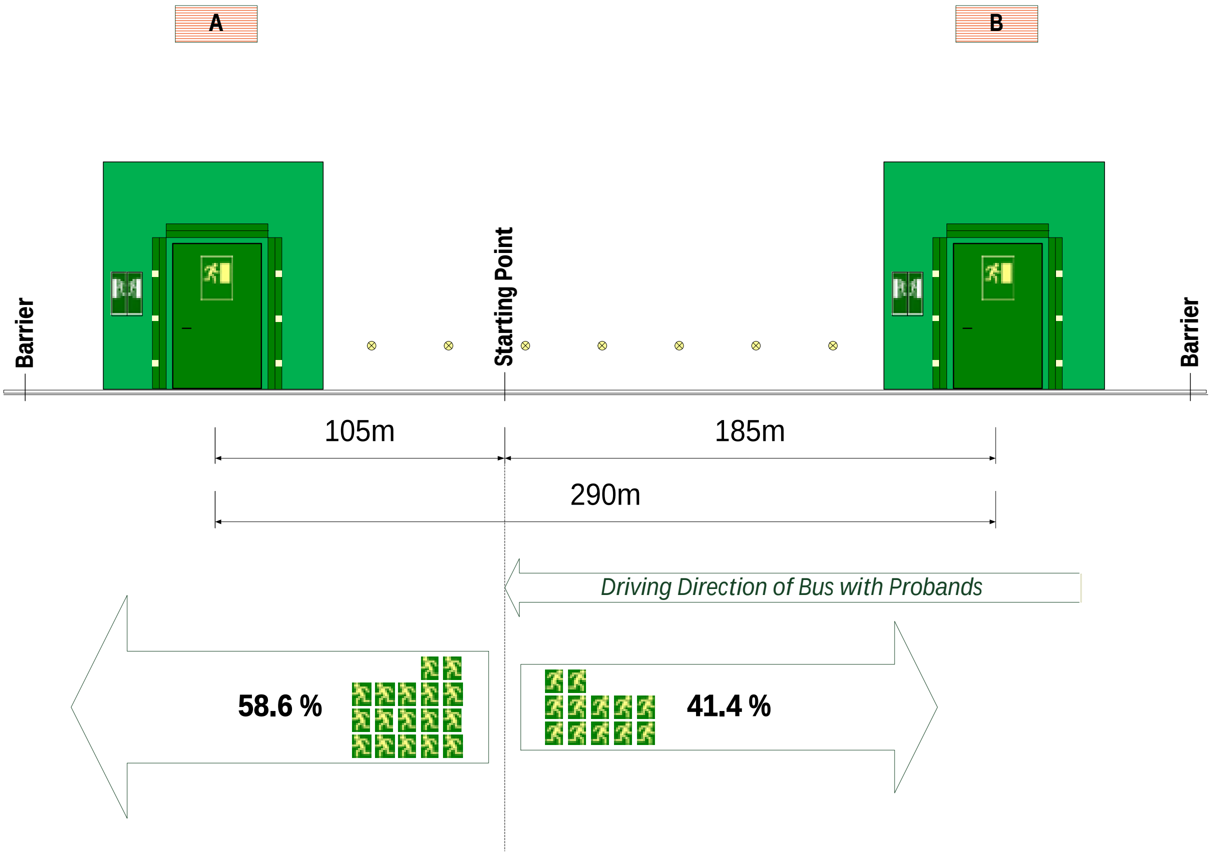

Figure 5: Flight direction without acoustical guidance

It was ascertained that the majority of the people gathering at the barriers of the experiment space, failed to use the emergency exits not because they could not find them, but because they could not open the push mechanism of the doors. After some failed attempts to enter the safety room the physically weaker probands left the emergency exit in search for another one and finally were picked up at one of the barriers.

It becomes clear that the special preconditions in road tunnels necessitate specific technical requirements, like overpressure in refuge installations. The human factor plays a decisive role. An intuitive operability of the exit doors must support the road users in evacuating the danger zone; an easily opening door will enable the spontaneous behaviour aimed for.

When timely rescue interventions are limited, a quick self evacuation becomes all the more important. The strength of the chain of all available safety measures is dependent on its weakest link. In this case study, the doors of the emergency exits materialised as this weakest link. In general, this circumstance tends to limit the effectiveness of even the best guidance methods, resulting in dangerous delays when time is the critical factor.

3.3. Outlook

After having shown the positive effect of acoustical guidance, the actual acoustical signal needs to be examined more closely. Several studies have proposed different kinds of signals, be it a speech transmission, a signal tone or a combination of the two. As for multilingual Switzerland, it is recommended to review the available signals and to analyze the advantages of speech transmission and signal tones.

Overall tunnel safety is influenced substantially by individual human behaviour. The importance of the human factor in technical systems design has been discovered long ago and has not lost any of its relevance since (Manzey, 2008, [7]; PIARC, 2008, [9]). A stronger integration of the human-factor-aspect is also recommended in the planning of safety installations in road tunnels. The rather unexpected finding of the heavy swing doors serves as a significant illustration.

Similar studies (see Lellig *et al.*, 2010, [6]) place emphasis on the fact that a specific "tunnel training" for drivers only gets efficient to improve self evacuation, when complemented with other measures. This paper agrees and suggests design adjustments of safety installations to account for human behaviour in complex situations.

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SIMPLIFIED METHOD FOR LONGITUDINAL VENTILATION SYSTEM DESIGN IN FIRE SITUATIONS

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ABSTRACT

The fundamental aim of a ventilation system in tunnels must be to reach the major possible safety levels both in service and fire situations; being the fire one, the most relevant when designing the system.

When studying a longitudinal ventilation system, the method to evaluate the capacity of the system is basically the same both in service and fire situation, with the exception of the chimney effect and the phenomena of thermal transfer which it's the responsible of the changes in the air density which will be no longer constant. This thermal transfer concerns all the effects of the balance equation, but it is of a special importance for the jet fans that will have to offset the existing losses along the whole tunnel; and which performance will be decrease due to the temperature's increase of the air.

The aim of this study it's been to provide a simplified one-dimensional method to estimate the sizing of a longitudinal ventilation system based on jet fans, which could be of help for non-experts in ventilation systems.

Keywords: Tunnel, fire, temperature, heat release rate, longitudinal ventilation, heat transfer, ventilation design, incident ventilation

1. INTRODUCTION

The aim of a tunnel ventilation system is to reach the major safety levels as possible both in fire and service situations.

In service situation the system has to guarantee that the atmosphere of the tunnel assembles a suitable condition of comfort and safety for the users; assuring the dilution of the pollutants from the vehicles to admissible limits, and allowing a suitable reaction capacity in case of a quick demand of flow. On the other hand, in case of fire the aims would be to control the smoke layer as far from the users as possible, to avoid the spreading of the incident to zones not implied in the fire and to support in rescue tasks.

Due to the progressive reduction of the emission levels of pollutants when designing a ventilation system in a tunnel the situation of service is not the designing one, being the fire situation the one that would tell the requirements of the system. To achieve this design, criteria and methodology can be found in literature, however, for those professionals not specialized on the ventilation design (the ones related with the electrical needs, for example) this may be too complex for what they really need.

So the aim of this study is to provide a simplified one-dimensional method for designing a longitudinal ventilation system.

2. VENTILATION DESIGN GUIDELINES

In Spain the only mention done in the existing regulations to the sizing of the ventilation systems is referring to the minimum fire size of 30 MW [ref. 1]. In this way, since in Spain there is no design guideline or recommendation available for the designing of ventilation systems for road tunnels, designers need to fulfill the requirements and methodologies in foreign regulations, for example the French one, *Dossier Pilote du ventilation* [ref. 2].

These guidelines describe in detail the methodology to be followed to properly design and determine the total thrust to be installed in a longitudinally ventilated tunnel based in jet fans. However, the methodology proposed requires a detailed knowledge of fluid dynamics and thermodynamic aspects related to the problem. This is especially relevant when considering the influence of the thermal effects (reduction of the air density caused by the temperature increase) in the computation of the installed thrust of the jet fans.

Some regulations, as the French inter-ministry circular nº 2000-63, allow some simplified calculations to be used: "In tunnels less than 800 meters long it is not generally possible to comply strictly with the condition above (reduction in fan performance). These effects can then be taken into account by increasing the thrust deriving from the above mentioned paragraphs by a figure of 30% in tunnels less than 500 m long and by 50% in other circumstances".

Other regulations (e.g. RVS 09.02.31 [ref. 3] or FEDRO [ref. 5]) do not give detailed information on how to take into account the losses due to the thermal effects although they do propose to take these effects into account.

In the cases, where an approximated value of the electrical power to be considered for the ventilation system of a tunnel is needed, it would be of great help to count with a simplified method which allows parametric studies for different designing criteria (total heat release, critical air velocity, etc) without the need of complex computer programs or worksheets.

3. GENERAL METHODOLOGY FOR VENTILATION DESIGN IN CASE OF FIRE

It is out of the scope of this paper to describe in detail the methodology and criteria to be adopted when designing a ventilation system based on jet fans. A detailed description of the effects to be considered can be found in the literature [ref. 2]. However, to explain the basic concepts under the simplified model, it is necessary to summarize the process.

In general, the designing methodology is based on the computation of the load losses due to the different effects that can be found during a fire situation in the tunnel and the real thrust obtained from the jet fans installed:

- The linear losses per unit of length (δH)[1] are define by,

$$\delta H = \lambda \cdot \frac{\rho W^2}{2} \cdot \frac{\delta l}{D_H} \qquad \text{Eq. 1}$$

  Where ρ is the air density, W the air velocity, D_H the hydraulic diameter of the tunnel, δl is the length of tunnel considered and λ the friction coefficient.

[1] The notation that has been used in this paper is deliberatelly the same as used in the Dossier Pilote du CETU.

- The sudden changes on forms (enter and exit of the tunnel, changes of section) or the presence of obstacles of big dimensions (traffic signals or boards for messages) drive to singular load losses (*ΔH*), expressed by,

$$\Delta H = \xi \cdot \frac{\rho W^2}{2} \qquad \text{Eq. 2}$$

  Where ξ is the coefficient of singular losses (ξe at the entry of the tunnel generally 0.5 and in the exit ξs 1), ρ the air density and W the air velocity in the tunnel.

- The chimney effect which is the force that tends to make go the warm and lighter gases up. For a tunnel of length dl and a slope of γ (positive in rise, negative in descent), this effect is translated by a variation of load per unit of length dH that can be calculated by,

$$\delta H = i \cdot (\rho_0 - \rho) \cdot g \cdot \delta l \qquad \text{Eq. 3}$$

  Where i is the slope of the tunnel, g is the acceleration of the gravity, ρ is the density of the hot air and ρ_0 the density of the air at the altitude of the tunnel.

- The piston effect ΔH_{pisto}, representing the force on the air mass generated by vehicles rolling; this force is expressed by

$$\Delta H_{\text{piston}} = \frac{1}{2} \cdot \frac{C_x \Sigma}{S} \cdot \rho \cdot (U - W)|U - W| \qquad \text{Eq. 4}$$

  Where $C_x\sum$ takes an average of the product of the aerodynamic coefficent of the vehicles and their cross section (to consider the heterogeneity of the traffic park), ρ is the density of the air, S the tunnel cross section, U the speed of the vehicles and W the air velocity.

- The effect of the atmospheric pressure which is an effect of random character that must be included for the designing of the ventilation system. It is responsible for the natural draught and there is a certain polemic in the technical literature on the form in which it must be evaluated. Generally the phenomenon appears studying separately the effect generated by the difference on temperature between the inside and the outside of the tunnel (at ambient conditions), the height difference between the portals, the barometric differences and the effect of the wind. Since the previous effects are difficult to add generally they get in the calculations as pressures to be beaten by the ventilation system.

- By calculating all the previous effects it is possible to set the number of jet fans needed in the tunnel, taking into account that the thrust of a jet fan is affected by the environmental conditions at which it is used and so it is not the same as the one from catalogues (F_0).

$$\Delta H_{\text{fan}} = k \cdot \frac{F_0}{S} \frac{\rho}{\rho_0} \left(1 - \frac{W}{W_{jet}}\right) \qquad \text{Eq. 5}$$

  In the expression k is a coefficient of efficiency, ρ_0 the air density of reference, W_{jet} the velocity of the air jet (at ρ_0), S the tunnel cross section and ρ and W the air density and velocity at the tunnel respectively.

For the designing stage the maximum temperature at the fire must be estimated taking into consideration the heat exchanges with the walls of the tunnel to calculate the longitudinal decrease of the temperature. The thermal power of the fire is removed by radiation transfer to the walls of the tunnel and by convective transfer to the air of the tunnel. Usually the radiative transfer is considered as one third of the total power of the fire Q_{tot} and so the average temperature of the air immediately under the fire is determined by equation [6].

$$T_{max} = T_o + \frac{Q_{conv}}{\rho_o . S . C_p . W_0} \qquad \text{Eq. 6}$$

Where ρ_0 is the fresh air density, C_p the specific heat at constant pressure of the air, S the cross section of the tunnel, T_0 the temperature of the fresh air and W_0 the fresh air velocity.

The exact calculation of the air's temperature in any part of the tunel (x) it's calculated by connecting the conduction to the walls with the equation of the temperature's evolution at the air of the tunnel. A simplified and secure calculation of this temperature can be obtained by using the coefficient of thermal apparent exchange, h_{app}[2]; and depends on the fire location (x_{inc}).

$$T_x = T_o + \frac{Q_{conv}}{\rho_o . S . C_p . W_0} . e^{-\frac{4\, happ}{\rho_o . S . DH . W0}(x - xinc)} \qquad \text{Eq. 7}$$

It is interesting to note the enormous influence that the value of h_{app} can have in the final figures obtained. An interesting discussion on this topic can be found in Sturm and all [ref. 6]

While implementing the equilibrium equations for a given case (tunnel, HRR, vehicles, air velocity, type and location of the jet fans) it is possible to obtain the number of jet fans needed for every fire position in the tunnel to fulfill the equation of momentun balance for stationary regime.

The result of the process of calculation can be gather as a graph (x- axis represents the fire position considered, not the tunnel's lenght) in which it is represented for the implantation of jet fans (black squares) the thrust contributed by the them (red line) opposite to the demand of thrust due to the losses of load (blue line), being valid the scenarios in which the first one stays over the second.

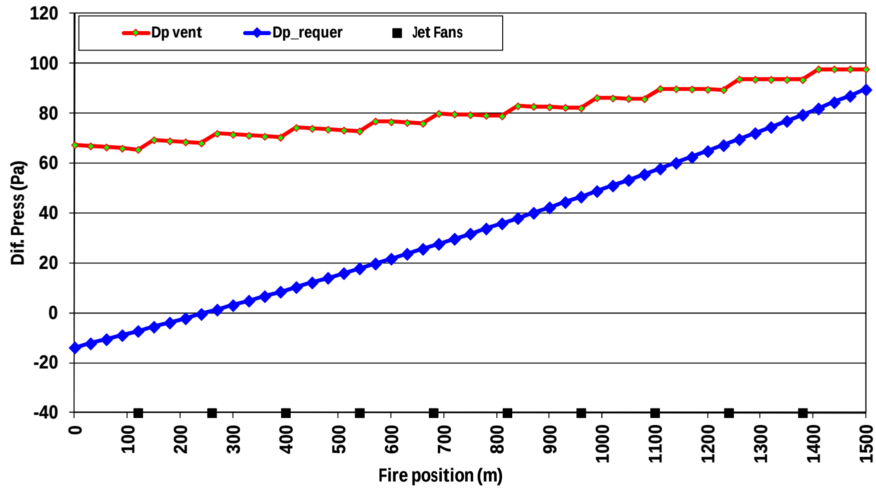


Fig. 1: Typical representation for comparison of available and required thrust.

4. SIMPLIFIED METHOD FOR VENTILATION DESIGN IN CASE OF FIRE

When designing a tunnel there are many installations which size, and consequent cost, is strongly related to the ventilation system. A simplified method could help at the early stages of a tunnel design to obtain a quick number of the needed thrust that the jet fans would have

[2] This value deppends on the air velocity and the time wanted to maintain this velocity in the tunnel, see chart 5.7 of the Dossiers Pilotes of Ventilation from CETU

to give in order to beat all the losses of load; so that other systems, as the energy one can be design with more knowledge of the future final stage.

The base of this method consists on simplify the effect of the increase of the temperature due to the fire. In this way, **the pressure losses would be calculated at ambient temperature and then by applying some coefficients the effect of the temperature will be gathered.**

So for a given tunnel (length (L), slope, section, hydraulic diameter, number of lanes, friction and singular losses coefficients), traffic (vehicles characteristics, percentage of heavy vehicles, vehicles intensity), ambient conditions (i.e. temperature, air density, value of gravity acceleration), critical velocity, possible jet fans to install (jet velocity, efficiency (η)) and the HRR of the designing fire; the equations to be used in order to obtain the losses of load to beat at "Cold Air conditions" would be:

"Cold Air" friction losses	$\Delta H_{\mathrm{f}}^{\text{cold air}} = \lambda \cdot \frac{\rho_0 {W_0}^2}{2} \cdot \frac{L}{D_H}$	Eq. 8
"Cold Air" Singular losses	$= \xi \cdot \frac{\rho_0 {W_0}^2}{2}$	Eq. 9
"Cold Air" vehicles effect (U=0, vehicles stopped)	$\Delta H_{\mathrm{v}}^{\text{cold air}} = Nveh \cdot \frac{\mathrm{C_x}\Sigma}{\mathrm{S}} \cdot \frac{\rho_0 {W_0}^2}{2}$	Eq. 10
"Cold Air" Chimney effect (weight of fresh air column in tunnel)	$\Delta H_{chim}^{cold\ air} = i \cdot \rho_0 \cdot g \cdot L$	Eq. 11
"Cold Air" Atmopheric pressure effect	ΔH_{atm}	Eq. 12

There is no affection from temperature for the atmospheric pressure effect since it's independent of what happens in the inside of the tunnel; as well as for the piston effect, since this effect happens upstream the fire and as long as the air velocity is enough to avoid the back layering (critical velocity which for what a longitudinal ventilation is design) temperature upstream would be at ambient conditions.

Fig. 2: Example of vehicles stopped for the piston effect

The goal is to obtain some weighting coefficients (depending on the HRR, the target air velocity, and the length of the tunnel) that will affect the losses at "Cold Air conditions" that will help to calculate the total thrust installed as follows:

$$\Delta F_{installed\ thrust}^{simplified} = \frac{S\left(\Delta H_{\mathrm{f}}^{\text{cold air}} \cdot coef1 + \Delta H_{chim}^{cold\ air} \cdot coef2 + \Delta H_{\mathrm{s}}^{\text{cold air}} \cdot coef4 + \Delta H_{\mathrm{v}}^{\text{cold air}} + \Delta Hatm\right)}{\left(coef3 - \frac{W_0}{W_{jet}}\right)\eta} \qquad \text{Eq. 13}$$

To obtain these coefficients it is only necessary to identify the influence of the temperature effects in the different pressure losses:

Where:

- Coef1, coefficient that affects the "cold air" friction losses by temperature:

$$coef1 = \frac{1}{L}\left[\int_0^{xinc} \frac{T_x}{T_o} dx + \int_{xinc}^{L} \frac{T_x}{T_o} dx\right] \quad \rightarrow \quad coef1 = \left[L + \frac{K}{B}\left(1 - e^{B(xinc-L)}\right)\right] \cdot \frac{1}{L} \qquad \text{Eq. 14}$$

- Coef2, coefficient that affects the "cold air" Chimney effect by temperature (if there is no fire this effect has to be zero)

$$coef2 = \frac{1}{L}\left[\int_{xinc}^{L} 1 - \frac{T_o}{T_x}dx\right] \rightarrow \quad coef2 = \frac{1}{L}\left(-\frac{1}{B}\ln\frac{K.e^{B(xinc-L)}+1}{K+1}\right) \qquad \text{Eq. 15}$$

- Coef3, coefficient that affects the behaviour of the jet fans by temperature (in this case a unifor thrust of the fans along the tunnel it's been supposed, other distribution can be studied as well; e.g jet fans at the portals)

$$coef3 = \frac{1}{L}\left[\int_{0}^{xinc} \frac{T_0}{T_x}dx + \int_{xinc}^{L} \frac{T_o}{T_x}dx\right] \rightarrow \quad coef3 = \frac{1}{L}.\left[L + \frac{1}{B}\ln\frac{K.e^{B(xinc-L)}+1}{K+1}\right] \qquad \text{Eq. 16}$$

- Coef4, coefficient that affects the "Fresh" Singular losses by temperature (ξ =0.5, ξ_s=1)

$$coef4 = \left(\zeta_e + \zeta_s\frac{T_s}{T_o}\right) \rightarrow \quad \frac{T_s}{T_o} = \frac{T_o + \frac{Q_{conv}}{\rho_o.S.C_p.V_a}\, e^{-\frac{4\,happ}{\rho_o.S.D_l.V_a}(L-xinc)}}{T_o} \qquad \text{Eq. 17}$$

$$\rightarrow \qquad coef4 = 1.5 + K.e^{-B(L-xinc)}$$

Where:

$$A = \rho_o.S.C_p.V_a \qquad B = \frac{4\,happ}{\rho_o.S.DH.V_a} \qquad K = \frac{Q_{conv}}{A.T_o} \qquad \text{Eq. 18, Eq. 19, Eq. 20}$$

Once calculated these terms, a general expression for Coef1, Coef2 and Coef3 can be obtained by a fitting from a parametric study on W_0, S and D_H for different tunnel lengths (500-5000 m every 500 m), HRR's (5, 10, 30, 50, 100, 150 and 200 MW) and fire locations (50 fire positions for each tunnel length); as shown in these next graphs (for Coef4 no fitting is needed).

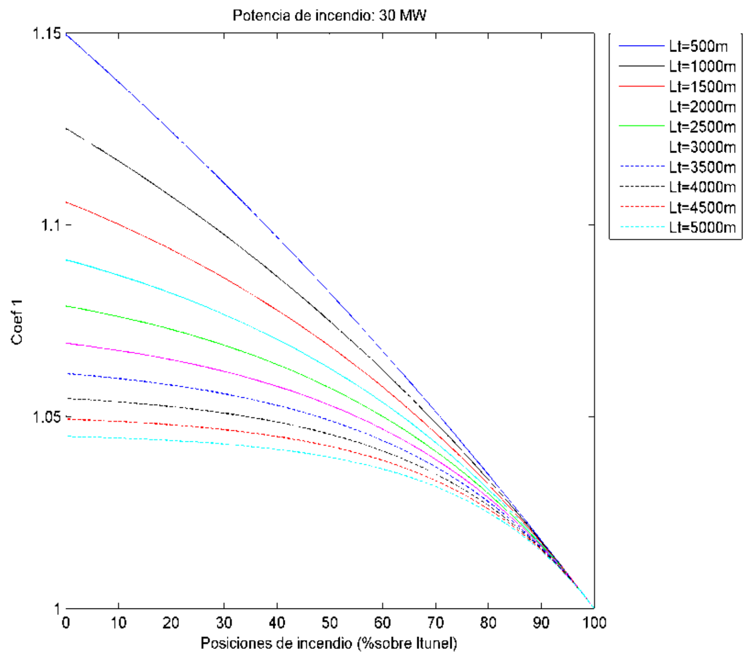


Fig. 3: Example of graphs for the fitting of the weighting factor to be applied on friction losses

The final expressions obtained for each coefficient have been done dependent on the tunnel lenght (L), the HRR of the fire ($\dot{Q}$), the fire position (X_{inc}), and the general characteristic of the case of study (W_0, S and D_H), obtaining:

$$coef1 = 1 + 5.67e^{-003}(\dot{Q}) - 1.63e^{-006}(\dot{Q} \cdot L) - 5.07e^{-003}(\dot{Q} \cdot X_{inc}) + 2.79e^{-006}(\dot{Q} \cdot L \cdot X_{inc}) + 1.58e^{-010}(\dot{Q} \cdot L^2) - 6.13e^{-004}(\dot{Q} \cdot X_{inc}{}^2) - 3.24e^{-010} * (\dot{Q} \cdot L^2 \cdot X_{inc}) - 1.11e^{-006}(\dot{Q} \cdot L \cdot X_{inc}{}^2) + 1.64e^{-010}(\dot{Q}^2 \cdot L^2 \cdot X_{inc}{}^2) \qquad \text{Eq. 21}$$

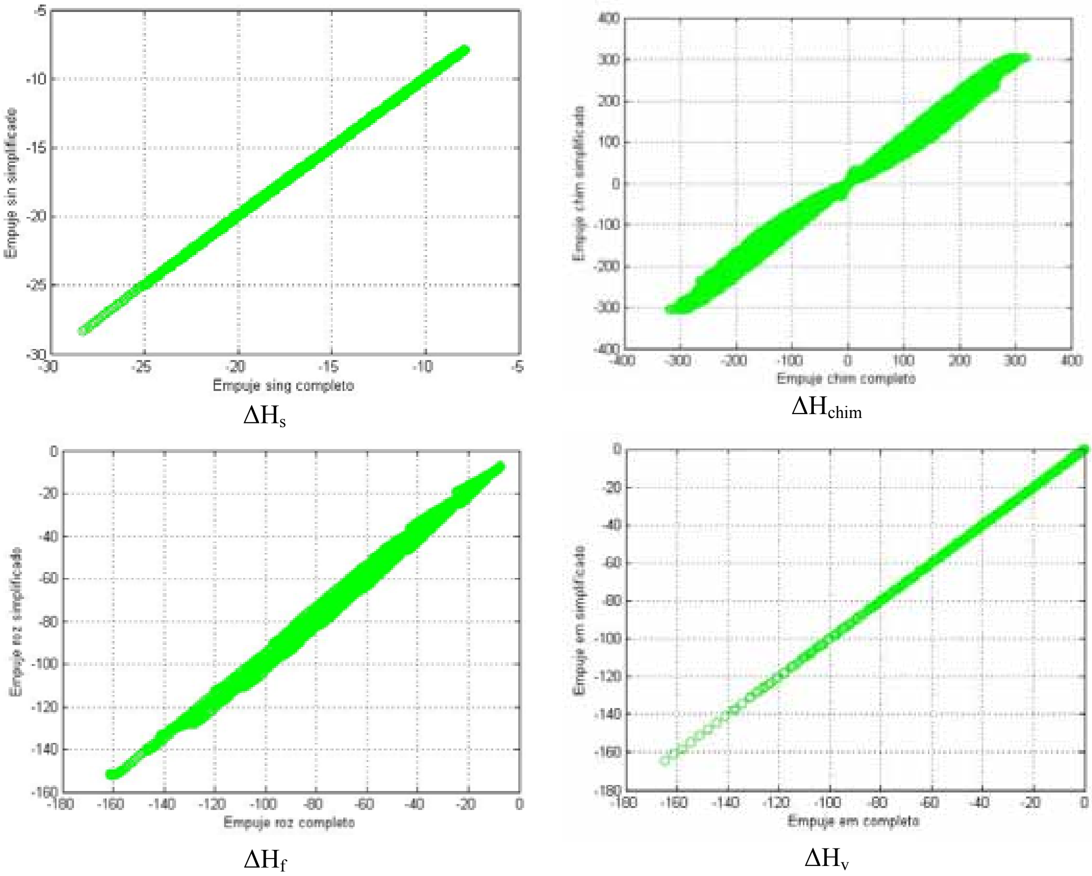
$$coef2 = 4.52e^{-002} + 2.78e^{-003}(\dot{Q}) - 7.11e^{-006}(L) - 3.94e^{-002}(X_{inc}) - 6.28e^{-007}(\dot{Q} \cdot L) - 2.81e^{-003}(\dot{Q} \cdot X_{inc}) + 5.07e^{-006}(L \cdot X_{inc}) + 1.31e^{-006} * (\dot{Q} \cdot ltunel \cdot X_{inc}) + 5.16e^{-011}(\dot{Q} \cdot L^2) - 1.28e^{-010} * (\dot{Q} \cdot L^2 \cdot X_{inc}) - 6.66e^{-07}(\dot{Q} \cdot L \cdot X_{inc}{}^2) + 9.95e^{-011} * (\dot{Q} \cdot L^2 \cdot X_{inc}{}^2) - 1.26e^{-013}(\dot{Q}^2 \cdot L^2 \cdot X_{inc}{}^2) \qquad \text{Eq. 22}$$

$$coef3 = 9.55e^{-001} - 2.78e^{-003}(\dot{Q}) + 7.11e^{-006}(L) + 3.94e^{-002}(X_{inc}) + 6.28e^{-007}(\dot{Q} \cdot L) + 2.81e^{-003}(\dot{Q} \cdot X_{inc}) - 5.07e^{-006}(L \cdot X_{inc}) - 1.31e^{-006}(\dot{Q} \cdot ltunel \cdot X_{inc}) - 5.16e^{-011}(\dot{Q} \cdot L^2) + 1.28e^{-010}(\dot{Q} \cdot L^2 \cdot X_{inc}) + 6.66e^{-007}(\dot{Q} \cdot L \cdot X_{inc}{}^2) - 9.95e^{-011}(\dot{Q}^2 \cdot L^2 \cdot X_{inc}{}^2) \qquad \text{Eq. 23}$$

$$coef4 = 1.5 + \left(\left(\frac{2 \cdot \dot{Q}}{S \cdot W_0}\right) \cdot exp\left(-0.03 \cdot \left(\frac{L - X_{inc}}{W_0 \cdot D_H}\right)\right)\right) \qquad \text{Eq. 24}$$

5. VALIDATION

The thrust obtained for the jet fans with the complete design method and with the simplified one has been compared for 75600 cases of study (3 cross secctions: 65, 85, 100 m^2, 6 tunnel lenghts: 500, 1000, 1500, 2000, 2500, 3000 m, 7 tunnel slopes: -3, -2, -1, 0, 1, 2, 3 %, 2 air velocities: 3, 4 m/s, 6 fire HRRs: 5, 30, 50, 100, 150, 200 MW and 50 fire positions: on each tunnel lenght). For each of the load losses, except for the value of ΔP_a, the ratio between them calculated with both methods are gather in **Fig. 4**.



ΔH_s ΔH_{chim} ΔH_f ΔH_v

Fig. 4: Correlation between the complete (abscissa) and the simplified (ordinates) methods

The correlation obtained between the total thrust calculated for the jet fans with the complete method and the one calculated with the simplified one is presented in **Fig. 5**; for the whole set of cases. As it can be seen, the results obtained with the simplified method are quite similar to those obtained by the complete method, with a maximum error below 30%.

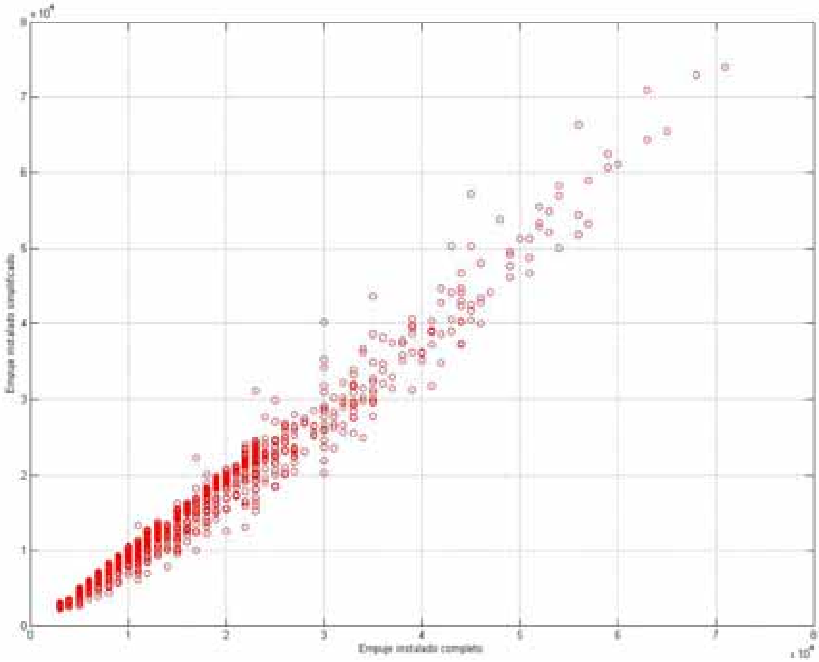


Fig. 5: Dispersion in the thrust needed for the jet fans (simplified vs. complete)

6. CONCLUSIONS

This paper presents a simplified method for longitudinal ventilation design, though it does not contribute for an exhaustive design, it could be useful for obtaining quick numbers in pre-designing to be able to have a whole picture of the ventilation system and see its interaction with other installations.

In addition, this tool is interesting to explore the influence of the designing criteria (e.g. fire heat release rate) in the total thrust to be installed and would allow the use of probabilistic approaches on the study parameters which could be of interest for the designing of systems.

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NUMERICAL SIMULATION OF RUNEHAMAR TUNNEL FIRE TESTS

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ABSTRACT

This paper focuses on numerical simulation of a Runehamar tunnel fire test, i.e. a large tunnel fire with heat release rate around 200 MW. The widely used CFD tool Fire Dynamics Simulator (FDS) is employed in the simulations. The Runehamar tunnel fire tests performed by SP were well designed and valuable data were obtained. This makes it possible to assess CFD modelling of large tunnel fires. The paper further explores the fire dynamics in large tunnel fires. Different parameters are investigated and compared, including gas temperatures and heat fluxes in the vicinity of the fire, gas temperatures and velocities downstream of the fire.

Keywords: tunnel fire, large fires, CFD, fire dynamics

1. INTRODUCTION

Tunnel fire safety is a key issue while designing a new tunnel or rebuilding a tunnel. The computational fluid dynamics (CFD) technology is widely used to aid the design of fire safety systems in tunnels. Note that any CFD tool is built on many assumptions and simplifications. The users need to have knowledge of its credibility and limitations.

Especially in a large tunnel fire, the fire dynamics is difficult to simulate since the combustion is complex including both vertical flame and horizontal flame regions. However, the regions close to the fire source are in focus for many design aspects. Examples of such focus are the design of the ventilation system and the fire protection of the tunnel structures.

In order to fully understand the mechanisms of fire dynamics in a catastrophic tunnel fire, SP initiated, planned and performed the Runehamar tunnel fire tests in 2003 [1-3] (Ingason and Lönnermark 2005; Lönnermark and Ingason, 2006; Lönnermark et al., 2006). Recently, the comprehensive Runehamar tunnel fire tests report has been published with all the test data available [4] (Ingason et al., 2011).

The Runehamar tunnel fire tests were well designed and valuable data were obtained, which makes it possible to assess CFD modelling of large tunnel fires. The paper further explores the fire dynamics in large tunnel fires. Different parameters are investigated and compared, including gas temperatures and heat fluxes in the vicinity of the fire, gas temperatures and velocities downstream of the fire.

2. SHORT DESCRIPTION OF THE RUNEHAMAR FIRE TESTS

The Runehamar tunnel is situated about 5 km from Åndalsnes, 40 km south of Molde in Norway and is a two-way asphalted road tunnel that was taken out of use in the late 1980s. It is approximately 1600 m long, 6 m high and 9 m wide with a cross-section of about 47 m^2. The tunnel has an average uphill slope of 0.5 % up to about 500 m from the east portal (where the fans were located) to the west portal, followed by a 200 m long plateau and then a 900 long downhill section with an average slope of 1 % towards the west portal. The longitudinal flow inside the tunnel was created using two mobile fan units.

The fire was mainly located about 1037 m from the east portal, i.e. on the downhill section of the tunnel. The commodities were placed on particleboards on a rack storage system to simulate a HGV measuring 10.45 m by 2.9 m. The total height was 4.5 m and a 0.5 mm thick polyester tarpaulin covered the cargo. The height of the platform floor was 1100 mm above the road surface.

Before the mock-up tests, a pool fire test (T0) was carried out. This test was carried out to check the instrumentation and calibrate the measurements of the heat release rate measurements. The fire source consisted of diesel loaded in a pan with a diameter of 2.27 m. The total volume of the fuel was 200 L. No data or information about this test has been published previously.

For the safety of the personnel, the tunnel was protected by Promatect T fire protection boards near the position of the fire. The boards were attached to a steel frame system from GERCO consisting of crossbar steel beams and pipes over a length of 75 m. The steel frame system was in a straight line and equal in geometry over the entire 75 m length. The ceiling consisted of boards covering the entire length of the steel framework (75 m). The walls were 39 m long and consisted of vertical boards (30 mm thick) attached to the steel framework (see Figure 1).

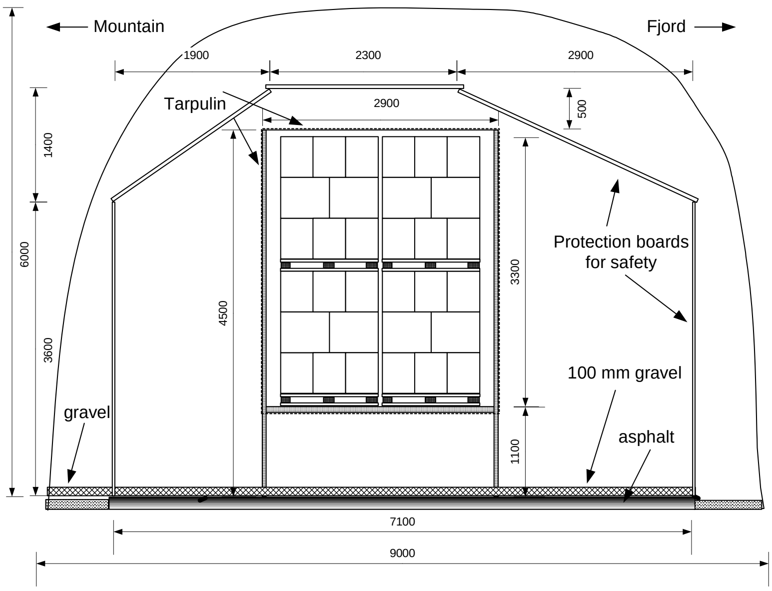


Figure 1: Tunnel cross section at the fire site.

Temperatures were measured at several positions along the tunnel, from -100 m upstream of the fire to a measurement station +458 m downstream of the fire, i.e. 105 m from the west entrance. Upstream of the fire the thermocouples were located at -15 m, -25 m, -40 m, -70 m and -100 m and 0.3 m beneath the ceiling. Downstream of the fire the thermocouples were located at 0 m, +10 m, +20 m, +40 m, +70 m, +100 m, +150 m, +250 m, +350 m and +458 m. The majority of the temperatures were measured using unsheathed thermocouples, 0.25 mm type K. Most of the gas temperatures downstream of the fire were measured 0.3 m below the tunnel ceiling, which means 4.8 m above the road surface in the region with fire protection boards and about 5.7 m above the road elsewhere. At the measurement station at + 458 m, thermocouples were placed at five different heights; 0.7 m, 1.8 m, 2.9 m, 4.1 m, and 5.1 m. Gas concentrations were also measured in the corresponding locations.

Five bi-directional pressure difference probes were used at the measurement station at +458 m, together with one located upstream at -50 m and 3 m above the road surface. The gas velocity was determined with aid of the measured pressure difference for each probe and the corresponding gas temperature.

Four plate thermometers were placed on the ceiling at 0 m, 10 m, 20 m and 40 m downstream of the fire centre respectively, and a plate thermometer was placed under the target and towards the fire load at 20 m downstream.

3. NUMERICAL SIMULATION METHOD AND VERIFICATION

3.1. Numerical method

The simulations were conducted using Fire Dynamics Simulation (FDS 5.5.3) developed by NIST [5-6] (McGrattan et al., 2010). FDS is widely used in fire community and in tunnel fire engineering application.

Large eddy simulation (LES) mode is chosen. Large eddies are modelled directly and small ones are simulated using Smagorinsky sub-models.

The default combustion model is mixture fraction model. Note that the diffusion flame immersed in a vitiated atmosphere could extinguish before consuming all the available oxygen. A simple model of flame extinction is embedded in FDS 5. The critical oxygen concentration, $Y_{O2,lim}$, below which the combustion doesn't occur is directly correlated with the gas temperature in the mesh. Virtual sparks are assumed in every mesh which fulfils the above equation. This method should be paid much attention to since a large tunnel fire produces really vitiated atmosphere in the vicinity of the fire and this equation will have strong influence on location of the combustion zone.

The radiation from the fire is one of the most important parts while simulating a large tunnel fire. Since the radiation from the fire is a function of the flame temperature and chemical composition, neither of which are reliably calculated in a large fire simulation, FDS use a very simple way to solve this problem mainly by introducing the radiative fraction of the heat release rate. It is known that the radiative fraction of an open fire ranges from 20 % to 40 % for most common fuel sources. By default it is 0.35 for LES. However, note that the flame extends along the tunnel ceiling, and the flame length in a large tunnel fire is significantly longer than the flame height of an open fire, the radiative fraction could be higher. In the present paper, 0.45 is used. Note that this fraction doesn't include the reabsorption of the thermal radiation.

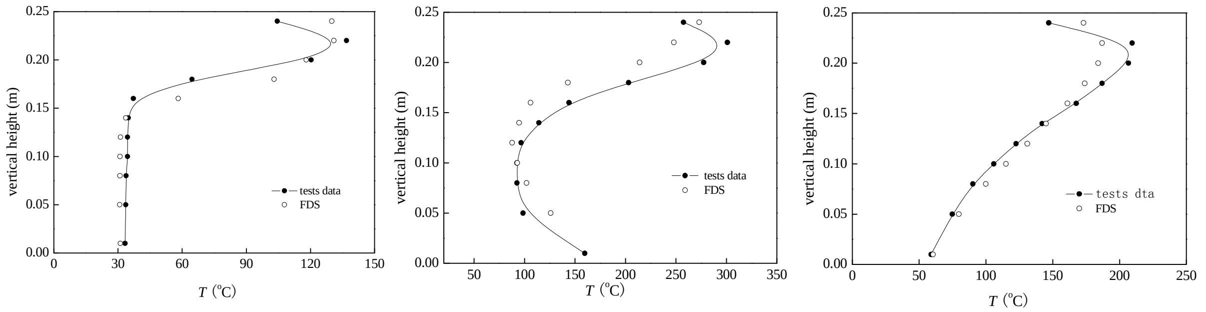
The convective heat transfer is solved simply by semi-empirical equations for natural and forced convection. The heat conduction through the tunnel walls is solved using one-dimensional conduction equations and 20 meshes are used by default. Wall functions are introduced to predict the velocity close to the surface and the viscous stress.

Clearly the numerical method is still quite simple and some of these parameters need to be verified in large tunnel fires.

3.2. Verification of modelling

Data from one of our earlier model scale tests [7-8] (Li et al., 2010; Li et al., 2011) was used to verify the modeling. The model scale tests were carried out in a model tunnel with a dimension of 12 m (L) × 250 mm (W) × 250 mm (H). The propane fire burner was set at the floor level and 6 m away from the downstream exit. In the simulation, the tunnel is closely the same as that used in the model-scale tests except a length of 8 m rather than 12 m. The ambient pressure is 95590 Pa and the ambient temperature is 23.8 ^{o}C. The heat release rate is 9.45 kW and the longitudinal ventilation velocity is 0.51 m/s. The fire source was placed in the centre of the tunnel. Only half of tunnel was simulated due to fully symmetry. The mesh size used in the simulation is $0.075D^*$, which has been proved to be a reasonable mesh size according to the above analysis.

The simulated vertical temperature distribution at different places was compared to the tests data, as shown in Figure 2. It is shown that the simulated results correlate well with the tests data measured upstream and downstream of the fire. The relative error is within 20 %.



(a) 0.9 m upstream of the fire *(b) fire centre* *(c) 1.8 m downstream*

Figure 2: A comparison of gas temperatures between the simulations and the tests.

3.3. Simulations of Runehamar tunnel fire tests

A total tunnel length of 700 m was simulated, including 100 m upstream and 600 m downstream of the fire. The fire source has a width of 3 m and a length of 10 m. Propane was used as fuel. The default wall surface was granite and the fire protection board promatect T close to the fire was simulated. The boundary of inlet was velocity boundary and the outlet was ambient. To reduce computation time, half of the tunnel was simulated. The mesh size was approximately 20 cm.

Runehamar test T1 was simulated. The maximum heat release rate was 202 MW and the average longitudinal velocity ranged from 2 m/s to 2.5 m/s. The ambient temperature was approximately 11 ^{o}C. The estimated average heat of combustion is 18.5 MJ/kg. The fraction of soot production and CO production in the fuel is 2.2 %, and 0.88 % respectively.

4. RESULTS AND DISCUSSION

4.1. Ceiling gas temperatures

The ceiling gas temperatures from 40 m upstream (–40 m) to 350 m downstream of the fire are presented and compared in Figure 3. All the thermocouples were placed at the centre line of the tunnel and 0.3 m below the ceiling. Generally, the simulation results correlate well with the measured values, especially from 10 m to 150 m downstream of the fire. However, the ceiling gas temperatures at 250 m and 350 m downstream were underestimated approximately 30 % in the peak period. Further, the maximum temperature beneath the tunnel ceiling is approximately 1350 ^{o}C. This confirms the reliability of the measurement. It should be noted that the ceiling gas temperature is overestimated upstream of the fire. This may indicate that the backlayering length of a large tunnel fire could be overestimated using FDS 5. Also, the gas temperatures above the fire are overestimated in the peak period. This may arise from the difference in the fuel configuration, that is, the fuel consisted of solid fuels in full scale test but gas burners in the simulation. Despite this, well agreement can be found.

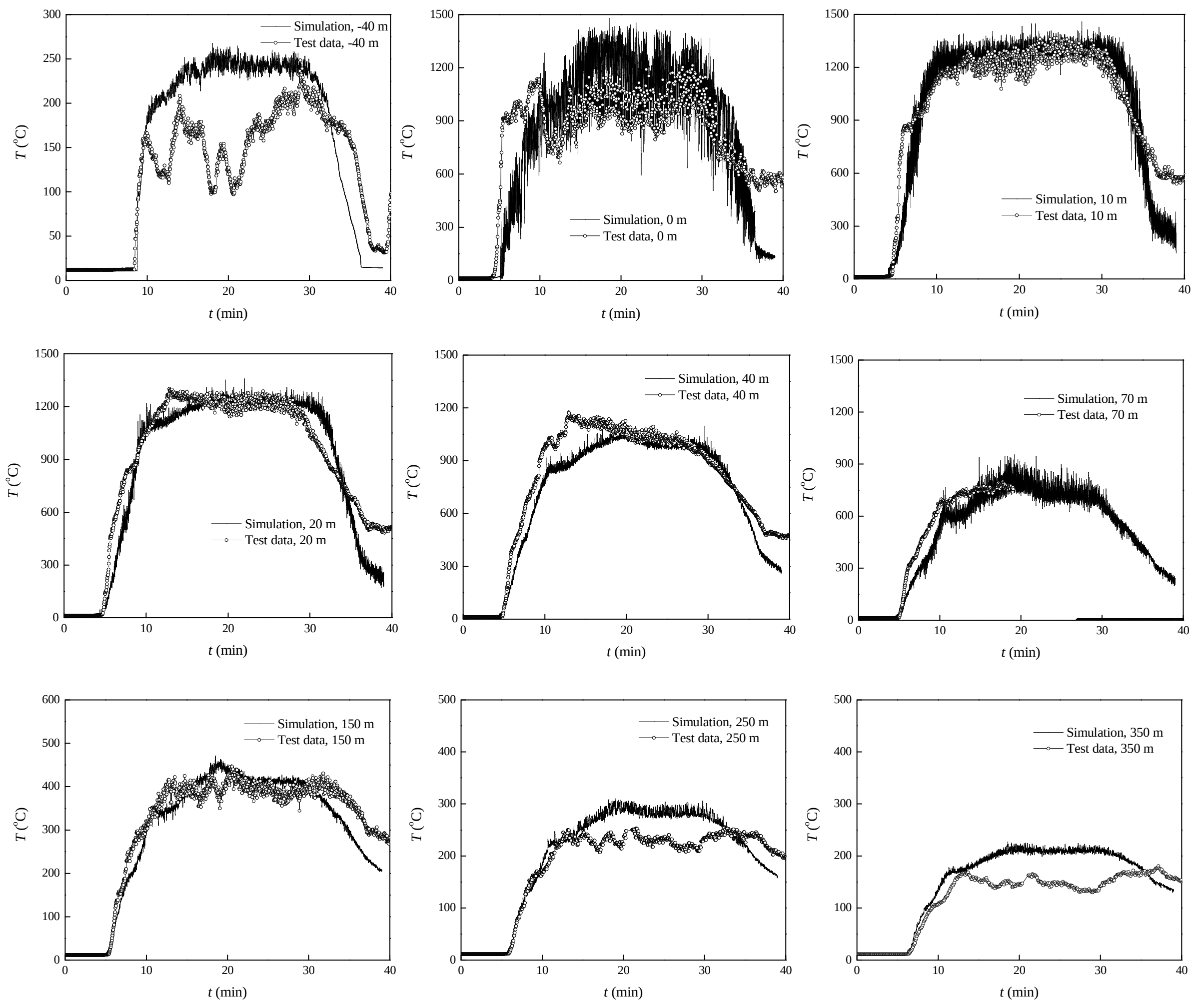


Figure 3: Gas temperature below the ceiling in the vicinity of the fire.

4.2. Radiation

The incident heat fluxes measured by plate thermometers and the numerical results are presented and compared in Figure 4. Note that the figures correspond to 4 plate thermometers on the ceiling and 1 plate thermometer toward the fire at 1.6 m above the floor. Comparing the measured and simulated results shows that a relatively good agreement can be found, however, not as good as in ceiling gas temperatures. The reason is that the heat flux is quite sensitive to the temperature, that is, 4th power of the temperature (Kelvin). Clearly, it is shown in Figure 4 that the simulated incident heat fluxes were correlated well with the measured values at 10 m. However, the incident heat fluxes were overestimated at fire site, slightly underestimated at 20 m and significantly underestimated at 40 m downstream of the fire.

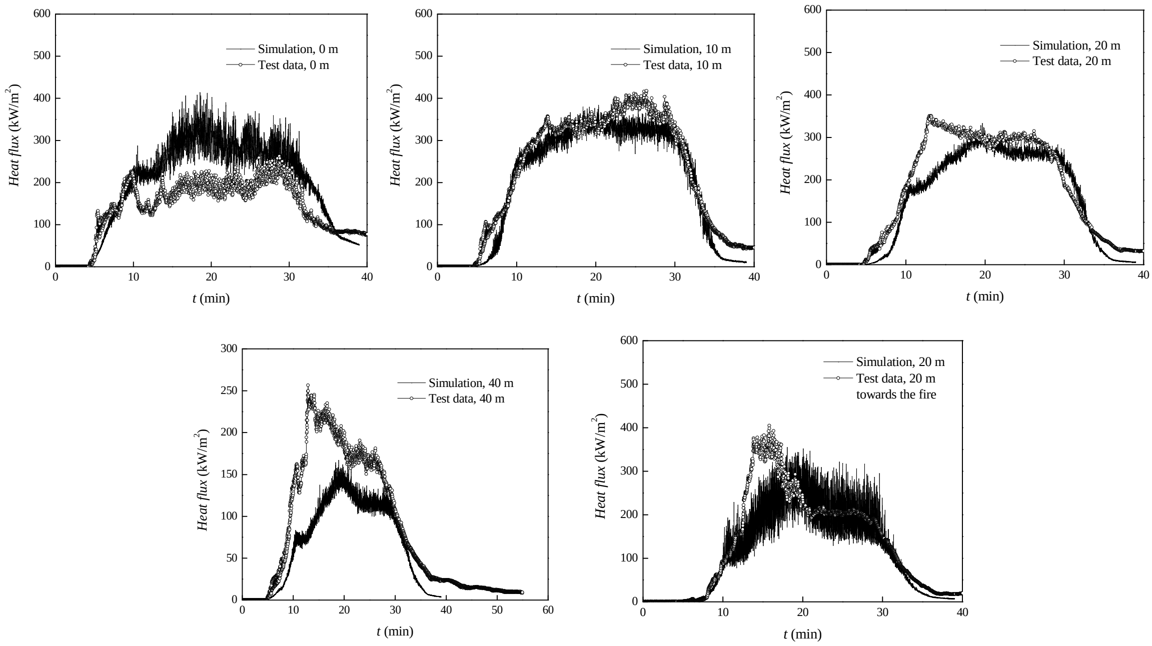


Figure 4: Incident radiation in the vicinity of the fire.

Figure 5 shows the simulated net heat flux at the tunnel ceilings. The data plotted here corresponds to 30 s average values. Note that the net heat fluxes are much lower than the incident heat fluxes presented in Figure 4. The maximum net heat flux of about 40 kW/m^2 was found at around 10 m from the fire. In the growth period of the fire, the ceiling close to the fire has higher net heat flux. However, after around 10 min when the fire grows up to 100 MW, the heat fluxes found at these four locations are approximately the same and decreases gradually with time. The reason is that in this period the thermal resistance of the tunnel structures dominates the heat transfer to the ceiling, and this region has similar gas temperatures since it is surrounded by the flame in the peak period. Further, the net heat fluxes become negative after about 33 min, that is, the hot walls heat up the gas flow.

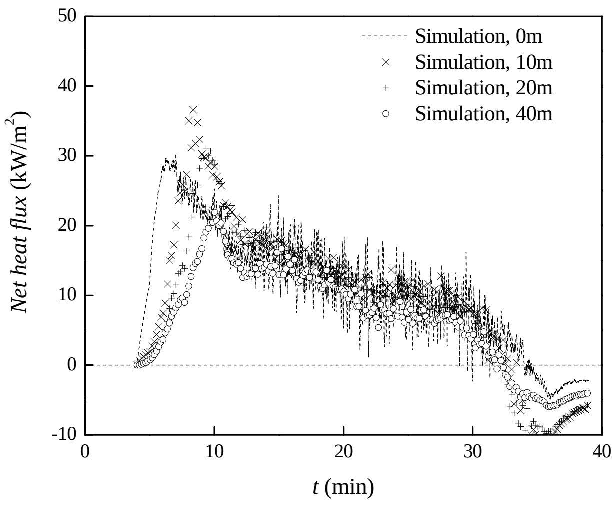


Figure 5: Net heat flux absorbed by the tunnel ceilings at different location in the simulation.

4.3. Gas temperature and velocity at the measurement station

The measurement station was located at 458 m downstream of the fire. The gas temperatures at five different heights are shown in Figure 6. The gas temperatures are significantly overestimated at all heights. The reason could be the accumulation of underestimation of the heat transfer along the tunnel. This suggests that the heat transfer to the tunnel walls could not be simulated well in the far-field region away from the fire using FDS5.5.

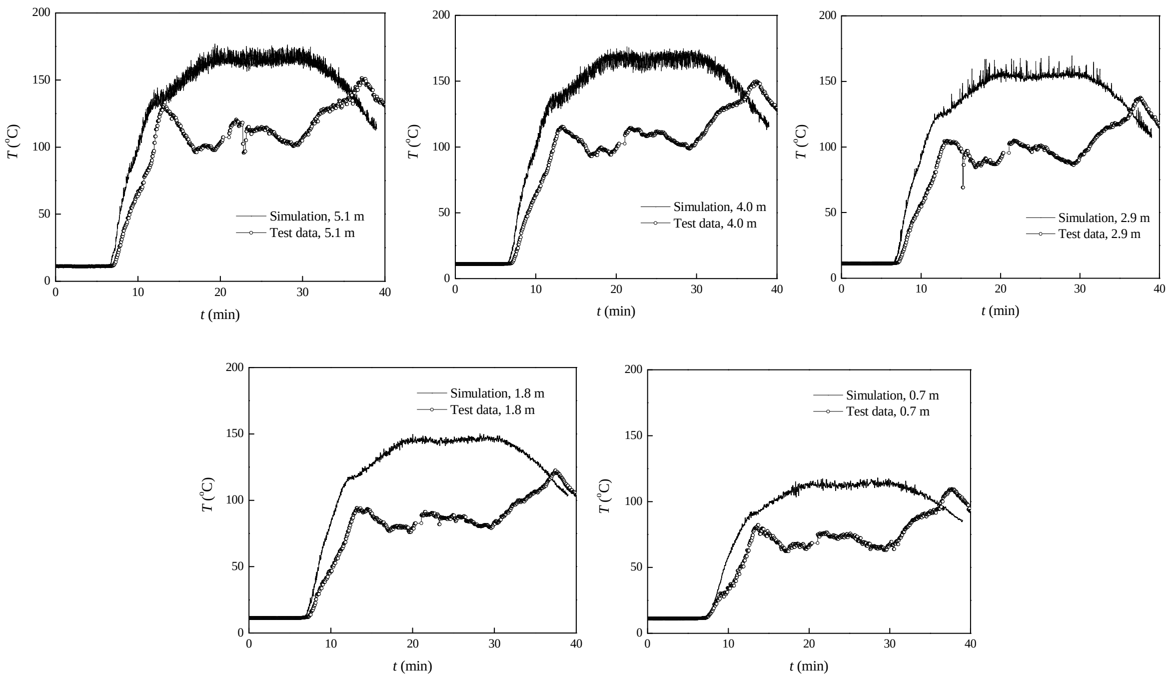


Figure 6: Gas temperatures at 458 m downstream of the fire source.

Figure 7 shows the gas velocities at five different heights. The gas velocities above 0.7 m are significantly overestiamted and gas velocities at 0.7 m are slightly underestimated. This suggests that the thermal stratification is not simulated well, and further, the wall function in FDS 5 may need to be improved.

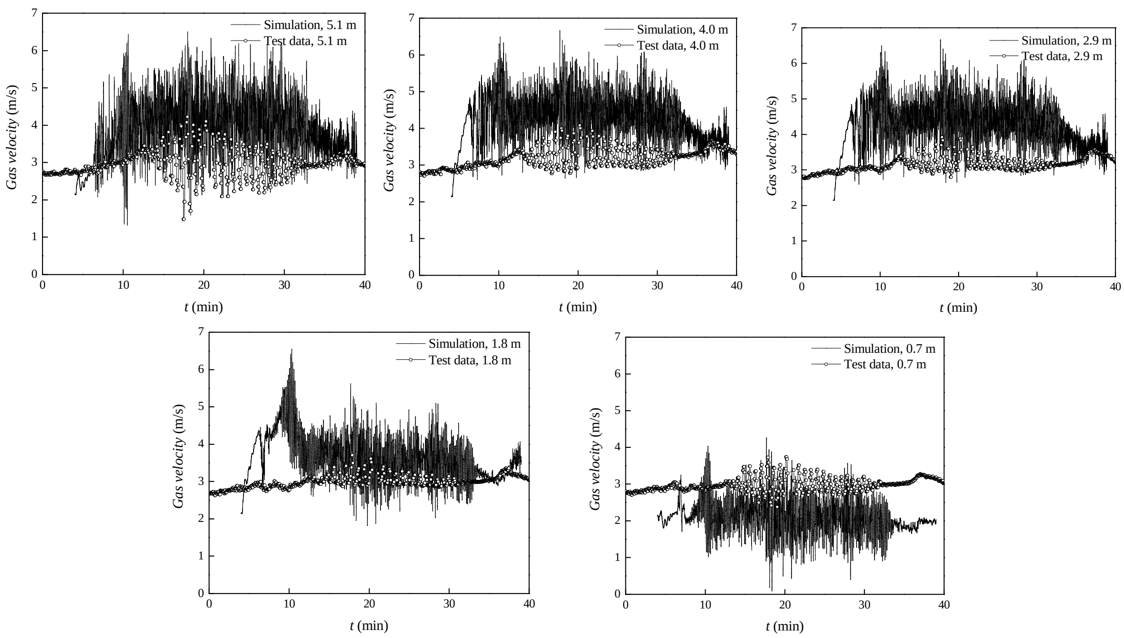


Figure 7: Gas velocities at 458 m downstream of the fire source.

5. CONCLUSION

The simulated ceiling gas temperatures correlate well with the measured values from 10 m to 150 m downstream of the fire, however, the gas temperature at 250 m and 350 m downstream are underestimated by approximately 30 % in the peak period. The gas temperatures at 458 m away from the fire are significantly overestimated at all heights. The gas velocities at 458 m are significantly overestimated at heights above 1.8 m and underestimated at lower height.

The incident heat fluxes at the ceiling are overestimated at 20 m and 40 m downstream of the fire. The maximum net heat flux of about 40 kW/m^2 was found at around 10 m from the fire. In the growth period of the fire, the ceilings close to the fire have higher net heat fluxes. However, after around 10 min when the fire grows up to 100 MW, the heat fluxes found at these four locations are approximately the same and decreases sharply with time.

Much attention should be paid on the combustion region and soot production of the fuel.

6. ACKNOWLEDGEMENT

The study was sponsored by SP Tunnel and Underground Safety Centre which is gratefully acknowledged.

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IMPACT OF THE CONSIDERATION OF HOT SMOKE GASES IN THE DESIGN OF TRANSVERSE VENTILATION SYSTEMS

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ABSTRACT

Design fire size is an important parameter in ventilation design. However, merely stating a number for the heat release rate is not sufficient. A fire produces two effects which need to be considered in the design phase. For longitudinal ventilation systems the most important effect is buoyancy. In transverse ventilation systems, however, the change in air/smoke density leads to significantly higher volumetric flow-rates resulting in higher pressure loss.

This paper focuses on the impact of variations in air/smoke density on the design of transverse ventilation systems. The goal is to establish a simple calculation method which can easily be added to national design regulations such as the Austrian RVS 09.02.31, (2).

In order to obtain relevant information for transverse ventilation systems, one-dimensional calculations were first performed on two different existing tunnel constructions, followed by further calculations on two exhaust air duct cross sections (9 m² and 12 m²) with heat release rates of 30 MW and 50 MW respectively.

The required ventilation power of the considered exhaust air duct geometries was determined for cold air conditions (air temperature of 20 °C) and for hot air conditions (resulting from heat release). The investigation of the existing tunnel constructions showed that required ventilation power upon heat release was up to 20 % higher compared to cold air conditions.

Sensitivity analysis revealed that the increase of required ventilation power due to the temperature influences depends mainly on the design fire load and is largely independent of the cross section of the exhaust air duct. With a design fire of 30 MW the required ventilation power increases, depending on the length of the exhaust air duct, by between 50 % (exhaust air duct length of 600 m) and 16 % (exhaust air duct length of 2500 m) and for a design fire of 50 MW by between 90 % and 25 % compared to cold air conditions. Such differences have a big impact on the operation curve of the axial fans.

The investigations allowed for a simple calculation method to be derived which is capable of taking the impact of temperature changes into account.

Keywords: ventilation design, transverse ventilation system, incident ventilation

1. NOTATION

$\dot{V}_L$	[m³/s]	Leakage rate
p_u	[Pa]	System pressure / pressure difference
ξ	[-]	Leakage resistance coefficient
ρ_L	[kg/m³]	Density of the leakage air
A_L	[m²]	Area of the leakage
T_B	[K]	Mean air temperature at the damper
$\dot{Q}$	[W]	Heat release rate

η_{fire}	[-]	Fire efficiency
$\dot{m}$	[kg/s]	Mass flow rate of the extraction
c_p	[J/(kg K)]	Specific heat capacity at constant pressure
T_i	[K]	Initial air Temperature
U	[m]	Circumference of the exhaust air duct
T_W	[K]	Wall temperature of the exhaust air duct
T_x	[K]	Mean air temperature at location x in the exhaust ait duct
F_V	[-]	Temperature dependent parameter for the volume flow correction
T_{fan}	[K]	Temperature at the axial fan for hot air conditions
T_k	[K]	Temperature at the axial fan for cold air conditions
$\dot{V}_w$	[m³/s]	Volume flow rate at the axial fan for hot air conditions
$\dot{V}_k$	[m³/s]	Volume flow rate at the axial fan for cold air conditions
F_p	[-]	Temperature dependent parameter for the correction of the pressure losses
a	[-]	Parameter for the calculation of F_p
x	[m]	Distance from the location of the extraction along the axis of the exhaust air duct in flow direction
g	[m/s²]	Gravity
s	[-]	Slope of the exhaust air duct
ρ_i	[kg/m³]	Initial air density
Δp_w	[Pa]	Pressure losses for hot air conditions
Δp_k	[Pa]	Pressure losses for cold air conditions
Δp_A	[Pa]	Pressure difference due to the buoyancy effects

2. INTRODUCTION

Heat release in the event of a fire can result in rapid and marked changes in temperatures and air densities in the tunnel section affected. Thus, tunnel safety and rescue support conditions during a fire are decisive factors in the field of tunnel ventilation design.

Unfortunately most design guidelines provide no information on how to address the impact of temperature variation in the design of ventilation systems. It is largely left to the designer to decide what is to be done.

A previous paper (1) has already dealt with the consideration of the buoyancy forces in the design phase (with a focus on complex tunnels with longitudinal ventilation). Based on three-dimensional calculations for tunnels with varying tunnel cross sections and heat release rates a one-dimensional calculation method to consider the buoyancy forces was derived. This approach will be implemented in the Austrian guideline RVS 09.02.31 (2). The current paper, in contrast, deals with the temperature impact on transverse ventilation systems as a result of fire, and the related changes in terms of pressure losses, negative pressure loads of the intermediate ceiling and required ventilation capacity in existing and future tunnel projects.

In transverse ventilation systems smoke extraction and transport take place mostly within ducts and at velocities > 10m/s. Thus pronounced 3D flow behaviour can be neglected. Hence, the following calculations were performed in terms of a one dimensional approach applied to real tunnel geometries (tunnels with transverse and semitransverse ventilation systems). Unlike in tunnel traffic space, where three-dimensional flow and bouncy effects are prevalent, exhaust air ducts exhibit a much smaller cross-section. The resulting relatively high flow velocity means that such effects can safely be neglected in the present calculations. Based on the Austrian design guideline RVS 09.02.31 (2) a heat release rate of 30 MW and

50 MW, and an extraction volume flow of 120 m³/s (for transverse and semi transverse ventilation systems) and 200 m³/s (for a ventilation system with a massive point extraction) formed the starting point for the analysis. Depending on the various design guidelines the design fire size may vary from 3MW to more than 100 MW. In 1999 PIRAC also defined (and confirmed in 2004) that a heat release rate of 30 to 50 MW and a smoke production rate of 80 to 120 m³/s are feasible. An extensive discussion of design fires can also be found in (1), (5), (6) and (8).

To clarify matters, in the context of this paper, the term 'design fire' is used only with respect to the design of the ventilation system and related safety issues, and not with respect to the dimensioning of structures.
Calculations for a design fire of 30MW were performed for two different existing tunnel constructions (Katschbergtunnel and Tauerntunnel), taking account of ventilation buildings such as cavern, vertical shaft and so on. The “Katschbergtunnel” and the “Tauerntunnel” are typical tunnels in Austria and both exhibit a transverse ventilation system (7).
In order to perform a sensitivity analysis, further calculations for two exhaust air duct cross sections were also considered. A 9 m² cross section, typical for a full transverse ventilation system, and a 12 m² cross section offering a typical profile for a semitransverse ventilation system. Calculations were carried out with respect to both cross sections for design fires of 30 MW and 50 MW respectively, excluding ventilation buildings. An overview of the calculation cases can be found in Table 1.

Table 1: Overview of the performed calculation cases

Geometry	Design fire	Fire efficiency
existing tunnels		
Katschbergtunnel	30 MW	75 %
Tauerntunnel	30 MW	75 %
sensitive analysis		
full transverse 9 m²	30 MW and 50 MW	75 %
semitransverse 12 m²	30 MW and 50 MW	75 %

3. CALCULATION PARAMETERS AND BOUNDARY CONDITIONS

According to the current version of the Austrian design guideline RVS 09.02.31 (2) all calculations have to be done with respect to a reference density for air of 1.2 kg/m³. Thermal influences are only taken into account in the form of extra buoyancy forces. In order to ascertain the impact of temperature changes in transverse ventilation systems, each calculation case listed in table 1 was performed both for cold air conditions, i.e. a temperature of 20 °C (standard design), and also for hot smoke conditions (based on the heat release rate of the design fire).

3.1. Geometry

3.1.1. Katschbergtunnel

The hot smoke gases in the case of a fire are extracted by two parallel exhaust fans. Hence each exhaust fan has to provide only a half of the extracted flow rate and both exhaust fans together need to make up for the pressure loss arising from flow into the exhaust air duct (see

Figure 1). The exhaust air duct of the Katschbergtunnel has a cross section of 9.01 m², a circumference of 12.9 m, and a length of 2600 m .The longitudinal gradient from the extraction point to the axial fans is 1.5 %. In the proximity of the exhaust fans the exhaust air duct is evenly divided into two air ducts each with a cross section of 8.33 m², a length of 100 m and a circumference of 11m. Behind the exhaust fans the air duct is combined again where finally the exhaust air, after passing some bends leaves the ventilation building. More details about the ventilation system can be found in (7).

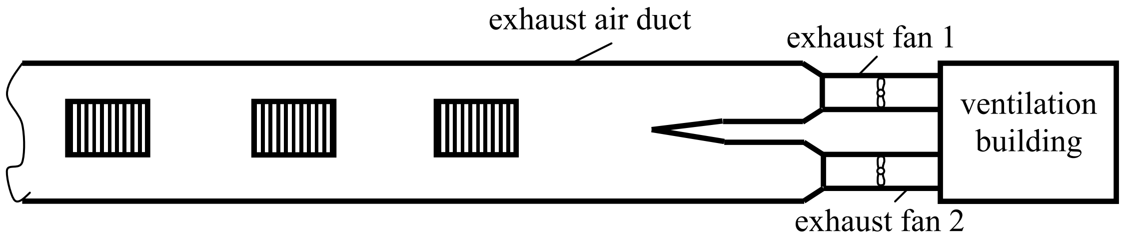

Figure 1: Sketch of the ventilation system of the Katschbergtunnel

3.1.2. Tauerntunnel

In the Tauerntunnel, both tubes (east and west) consist of four ventilation sections. Here, the focus is placed on the southern ventilation section of the east tube. The hot smoke gases in the case of a fire are extracted by one exhaust fan. The exhaust air duct under consideration has a length of about 1400 m, a cross section area of 9 m² and a circumference of 12.8 m. Within the ventilation building several changes in direction and cross section occur.

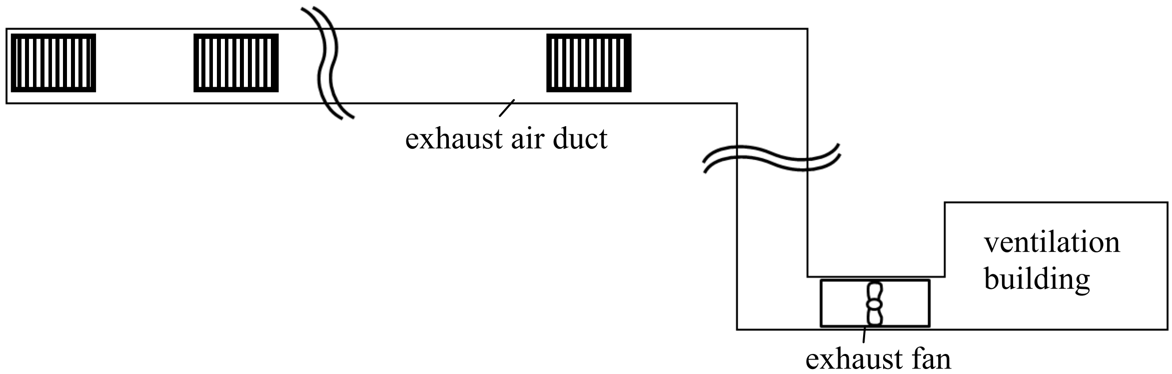

Figure 2: Sketch of the ventilation system of the Tauerntunnel

3.1.3. Sensitivity analysis

For the sensitivity analysis, a profile typical of a semitransverse ventilation system with a cross section of 12 m² and a circumference of 17.81 m, and a profile typical of a full transverse ventilation system with a cross section of 9 m² and a circumference of 13.13 m were chosen (see Figure 3). In both cases the exhaust air duct has a length of 2500 m, which according to the Austrian guideline (2), is the maximum accepted length for an exhaust air duct within a ventilation section.

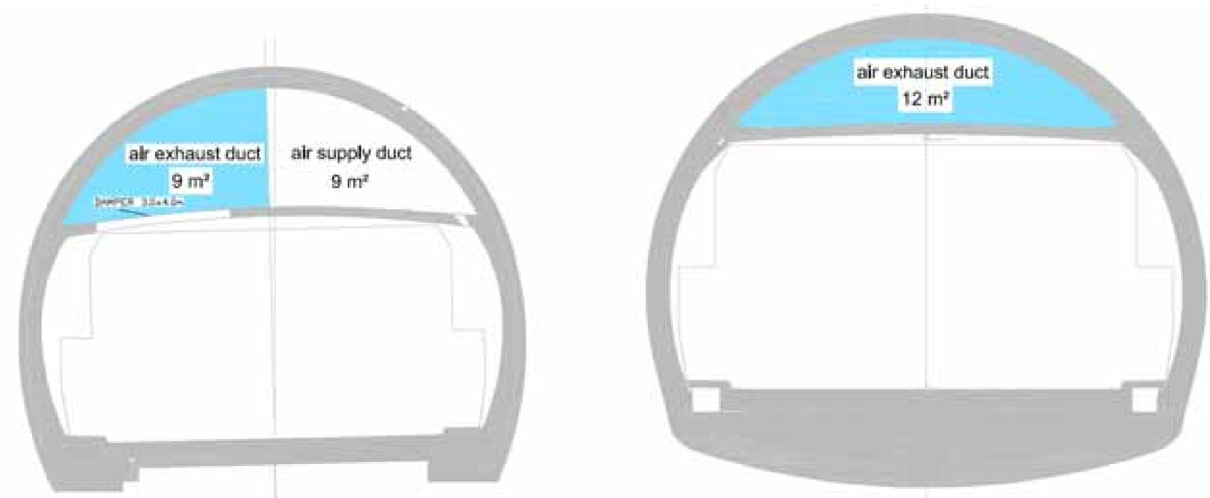

Figure 3: Typical profile of a semitransverse ventilation system (right) and of a full transverse ventilation system (left).

3.2. Extraction quantity

As mentioned in the introduction an extraction flow rate of 120 m³/s, corresponding to a semitransverse or full transverse ventilation system, and an extraction flow rate of 200 m³/s, corresponding to a massive point extraction, were defined for an air temperature of 20 °C and an absolute pressure of 1013.25 hPa. This boundary condition gives a mass flow rate of 144.54 kg/s (120 m³/s) and 240.87 kg/s (200 m³/s). These mass flow rates are thus used as boundary conditions for the investigations.

3.3. Parameters of damper and resistance coefficients

The extraction dampers are 3 m x 4 m and exhibit a free flow cross section of 9.6 m² (at a damper flap angle of 90°). The distance between the dampers is 100 m, the resistance coefficient with respect to the mean flow velocity through the damper is 1.65. In addition, a resistance coefficient of 0.017 was also assumed in order to take account of friction losses in the exhaust air duct.

3.4. Definition of the leakage rate

The flow rate in the exhaust air duct increases between the open damper and the exhaust air fan due to leakages from the remaining closed dampers and from the building (between air duct and traffic tube). Leakage rates for the closed dampers were selected according to the values given in (2) and are a function of the pressure difference between exhaust air duct and traffic tube. This leads to an increase in flow rate and pressure losses and, in addition to the convective heat transfer, to a further cooling of the air. Leakages have a significant impact and cannot be neglected.

3.4.1. Damper leakage

The maximum allowed damper leakage rates are defined with respect to pressure difference and temperature and are specified in the Austrian guideline (2). These have to be considered in the design of the tunnel ventilation system. The following Table 2 depicts the maximum allowed pressure-dependent leakage rates.

Table 2: Leakage rates with respect to system pressure according to (2).

Temperature (°C)	Pressure difference (N/m²)	Maximum allowed leakage (m³/s/m²)
20	4000	0.10
20	3500	0.09
20	3000	0.08
20	2500	0.07
20	2000	0.06
20	1500	0.055
20	1000	0.05

Assuming a linear correlation, the information in the above table can be described using the following two equations:

$$\dot{V}_L = 2\cdot 10^{-5}\cdot\left(p_u - 2000\right) + 0.06 \quad \text{valid for } 2000 < p_u \leq 4000 \qquad \text{Equation 1}$$

$$\dot{V}_L = 10^{-5}\cdot\left(p_u - 1000\right) + 0.05 \quad \text{valid for } 1000 \leq pu \leq 2000 \qquad \text{Equation 2}$$

For $0 < p_u < 1000$ a linear interpolation between 0 and 0.05 m³/s/m² is assumed.

3.4.2. Building leakage

Building leakage as a function of pressure may be described thus:

$$\dot{V}_L = \sqrt{\frac{2\cdot p_{u\_j}}{\rho_{L\_j}}}\cdot\frac{A_L}{\sqrt{\xi}} \qquad \text{Equation 3}$$

According to the Austrian guideline (2) the leakage of the building must not exceed 10 m³/s/km and has to be accounted for in the design of the tunnel ventilation system. In order to obtain pressure dependent leakage, in equation 3, the ratio of the area of the leakage A_L to the square root of the leakage resistance coefficient $\sqrt{\xi}$ was adjusted for each calculation case so that it fit the defined leakage flow rate of 10 m³/s/km.

3.5. Physics

3.5.1. Air temperature at the location of the fire

Concerning the temperature of the extracted air, a worst case is adopted in that the fire is assumed to be located directly under the damper. Additionally, it is assumed that the airstream comes from both sides of the tunnel and that it does not exceed the extraction mass flow rates $\dot{m}$ (144.54 kg/s or 240.87 kg/s) (see Figure 4). By means of a simple energy balance, and based on the assumptions mentioned above, it is thus possible to use the following equation to obtain the temperature at the extraction location, T_B, for a design fire $\dot{Q}$.

$$T_B = \frac{\dot{Q}\cdot\eta_{fire}}{\dot{m}\cdot c_p} + T_i \qquad \text{Equation 4}$$

Equation 4 ignores the impacts of burning mass and heating of the fuel. If these two effects are taken into account, and under the assumption that the heat release rate remains constant, the mass flow rate and the specific heat capacity c_p will increase so that the average temperature at the location of the extraction will decrease.

Notice that local temperatures, for example at the damper, can clearly exceed the average temperature T_B . The former depend on several factors such as flow pattern (temperature layer in traffic room), radiation, and the development of the fire, etc. For the present investigations the initial temperature T_i of the incoming air was defined at 20 °C (RVS 09.02.31 (2)). It was assumed that the heat losses due to radiation amount to 25 % of the total heat release ($\eta_{fire} = 0.75$).

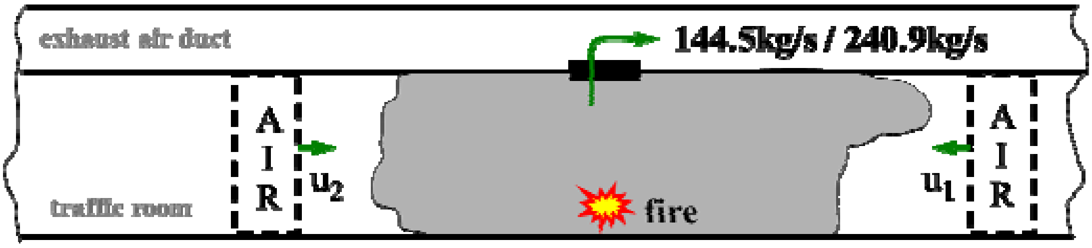

Figure 4: Ventilation scenario in the case of a fire for transverse ventilation systems.

3.5.2. Convective heat transfer in the exhaust air duct

As a result of the convective heat transfer to the surrounding concrete wall of the exhaust air duct, the temperature of the extracted air decreases in flow direction (from the damper to the exhaust fan). This convective heat transfer can be determined with the following thermal energy equation for one-dimensional gas flow in the longitudinal direction of the exhaust air duct (4).

$$\dot{m} \cdot c_p \cdot d\widetilde{T}_x + U \cdot \alpha \cdot (\widetilde{T}_x - T_W) \cdot d\widetilde{x} = 0 \qquad \text{Equation 5}$$

In the following analysis it is assumed, that the temperature of the exhaust air duct roughly remains constant during the self-rescue phase (approximately 20 minutes) and that the wall temperature is equal to the initial air temperature ($T_W = T_i$). Note if the exhaust air duct is covered with heat insulating materials this assumption is not acceptable. Due to the fact that the geometry of the exhaust air duct, the thermodynamic property of the air, and thus the heat transfer coefficient along the longitudinal direction of the duct all vary, equation 5 needs to be discretized (boundary condition of the first cell: $T_{x\_j} = T_B$). Also, owing to leakage, the mass flow rate increases along the duct.

$$T_{x\_j+1} = T_{x\_j} + \left(T_{x\_j} - T_W\right) \cdot \frac{U_j \cdot \alpha_{x\_j}}{\dot{m}_j \cdot c_{p\_j}} \cdot \Delta x \qquad \text{Equation 6}$$

In cases where the above properties are constant it is feasible to integrate equation 5 along the air duct axis ($d\widetilde{x}$) for values between x = 0 (location of the extraction) and x, and for $\widetilde{T}_x = T_B$ to T_x (for this purpose see equation 7)

$$T_x = T_W + (T_B - T_W) \cdot e^{\left(\frac{-\alpha \cdot U \cdot x}{c_p \cdot \dot{m}}\right)} \qquad \text{Equation 7}$$

As already mentioned, owing to the relatively small cross section and high velocity in longitudinal direction, three-dimensional flow and buoyancy effects in the exhaust air duct can be neglected. Consequently it is feasible to determine the heat transfer coefficient in a one-dimensional approach via the Nußelt number. The local heat transfer coefficient which is required for the calculation of the convective heat transfer (see equation 6) can then be calculated with the local Nußelt number (differentiation of the mean Nußelt number according to Gnielinski) for fully developed turbulent pipe flows with $Re \geq 10^4$ .This can be found in (3). The thermodynamic properties chosen are those based on the mean air temperature.

4. RESULTS OF THE INVESTIGATION

The following diagrams show as a function of the length of the exhaust air duct, the air temperature and the flow rate at the exhaust fan, the pressure losses, and the performance ratio. They all serve to clarify how ventilation requirements may change as a result of variations in temperature (i.e. the difference between hot and cold ventilation requirements).

4.1. Existing tunnel systems

Owing to the fact that the size of the design fire for both tunnels was the same, and since the respective tunnel cross-sections are very similar, under hot air conditions temperature at extraction and temperature distribution within the air ducts are almost identical (see **Figure 5**). The slight differences that do occur are due to the different shapes of the air duct surrounding the exhaust fans.

The flow rate at the exhaust fans depends on the distance between the exhaust fans and the extraction point. At relatively short distances flow rate under hot air conditions first decreases (because of the heat transfer to the duct wall), but as distance lengthens flow rate increases due to leakage (see **Figure 7**). In the case of the Katschbergtunnel the mass flow rate of 144.5 kg/s is extracted by two exhaust fans in parallel. Hence each exhaust fan has to provide only half of the total extracted volume (see section 3.1.1).

As the temperature rise produced by heat release results in lower densities and higher flow velocities, pressure losses increase. Thus pressure losses under hot air conditions are higher compared to those existing under cold air conditions (see **Figure 6**).

Figure 8 depicts the ratio of ventilation power of the hot air conditions to the ventilation power of the cold air conditions as a function of distance between axial fans and extraction point. As can be seen, there is an increase in ventilation power of between 15 % and 20 %, due to the temperature influences.

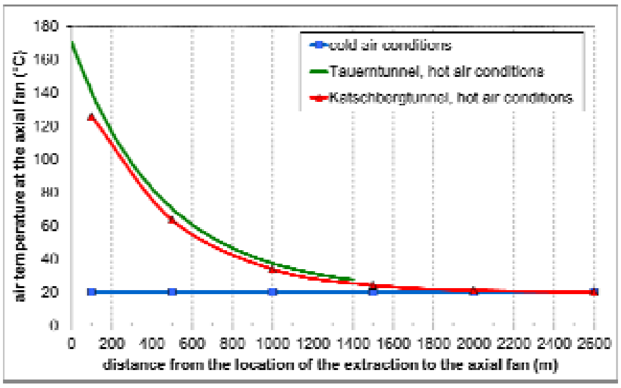

Figure 5: Air temperature at the axial fan depending on the position of extraction

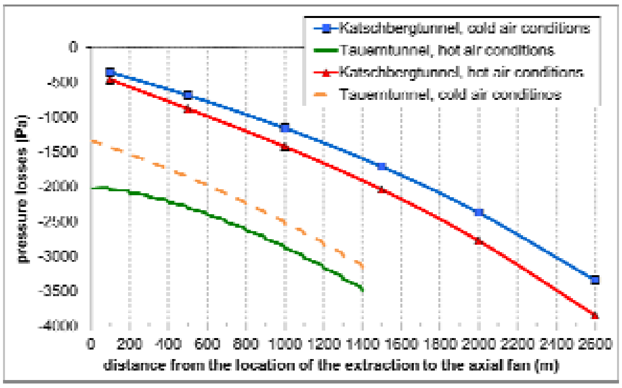

Figure 6: Pressure losses of the air duct flow depending on the position of extraction

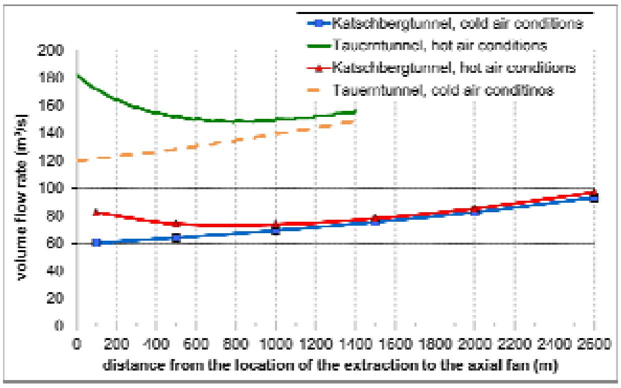

Figure 7: Flow rate at the exhaust fan depending on the position of extraction

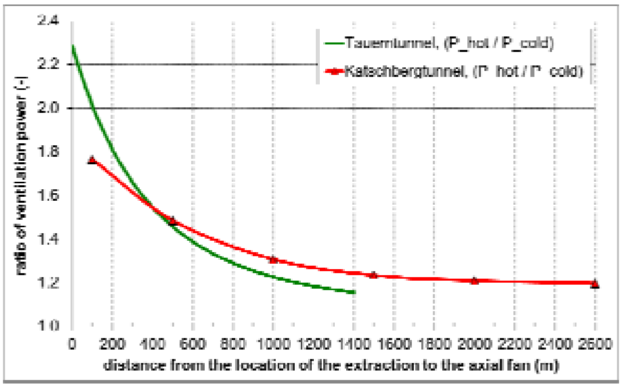

Figure 8: Power ratio of the exhaust fan (ratio of hot air conditions to cold air conditions) depending on the position of extraction

4.2. Sensitivity analyses

Compared to the air duct with a cross section of 9 m² the velocity and heat transfer coefficient in the 12 m² exhaust duct are lower, but the duct surface is higher. These two effects (lower heat transfer coefficient but higher duct surface) have nearly the same effect with respect to convective heat transfer. Hence, for both the 30 MW and the 50 MW case, the temperature distribution in flow direction is very similar (see **Figure 9**). Since the same extracted mass flow rate is used (see equation 4). The temperature at the extraction point (0 m) in both 30 MW cases (9 m² and 12 m²) is equal, as it is for both 50 MW cases (9 m² and 12 m²). The temperature decreases in flow direction until the initial temperature (the temperature of the duct wall) is reached. This occurs after an air duct length of approximately 1500 m.

Figure 11 shows the volume flow rate at the axial fan as a function of distance of axial fan to extraction point. It first decreases along the exhaust air duct in accordance with the temperature distribution but then increases due to the leakage rates.

Given the assumption that the extracted mass flow rate is the same for all cases the highest pressure losses occur in the air duct with a cross section of 9 m² and a heat release rate of 50 MW due to the area and temperature based relatively high flow velocity. As air duct cross section increases and/or heat release rate decreases, the pressure losses also decrease (see **Figure 10**).

Due to the fact that the temperature distribution and also the distribution of the volume flow rate are almost the same for the two 30 MW cases and for the two 50 MW cases the respect-tive power ratios of the axial fan are also nearly identical (see **Figure 12**). This means, that the additional ventilation power required as a result of the impact of temperature changes, de-pends only on the design fire size and on the distance between extraction location and axial fan.

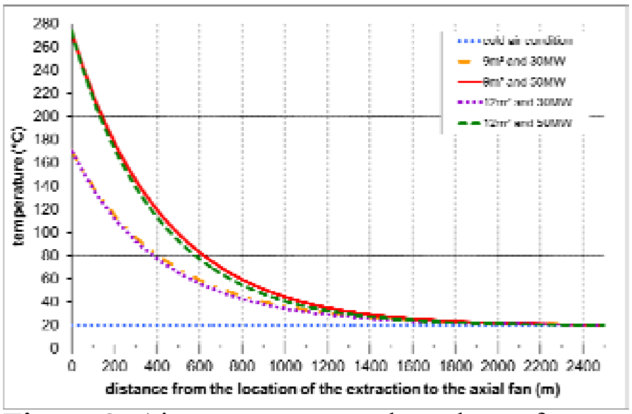

Figure 9: Air temperature at the exhaust fan depending on the position of extraction.

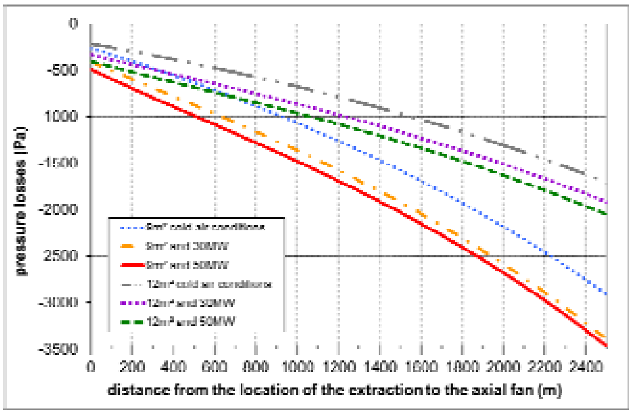

Figure 10: Pressure losses of the air duct flow depending on the position of extraction.

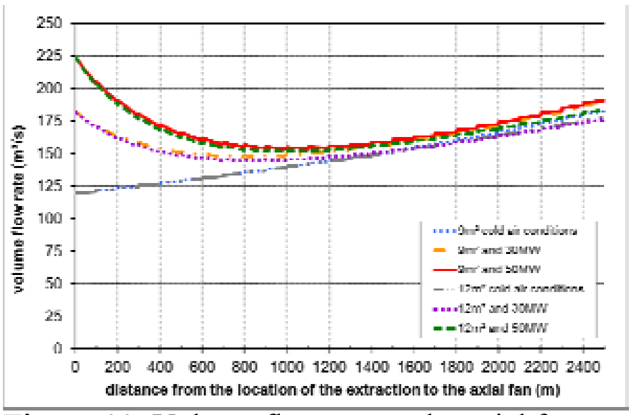

Figure 11: Volume flow rate at the axial fan depending on the position of extraction

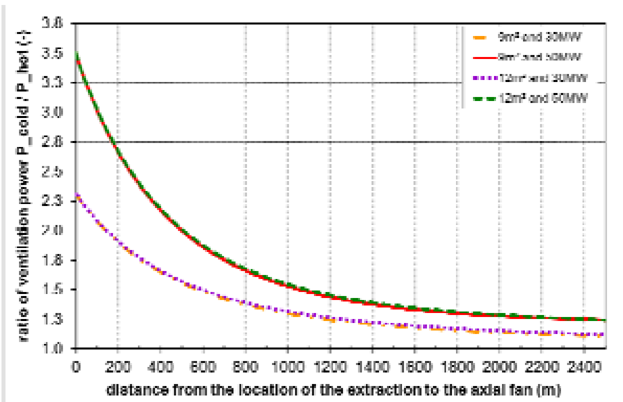

Figure 12: Power ratio of the axial fan (ratio of hot air conditions to cold air conditions) depending on the position of extraction

5. CONSIDERATION OF TEMPERATURE INFLUENCES IN THE DESIGN OF TRANSVERSE VENTILATION SYSTEMS

The introduction of temperature dependent parameters in the design of transverse ventilation systems makes it relatively easy to calculate the required ventilation power with sufficient precision (see Figure 13). Only two additional parameters are needed: one, to capture the influence of temperature change on flow rate, and one to account for the impact of temperature change on pressure loss.

The parameter for the volume flow rate correction is calculated using the ratio of the temperature at the axial fan under hot air conditions (T_{fan}) to the temperature at the axial fan under cold air conditions (T_k). The temperature T_{fan} can be calculated using equation 7, or, in the case of varying parameters, by means of equation 6. Variable x denotes the distance from the location of the extraction to the axial fan. For the discrete calculation the variable Δx denotes the length of the air duct where the parameters (U, $\dot{m}$, α and c_p) are constant. The local heat transfer coefficient for the discrete calculation and the mean heat transfer coefficient in the case of constant parameters can be calculated with the equations given in (3).

$$F_V = \frac{T_{fan}(x)}{T_k} \qquad \text{Equation 8}$$

Taking equation 8, it thus becomes possible to calculate the volume flow rate at the axial fan for hot air conditions using the following equation.

$$\dot{V}_w = \dot{V}_k \cdot F_V \qquad \text{Equation 9}$$

To determine the parameter for the correction of the pressure losses (equation 10), calculation of the temperature at the damper T_B is required in addition to calculation of the temperature at the axial fan. This temperature can be calculated using equation 4. The procedure for the calculation of the temperature at the axial fan is identical to that described above. The variable *a* depends on the heat release rate of the design fire and has a value of 0.00028 for a design fire of 30 MW and a value of 0.00023 for a design fire of 50MW.

$$F_p = \left(\frac{T_{fan}(x)}{T_k} - a \cdot x\right) \cdot \left(\frac{T_B - T_k}{T_B}\right) \qquad \text{Equation 10}$$

For the calculation of the pressure losses under hot air conditions, the pressure difference due to buoyancy effects has to be considered in addition to the parameter for pressure loss correction. This can be calculated with equation 11 (1). The calculation method needed to capture the buoyancy effects for non-constant parameters can be found in (1).

$$\Delta p_A = -\frac{g \cdot s \cdot \rho_i \cdot c_p \cdot \dot{m}}{\alpha \cdot U} \cdot \ln\left[\frac{T_W + (T_B - T_W) \cdot e^{\left(\frac{-\alpha \cdot U \cdot x}{c_p \cdot \dot{m}}\right)}}{T_B}\right] \qquad \text{Equation 11}$$

Finally, the pressure losses occurring under hot air conditions may thus be calculated using the following equation.

$$\Delta p_w = \Delta p_k \cdot F_p + \Delta p_A \qquad \text{Equation 12}$$

Figure 13 shows how calculations of required ventilation power using the simplified method described here deviate from calculations based on the one-dimensional model. As can be seen, deviations using the new method lie within ±4%.

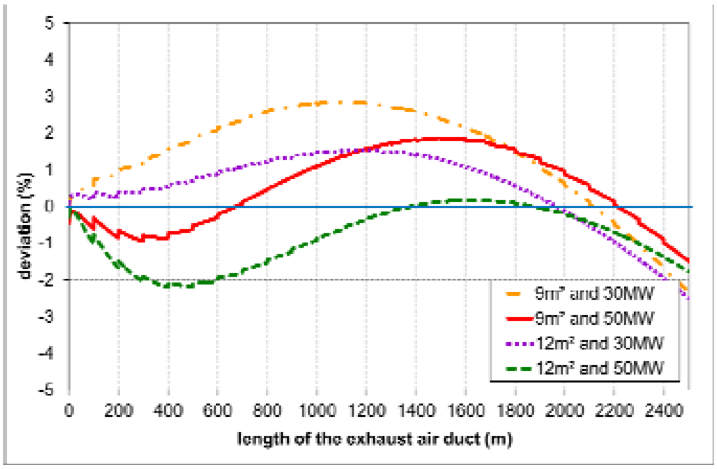

Figure 13: Deviations in ventilation power required: one-dimensional model calculations vs. simplified method.

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IMPACT OF DENSITY VARIATIONS IN THE EXHAUST DUCT ON SMOKE EXTRACTION AND FAN OPERATION POINT

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ABSTRACT

The design goals of smoke extraction systems in tunnels are a defined minimum volumetric cold air flow towards the fire and stable fan operation. For the fan design a constant air density is normally considered. In this approach, the volumetric exhaust flows in the tunnel and at the fans are assumed equal at any location, time and fire power, when neglecting the leakages through the false ceiling. This paper examines the joint effects of compressibility, leakages and heat exchange of the hot exhaust flow on both the fan operation point and the effective volumetric exhaust flow by varying the fire power and location. It is found that the shift in the fan operation point with fire power depends on the location of the fire. The cold exhaust flow in the tunnel is found to decrease with increasing fire power and time; the minimum design exhaust flow may not be reached for all cases. The physical reasons for the observed behaviour are explained and possible measures to reach the extraction requirements for all cases are discussed.

Keywords: smoke extraction, compressibility, density variation, fan characteristic

1. INTRODUCTION

According to the Swiss guideline for tunnel ventilation (ASTRA 2008) [1], the fans for smoke extraction systems are designed assuming a constant air density along the exhaust duct. The leakages between the tunnel and the duct are considered. The goals are to extract in all cases – i.e. fire locations, powers and times – a minimum volume flow of cold air out of the traffic compartment and to run the fans at a stable operation point for a 30 MW fire. The cold air flow must reach between 3 to 4 times the cross sectional area of the traffic compartment, in order to reach at least 1.5 $m \cdot s^{-1}$ air flow towards the fire from both sides, resp. 3 $m \cdot s^{-1}$ from one side. In reality the density is not constant along the exhaust duct but changes according to two mechanisms: First, decompression takes place along the duct due to the pressure drop from the exhaust point to fan so the density decreases by about 1% per 1 kPa pressure drop in cold state, resulting in a lower system resistance compared to that computed with constant density. Second, in the case of a fire, as the hot gases cool down along the duct, the very low density at the exhaust will increase along the duct towards the fan, resulting in a higher system resistance than that computed with constant density. Furthermore, the reference fan characteristic will be shifted to a lower pressure rise as the density at the fan decreases. In reality these three effects will interact in a complex manner leading to a shift in the operation point of the fans and to a change in the volume flow of cold air extracted at the fire. The main parameters governing this problem are: fire location, fire power and time. In this paper, two things are examined both theoretically and in a case study, considering the main parameters mentioned above:

1. The shift of the operation point of the fan with respect to the allowed domain of operation limited by the stall limit and the capacity limit;
2. The shift of exhausted cold air volume out of the traffic space.

2. FAN CHARACTERISTIC

The characteristic of a fan describes the total pressure rise over it as a function of the volume flow through it. The characteristic line is limited at its high pressure end by the stall limit and at its low pressure end by the capacity. The stall limit is given by the limit of stable fan operation. The capacity is given by the dynamic pressure line, i.e. the line of zero static pressure rise over the fan. The operation point is defined by the intersection of the fan and the system characteristics. These characteristics are only valid for a defined density although actual fan characteristics are delivered for a reference density, usually 1.2 kg·m^{-3}. Figure 1a shows these definitions for the actual fan used in this study. The operation point is located approximately at the volumetric flow 120 m^3·s^{-1} and the total pressure rise 5,280 Pa. This operation point was obtained with a conventional spread-sheet pressure loss calculation.

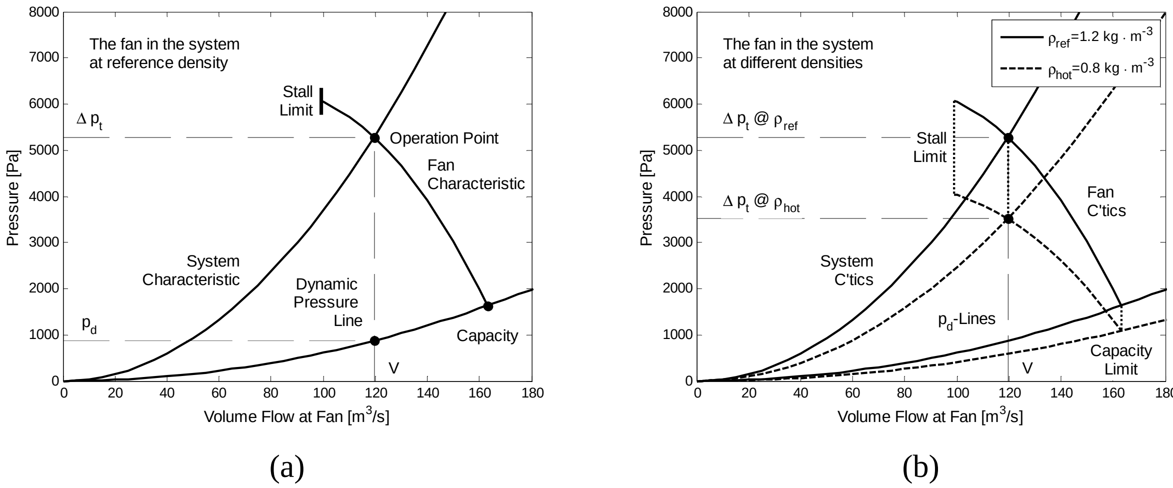

Figure 1: Fan and system characteristics (a) at reference density (b) at different densities

When the density in the whole system changes, the total pressure rise, the dynamic pressure and the system resistance are scaled proportionally to the actual density according to equation 1 (c.f. e.g. Jung 1999), [6]: Thus, the operation point is shifted to a lower total pressure rise of 3,520 Pa, the volumetric flow remaining constant at 120 m^3·s^{-1} (c.f. figure 1b).

$$\Delta p_{t,2} = \frac{\rho_2}{\rho_1} \cdot \Delta p_{t,1} \qquad \text{Eq. 1}$$

The stall limit and the capacity are scaled in the same manner, so that the domain of possible fan operation points is delimited at the top respectively the bottom by the fan characteristic of the highest respectively the lowest possible density, to the left by the vertical stall limit and to the right by the vertical capacity line. This is also valid if the density in the system is no longer constant but changes due to compressibility and heat transfer along the flow path: In this case, the domain defined above will remain the same and the effective operation point of the fan depends only on the cumulated pressure losses in the system and the density at the fan.

3. COMPRESSIBLE MODEL OF THE EXHAUST FLOW

The exhaust flow originates in the tunnel, is heated up in the fire, sucked through the dampers into the exhaust duct, cooled down, expanded and mixed with leakage flow along the exhaust duct until it reaches the fan, compressed in the fan, and expelled through the chimney (c.f.

Figure **2**). The relevant points of the flow path are:

- Point 0, in the tunnel: Ambient condition before the fire.
- Point 1, in the tunnel: Hot gases. Conditions between the fire an the exhaust dampers
- Point 2, in the exhaust duct: Hot gases after the dampers in the exhaust duct
- Point 3, in the exhaust duct: Cooled gases before the fan
- Point 4, in the chimney: Compressed gases after the fan
- Point 5, at the exit of the chimney: Exhaust to outside at ambient pressure

The model of the smoke extraction presented here follows this path as a one dimensional flow model without branching.

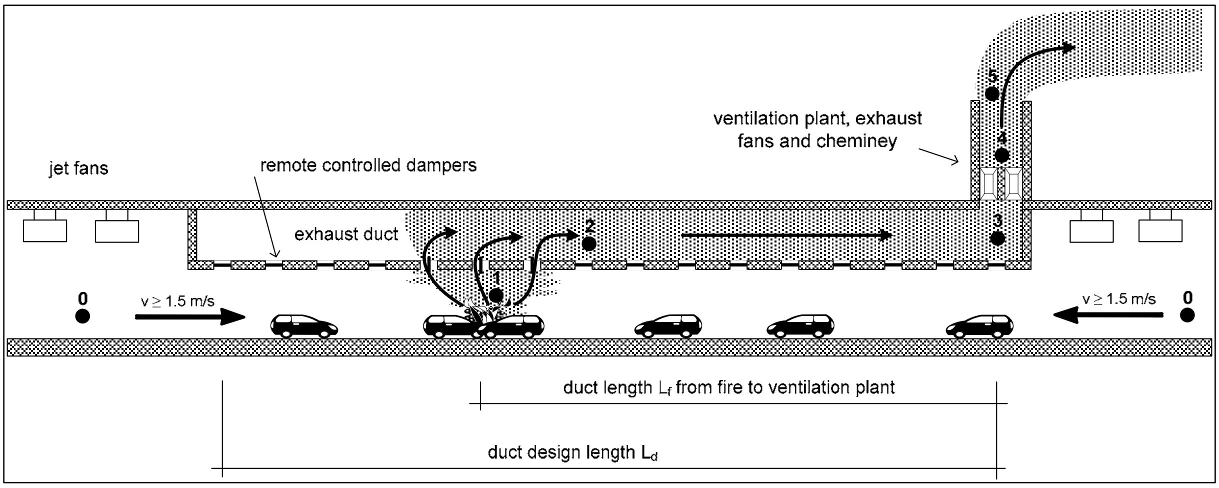

Figure 2: Flow path of air extracted air from tunnel to chimney.

In the following, the relevant assumptions and equations of the model are presented for each section of the flow path.

<u>Flow section 0 – 1: Tunnel</u>

The static pressure along the flow path from 0 to 1 has a saw-tooth shape due to the jet fans and the fire and changes only in the order of magnitude 10^1 Pa (c.f. CETU 2003), [4]. This is negligible compared to the pressure drops across the false ceiling and along the exhaust duct (~10^2 – 10^3 Pa). Thus the pressure along the flow path from 0 to 1 is assumed constant and the leakage losses into the false ceiling are neglected on this flow section. The fire is modelled as a heat source only. According to CETU (2003) [4], one third of the nominal heat release rate (HRR) is lost as radiation at the fire location. The remaining two thirds heat up the fresh air flow. The volumetric flow of combustion gases is neglected. The temperature at point 1 is given by the conservation of energy as documented in CETU (2003) [4], p. 63. The density and the volume flow can be found using the ideal gas law and the conservation of mass. Thus the flow from the portals to the fire is assumed adiabatic and incompressible, except at the fire.

<u>Flow section 1 – 2: Remote controlled dampers</u>

The flow through the dampers is assumed adiabatic and incompressible. The smoke is extracted from the tunnel through 3 opened dampers. The pressure loss coefficient of the dampers has been measured by Buchmann (2010), [2]. For 3 open dampers the loss coefficient has been found to be 2.5, referenced on the total open area of the dampers and measured with cold flow. It can be shown that the total pressure loss over the dampers increases proportionally to the power of the fire. For an 11.8 m^2 exhaust duct and 3 open 4.5 m^2 exhaust dampers, 204 $m^3 \cdot s^{-1}$ exhaust flow and normal atmosphere, the total pressure loss varies between 450 Pa and 680 Pa, when the fire power varies from 30 to 100 MW. These pressure differences account for about 10% of the pressure difference at the fan and are small (~10^2 Pa) compared to the absolute pressure (~10^5 Pa). The relative density difference between the state at reference pressure and at actual pressure at a given temperature can be estimated using the ideal gas law. In the case of the dampers, the change in density is smaller than 1%, thus negligible. Bernouilli's equation is sufficient for this approach.

Flow section 2 – 3: Exhaust duct

The exact steady theory of the flow along the duct with constant cross section, accounting for compressibility, pressure loss, convective and radiant heat transfer with the wall and for leakages, is given by the mass, momentum and energy equations in conservative formulation and the ideal gas law in equations 2 to 5. Notations are documented in chapter 7.

Cons. of mass $$\frac{d}{dx}(\rho u) = \dot{m}_l''' \qquad \text{Eq. 2}$$

Cons. of momentum $$\frac{d}{dx}\left(\rho u^2 + p\right) = -\frac{1}{2}\rho u \cdot |u| \cdot \frac{f}{D} \qquad \text{Eq. 3}$$

Cons. of energy $$\frac{d}{dx}\left[\rho u \cdot \left(h + \frac{1}{2}\cdot u^2\right)\right] = \dot{q}''' + \left(h_l + \frac{1}{2}\cdot v_l^2\right)\cdot \dot{m}_l''' \qquad \text{Eq. 4}$$

Ideal gas law $$p = \rho \cdot R \cdot \theta \qquad \text{Eq. 5}$$

The leakage is expressed in these equations as a specific mass source $\dot{m}_l'''$, defined in equation 9 on the basis of formulas derived by Haerter (1978), [5] for air tubes.

Mass source $$\dot{m}_l''' = \rho_l \frac{4}{D} f^* \sqrt{\frac{2|p_{tun} - p|}{\rho_l}} \left(\frac{p_{tun} - p}{|p_{tun} - p|}\right) \qquad \text{Eq. 6}$$

Equation 6 shows that the driving force for the leakage is the pressure difference between the tunnel and the exhaust duct. The leakage of the duct is described by the effective leakage area f^* which has been measured for exhaust ducts in an extensive research project documented in Buchmann (2010) [2]. Typical values for new exhaust ducts have been found to lie between 12 and 16 mm^2·m^{-2} and for old ducts between 20 and 35 mm^2·m^{-2}. In the present study, the effective leakage is set to 19.4 mm^2·m^{-2} which has been measured in the tunnel of the case study.

The specific heat source $\dot{q}'''$ is defined by the radiant and convective heat transfer to the wall described in equation 7.

Heat source $$\dot{q}''' = \frac{P}{A}\left[h_c \cdot (T_s - \theta) + \varepsilon\sigma F \cdot \left(T_s^4 - \theta^4\right)\right] \qquad \text{Eq. 7}$$

The convective heat transfer coefficient h_c can be found for instance with Petukhov's correlation. The parameters of radiant heat transfer have been set to the values recommended in CETU (2003) [4], p.64. For the heat conduction in the wall, the simplified approach from Carlotti (2004), [3] has been used, c.f. equation 8.

Heat exchange to the wall $$\frac{\lambda_w (T_s - T_w)}{\beta\sqrt{\pi\alpha t}} = h_c(\theta - T_s) + \varepsilon\sigma F \cdot \left(\theta^4 - T_s^4\right) \qquad \text{Eq. 8}$$

This equation can be solved according to the temperature of the wall surface. Thus the aerodynamic model of the exhaust duct is complete.

The flow section 3 – 4 (Exhaust fan) has already been described in chapter 2. The flow section 4 – 5 (chimney) is treated in the same way as the exhaust duct. The model has been solved using the extended solvers for ordinary differential equations provided by a software for scientific computation. As the fan defines how much air is sucked through the system, the equations of the flow path 0 – 5 have to be solved iteratively, adapting the cold exhaust flow V_0 at each step until the total pressure losses in the system are equal to the total pressure rise at the fan.

4. CASE STUDY

The model presented above has been applied to a Swiss tunnel requiring 204 $m^3 \cdot s^{-1}$ cold exhaust flow. The parameters for the different sections of the flow path are documented in Table 1. The fan characteristic is presented in chapter 2. The inlet conditions are set so that the density is equal to the fan reference density 1.2 $kg \cdot m^{-3}$.

Table 1: Geometric parameters of the flow path

Section	L m	A m^2	D m	k mm	ζ -	f^* $mm^2 \cdot m^{-2}$
Traffic compartment	-	51.0	-	-	-	-
Exhaust duct	1913.0	11.8	2.65	1.7	2.4	19.4
Exhaust gallery	146.0	11.3	3.42	1.4	2.4	0
Chimney	24.4	12.6	4.00	0.5	4.1	0

The following parameters have been varied in order to generate a performance map of the fan and the exhaust flow: the fire location with respect to the fan between 300 m and maximum duct length, the fire power between 0 and 100 MW, and time between 5 and 60 minutes.

5. RESULTS

The results of the study are best presented in carpet plots for fire power and fire location at a given time and specific leakage area. In Figure 3 are presented the fan performance curves at time t = 5 and 60 minutes for 2 fans working in parallel. All operation points computed are enclosed in the domain of possible operation points previously discussed in chapter 2. At zero HRR, the farther the open dampers are from the fans, the farther is the effective operation point from the incompressible solution due to leakages and decompression along the duct. At the farthest location, the fan operation point departs from the fan design point by about 10 Pa and 10 $m^3 \cdot s^{-1}$. This is negligible in practice. With increasing HRR, the operation points are in general displaced to lower pressure drops, as the density at the fan falls. The displacement of all the points to lower volumetric flow with fire power indicates an increasing system resistance with fire power. The operation points move to even lower pressure drops with time as the temperature of the gases reaching the fans increases with time, but not to a significantly lower volume flow. In no case was a critical shift towards the stall limit observed, even after 1 hour operation: The stall limit lies at 198 m^3s^{-1}, the closest operation point to this limit at 222 m^3s^{-1}; the surge margin, defined here as the horizontal distance between the stall limit an the operation point closest to it, is then approximately 12%. This is about half of its value at design point but still enough for stable operation. Thus one design goal – stable fan operation at HRR=30 MW – is reached in this case. Critical shifts towards the stall limit may occur with e.g. a steeper fan characteristic.

In Figure 4 are presented the exhaust performance curves at time t = 5 and 60 minutes for 2 fans working in parallel. The cold volumetric flow in the tunnel is plotted against the volumetric flow at the fans. Figure 3 and Figure 4 can thus be read together.

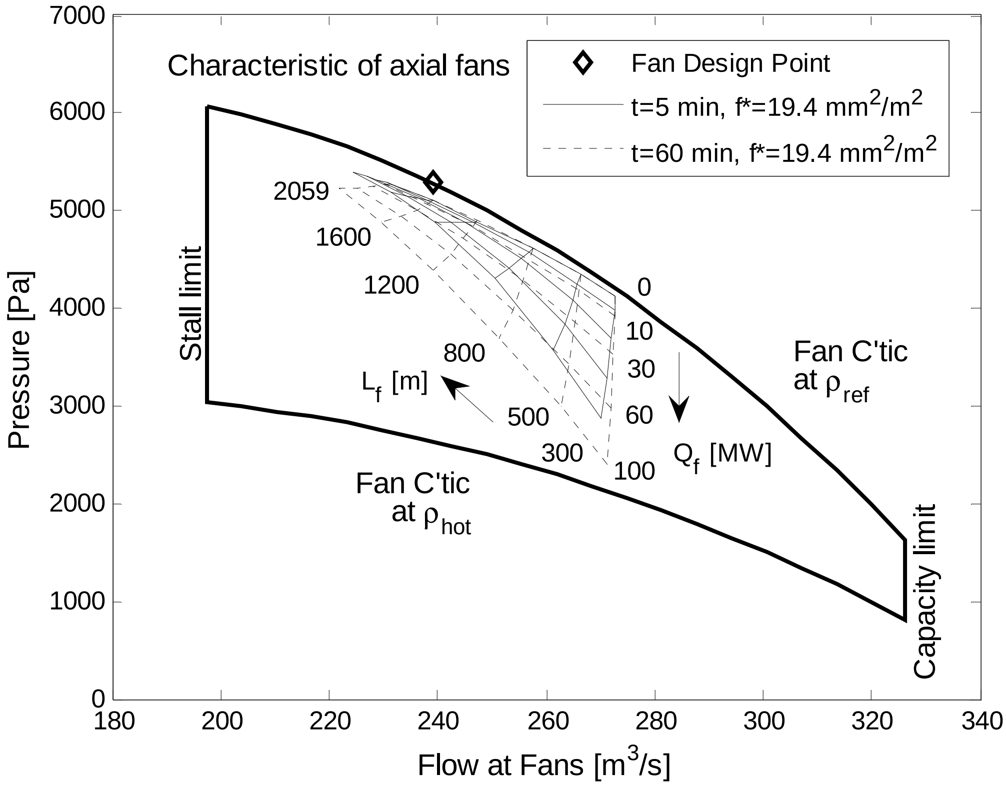

Figure 3: Fan performance curves.

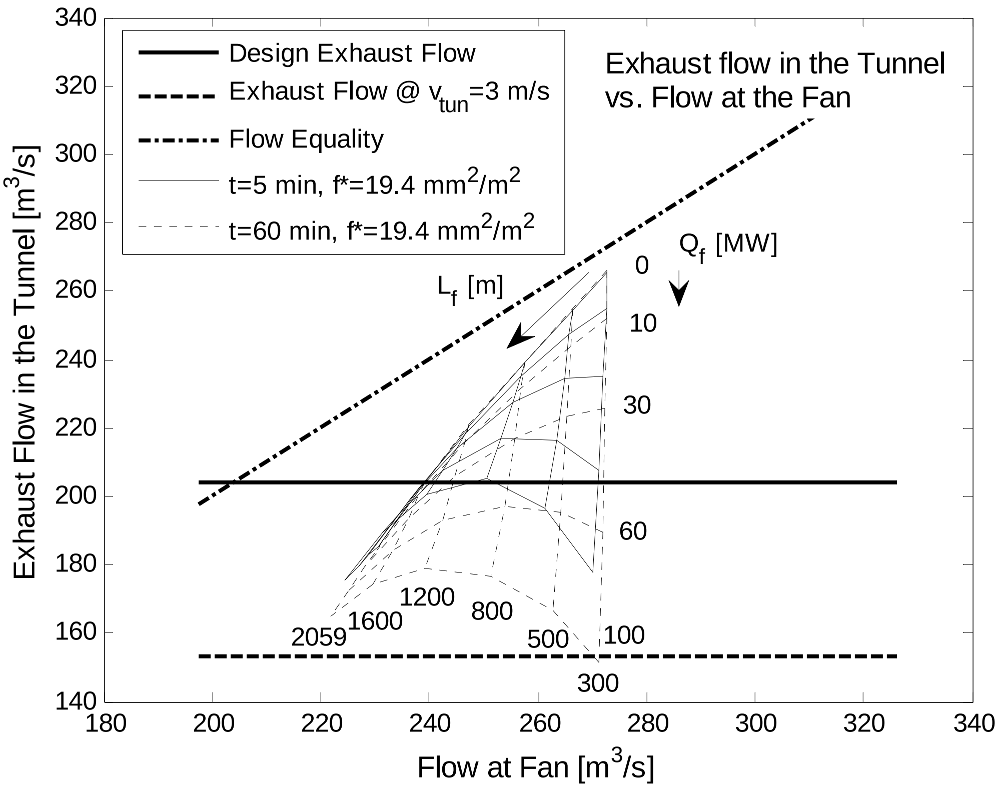

Figure 4: Extraction performance curves

The upper horizontal line represents the cold design volumetric flow; all points off the carpet plots below this limit do not reach the design goal. The lower horizontal line represents the cold volumetric flow in the tunnel to reach the required 3 m·s^{-1} towards the fire. The oblique line above the carpet plot is the bisecting line of the $\dot{V}_0$-$\dot{V}_{af}$ plane. The carpet plot has to be below this limit, as for a single flow path without branching, the volumetric flow in the tunnel must always be smaller or equal to the flow at the fans. At zero HRR, the farther away the exhaust point is from the fans, the greater the difference between these flows is, due to decompression and leakage flows. With increasing HRR, the cold exhaust flow gets even lower, especially at exhaust points close to the fans. This behaviour can be explained as follows: The farther the fire is from the fan, the colder are the gases when reaching the fan and thus the smaller is the shift in the exhaust flow; the closer the fire is to the fan, the hotter will be the gases when reaching it and the greater will be the shift in the exhaust flow. The results show that at HRR=30 MW, the design goal of $\dot{V}_0$=204 m^{3}s^{-1} is not reached for exhaust points farther than 1'200 to 1'600 m from the fans and that this deficit even increases with time and effective leakage (not shown here): At maximum distance, the exhaust flow is 187 m^{3}s^{-1} without fire and 179 m^{3}s^{-1} at HRR=30 MW after 60 minutes; the corresponding flow deficits are approximately 8% and 12% below the goal. This behaviour has not yet been observed during the cold commissioning of the exhaust ventilation of the tunnel modelled here. This is partly due to a conservative assumption in the friction coefficients for the cold design of the exhaust ventilation. These results show that one would not reach the design goal of minimum exhaust flow, if the pressure loss calculation would describe exactly the reality.

The results show that the minimum air speed in the tunnel could be theoretically reached at most times, fire powers and locations. However, the goal to reach at least 1.5 m·s^{-1} from both sides of the fire in all cases also depends on the abilities of the jet fans in the traffic compartment and their control system. To release this system, the minimum exhaust flow prescribed in the guideline is set to a significantly higher level than the 3 m·s^{-1} limit would require. For this reason, the exhaust flow should not fall below the prescribed value, at least for the design fire. This can be reached in the design phase by the following means:

- Either a conservative incompressible pressure loss calculation only, possibly leading to an oversized exhaust system;
- Or a progressive incompressible pressure loss calculation combined with a compressible model, possibly leading to a slenderer system.

6. CONCLUSION

When considering the joint effects of compressibility, heat exchange and leakages on the operation point of the exhaust fans and the design exhaust flow, one can draw the following general conclusions:

- The operation points are shifted towards lower flow. Part of the design stall margin is used up. The operation points may be shifted even closer to the stall limit in other case studies.
- The design goal of minimum cold exhaust flow may not be reached for all times, fire powers or locations.

This shows that compressibility and heat exchange should indeed be considered as a design check in the earliest phases of the design to ensure stable operation and the minimum exhaust flow at least at the design fire. By default, the cold design method should consider conservative friction coefficients.

7. NOTATIONS

Latin Letters			$\dot{m}_l'''$	$kg \cdot m^{-3} \cdot s^{-1}$	Specific mass source
A	m^2	Cross-section area	p	Pa	Pressure
c	$J \cdot kg^{-1} \cdot K^{-1}$	Heat capacity (air = 1,004; concrete = 1,000)	P	m	Perimeter
D	m	Hydraulic diameter	$\dot{q}'''$	$W \cdot m^{-3}$	Specific heat source
f	-	Friction coefficient	$\dot{Q}$	W	Total heat release rate of the fire
f^*	$m^2 \cdot m^{-2}$	Effective leakage area	R	$J \cdot kg^{-1} \cdot K^{-1}$	Ideal gas constant for air (= 287.0)
F	-	Form factor of the wall (= 1.0)	t	s	Time since inception of the fire
h	$J \cdot kg^{-1}$	Enthalpy	T	K	Temperature in and on solid walls
h_c	$W \cdot m^{-2} \cdot K^{-1}$	Convective heat transfer coef.	u	$m \cdot s^{-1}$	Air speed in the duct
k	mm	Wall roughness	v	$m \cdot s^{-1}$	Speed of leaking flow
L	m	Duct length	$\dot{V}$	$m^3 s^{-1}$	Volumetric flow
Greek Letters			θ	K	Air temperature
α	$m^2 \cdot s^{-1}$	Thermal diffusivity of the concrete wall (= $\lambda_w / (\rho_w c_w)$ = $8.75 \cdot 10^{-7}$)	λ	$W \cdot m^{-1} \cdot K^{-1}$	Thermal conductivity of the concrete wall (= 2.1)
β	-	Dimensionless parameter in Carlotti's (2003) wall model (= 0.75)	ρ	$Kg \cdot m^{-3}$	Density (air: variable; concrete = 2,400)
ε	-	Emissivity of the wall (= 0.8)	σ	$W \cdot m^{-2} \cdot K^{-4}$	Boltzmann's constant (=$5.6703 \cdot 10^{-8}$)
ζ	-	Pressure loss coefficient			
Indices			p		at constant pressure
af		axial fan	s		wall surface / static condition
d		dynamic condition / duct	tun		tunnel, resp. traffic compartment
f		fire	t		total condition
l		leakage	w		relating to the wall

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STALL AND PARALLEL OPERATION

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ABSTRACT

As for aircrafts stall is a fundamental problem for the operation of axial flow fans. Unstable aerodynamic conditions lead to high vibrations of the impeller blades and as a consequence leading to severe failures on fan units in the long-term.

It is discussed which conditions lead to stall operation on axial flow fans and which measures could prevent stall and its negative consequences on fans and performance of the ventilation system.

Keywords: Stall, parallel operation of axial flow fans, anti-stall device

1. DEFINITION OF STALL ON AXIAL FLOW FANS

Stall on axial flow fans means a status of non uniform flow through the impeller of the fans. Most axial flow fans have unstable fan curves with a peak point as an indication for Stall. During stall condition the flow separates from the blade shape. Eddies occur downstream close to the impeller hub and upstream close to the impeller tip. The size of the eddies varies during stall conditions. The maximum size is reached for zero volume flow. The air flow through the impeller becomes more and more radial when the size of the eddies enlarge, which is the reason why the maximum pressure is mostly reached for zero volume flow (Eck, 2003), [1].

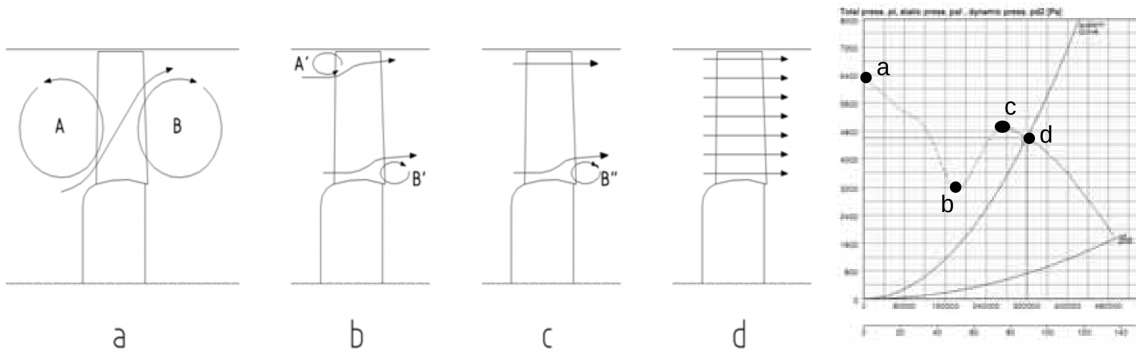

Figure 1: Flow conditions for an axial flow fan

Axial flow fans should not be operated for longer periods under stall conditions. The unstable aerodynamic conditions lead to poor efficiency, high noise levels and high vibrations on the impellers blades. Severe failures on fan units could be the consequence.

2. STALL SCENARIOS

2.1. Stall for operation of single fans

Axial flow fans should only operate on the part of the performance curve, which is steadily rising from maximum volume at free delivery.

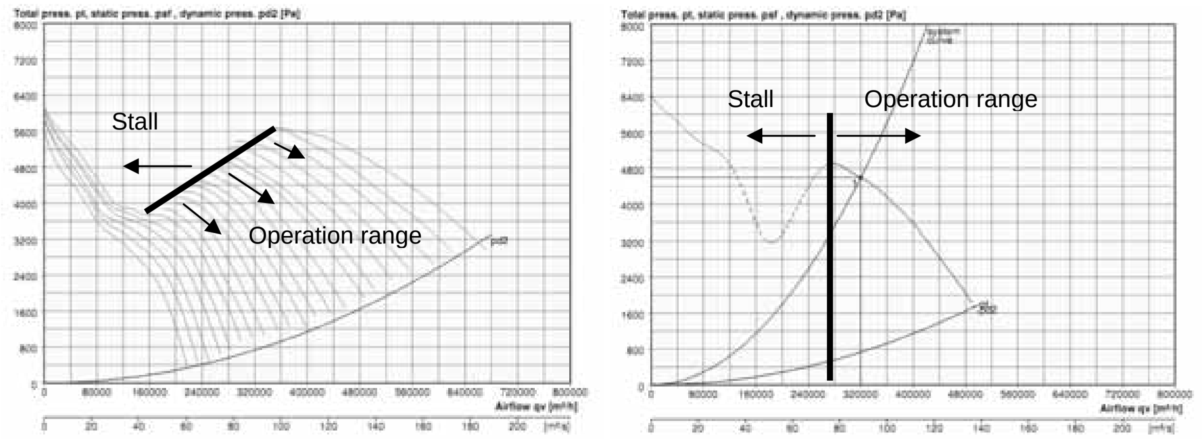

Figure 2: Stall and operation range for an axial flow fan

It has to be assured that plant resistance curve crosses the fan performance curve within that area. In order to cover uncertainties of the pressure drop calculation on one hand and manufacturing tolerance of the fan on the other hand adequate safety margins to the beginning of the Stall area have to be taken into account.

It has to be noticed that the plant layout is not only influencing the plant resistance curves but also the fan performance curve. Performance curves of fans refer to standardized test conditions, which assure proper aerodynamic conditions. Poor plant layout reduces the fan performance compared to the results obtained by standardized test conditions (Bohl, 1983), [2].

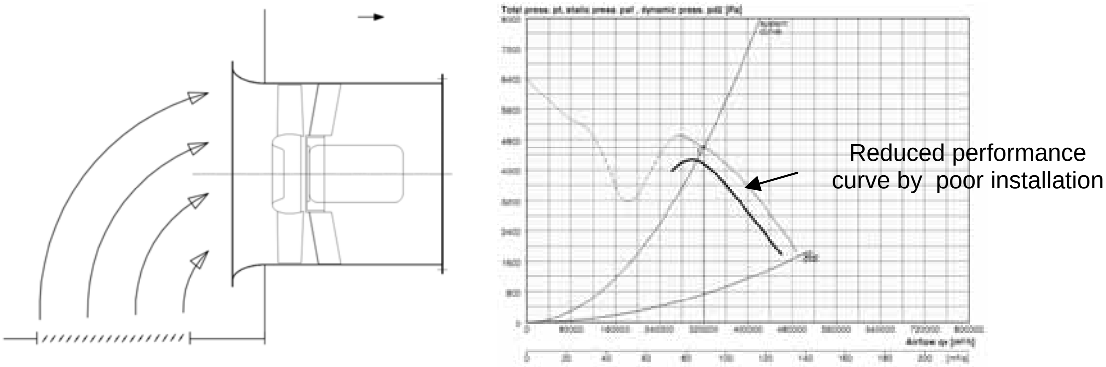

Figure 3: Changes of the fan performance curve due to poor installation

As a consequence the volume flow in the plant would be below the designed values although fan selection and pressure drop calculation itself had been conducted correctly. In worst case the fan operation point in the plant would be within the Stall area.
Therefore it is essential for the design of ventilation system to follow the guidelines for the installation of axial flow fans.

2.2. Temporary Stall by Piston effects

For some applications the plant resistance curves are fluctuating temporarily which is caused by pressure waves passing the ventilation system. As a consequence of these fluctuations the fan operation point is moving on the performance curve to larger or lower volume flow.

The most common application is the ventilation of Metro systems. In order to select the fans correctly, the size of the pressure fluctuations has to be known. It has to be assured that the fan operation point would not shift to the stall zone. Fan failures by fatigue due to high cycle load changes have to be excluded.

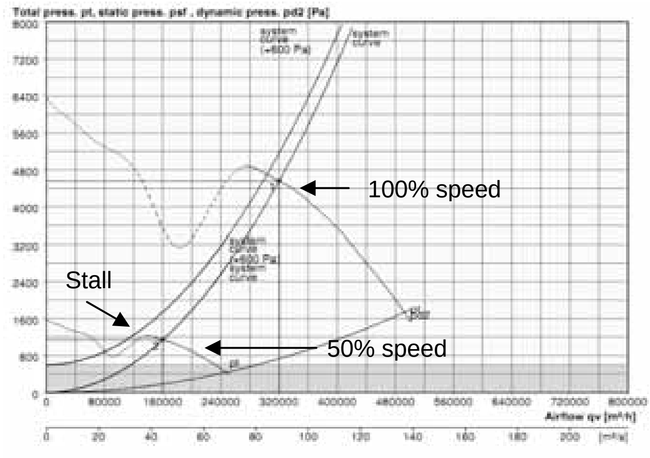

Figure 4: Fluctuation of the plant resistance curve by piston effect

This is most important point for fans used all day for comfort mode. Most critical issues are operations with partial load at reduced speed. Fans, which cover the piston effect easily at full speed may run in stall at 50% speed, since the fan pressure would be reduced to 25% of the full speed values while the piston effect generated by passing train stays constant. Please refer to figure 4.

It is therefore recommended to use relative small fans with high dynamics for Metro applications. Such kinds of fans do operate on the right side of the fan performance curve and provide the maximum safety between fan operation point and stall area.

It has also to be noted that depending on the characteristics even jet fans may run into stall by pressure fluctuations caused by the piston effect.

2.3. Stall by parallel operation

Mostly axial flow fans have unstable performance curves. In practice, there is some uncertainty about the parallel operation of axial flow fans. Even some literature about axial flow fans do not clarify the situation totally (Bohl, 1983) and just recommend to use axial flow fans with variable pitch in motion, in order to start-up the fans with low blade angle and steadily rising curves .These kind of fans do offer some advantages to adjust the fans towards the plant characteristics as already discussed on the 4th international conference 'Tunnel Safety and Ventilation' (Schiller, 2008), [3] but there is no automatism to use that kind of complex and cost intensive technology for each application with parallel operation.

Also axial flow fans with variable pitch at standstill could be operated in parallel. It is essential to know the complete performance curve of the axial flow fans from zero volume flow until free delivery including the Stall area. Critical areas could be excluded knowing that the total performance curve could be calculated as shown in figure 5.

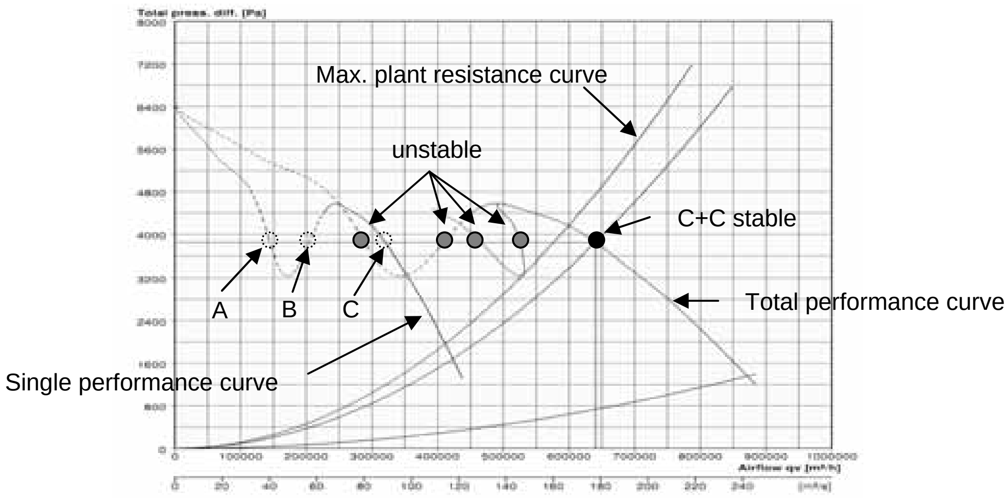

Figure 5: Parallel operation of fans with unstable performance curves

For pressure values close to the peak point three different volume flows (A, B and C) are possible. As a consequence the total performance curves have a characteristic with a loop (Eck, 2003), [1].

The maximum plant resistance curve for operation in parallel is defined by that loop. A crossing of the loop by the plant resistance curve has to excluded, since one fan may operate in stall conditions in case of parallel duty. For the selection of fans an adequate safety margin towards the maximum plant resistance curve has to be considered.

It has to be pointed out that this kind of investigation requires the knowledge of the complete fan performance curve including the stall area. Unfortunately not all fan manufacturers supply that kind of information. Based on such kind of information, conclusions about the suitability for parallel duty are doable.

3. MEASURES TO PREVENT STALL OPERATON

3.1. Stall sensors

Axial flow fans can be equipped with Petermann probes in order to detect stall. A change of pressure conditions caused by eddies on the blade tips is used for that. That kind of sensors react with a certain delay, since stall starts with eddies downstream close to the impeller hub. These turbulences are not detected by common stall sensors.

If the fan characteristic curve is known in detail, stall could be indirectly detected by the measurement of volume flow and speed. A critical flow speed ratio including some safety margin could be defined to avoid operation under stall conditions.

In any case stall detections help to prevent consequential damages by the detection of a problem but they do not solve the problem itself.

3.2. Design of plant and fan selection

The risk of stall could be also controlled if both issues are done correctly. Fan manufacturer have to select fans in a correct way. Pressure fluctuations by piston effects and parallel operation of two or several fans have to be taken into account.

On the other side it is up to the system designer to evaluate the size of piston effects correctly and to assure a proper fan station layout. It has to be assured that fan characteristic curves are not changed by poor aerodynamic conditions to unknown characteristics.

3.3. Use of fans with steadily rising performance curves

The use of fans with steadily rising performance curves is the easiest way to exclude stall problems.

Either pressure waves by piston effects or also parallel duty can be handled easily without complex control regime.

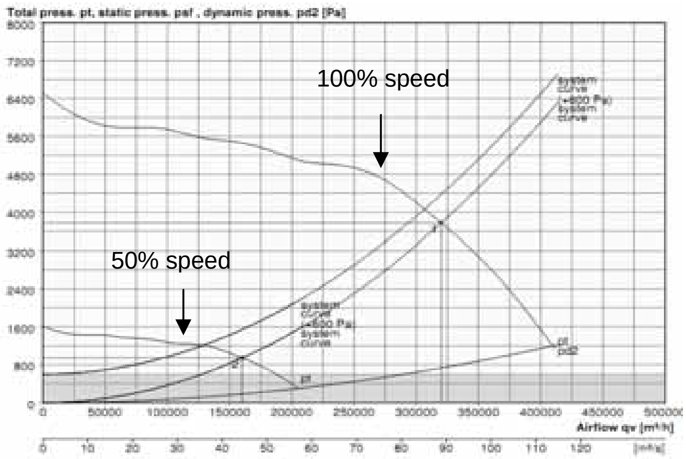

Figure 6: Influence of piston effects on fans with stable performance curves

For parallel operation the start up of any additional fan is no problem at all, since the risk that the fan may stuck in unstable aerodynamic conditions does not exist.

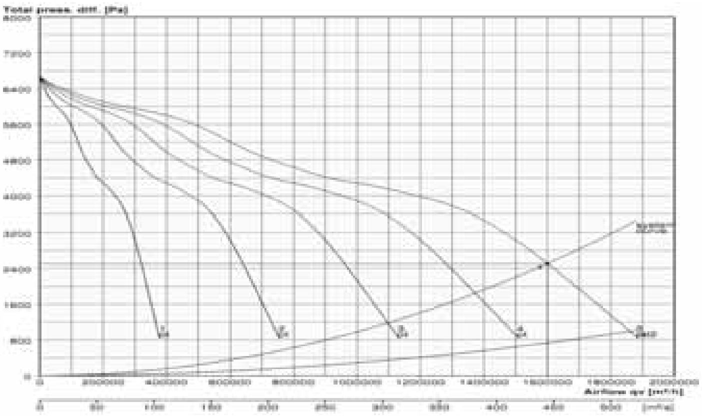

Figure 7: Parallel operation of fans with stable performance curves

Another issue has to be taken into account: In practice, several of fan rooms are not 100% symmetrical and the aerodynamic conditions are not similar for each fan running in parallel. This could become a problem for fans with unstable performance curves, while fans with stable operation curves would compensate such kind of differences.

Steadily rising performance curves on axial flow fans could be achieved by two measures. It is possible to select fans with low blade angles only or to stabilise the fans characteristics with increased blade angles by anti-stall devices.

Fans with low blade angle mostly provide anti-stall characteristics. Such kind of fans are used for several applications although the delivered volume flow and pressure rise is relatively small for the given fan size.

Anti-Stall devices extend the range of steadily rising curves for larger volume flow and higher pressures.

4. PRINCIPLE OF ANTI-STALL DEVICES

The intent of anti-stall devices is to limit eddies upstream near to the blade tip. Backwards flow is concentrated and returned towards the impeller with the main airflow. As a consequence the blockage of the main air flow is reduced.

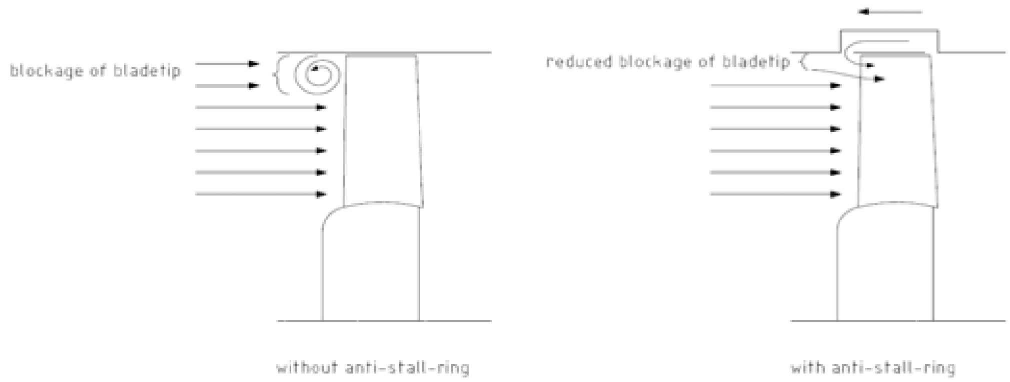

Figure 8: Principle function of anti-stall devices

Anti-stall devices are available for unidirectional but also for reversible axial flow fans. For reversible flow fans anti-stall devices have to be considered for both directions of operation.

Most important point for the function of an anti-stall device is the axial distance towards the impeller tip. The positioning has to be done for a certain blade pitch angle.

Anti stall device cause a slight decrease of aerodynamic fan efficiency and a slight increase of the fan noise levels. This could be of interest for large fans operating long periods with high power consumption but for fans operated in emergency case only or for fans with low power consumption the impact is economically mostly negligible.

5. CONCLUSION

Stall on axial flow fans is a severe problem to be considered for the ventilation of road and railway tunnels. The use of fans with steadily rising performance curves is the safest way to exclude negative impacts by stall. Compared to other strategies being in use today such kind of fans provide a higher level of reliability by the reduction of the fan complexity in combination with reduced investment cost and maintenance efforts.

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THE A10-TAUERN TUNNEL VENTILATION SYSTEM FROM A CONTRACTOR'S PERSPECTIVE.
(Experiences and lessons learned)

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ABSTRACT

In recent years, numerous existing road tunnels had to be extended with a second tube or an escape tunnel to meet with the current guidelines and safety standards.

Bringing the „extended" tunnels up to the current expectation levels poses many additional challenges.

The experience, gained during the design, installation and testing of the comprehensive ventilation system for the Tauern Motorway Tunnel Extension is presented and suggestions are made to benefit from "lessons learned".

1. INTRODUCTION

For tunnel extension projects like the A10 - Tauern tunnel it is important to realize that these tunnels are existing tunnels, which are extended with a second tunnel-tube.
In case of the Tauern tunnel, which originally was built in the mid 70-ties of the last century, the ventilation design already provided for the 2-tube tunnel to be built at a later stage.

As a consequence of that, the fan rooms and ventilation ducts, for the second tube, were in place.
The design of these structures was based on the guidelines and standards, applicable at the time.
After the large fire-accidents in the Mont Blanc tunnel and the Tauern tunnel in 1999, the Austrian and European Guidelines and Tunnel Safety Regulations were modified and one of the major conclusions was that safe escape routes and/or -passages should be realized for all high traffic tunnels.

Present guidelines for ventilation systems in Austria are:
<u>RVS Guidelines:</u>
RVS 09.02.31 Tunnel-Tunnelausrüstung-Belüftung-Grundlagen Ausgabe 1.8.2008
RVS 09.02.32 Lüftungsanlagen-Luftbedarfsberechnung Entwurf Dez. 2009
RVS 09.02.33 Tunnellüftungsanlagen-Immisionsbelastung an Portalen Ausgabe 1.5.2005
RVS 09.02.22 Tunnelausrüstung-Betrieb und Sicherheit Entwurf April 2010

Furthermore Austrian tunnel ventilations systems are to comply with:
Planungshandbuch Lüftung (PLaPB 800.542.10 Version 1.0 – Ausgabe vom 16.4.2009) der ASFiNAG.

The ventilation system for the second tube of the Tauern tunnel had to be based on these new traffic guidelines and safety instructions, however taking into account that the fan rooms and ventilation ducts were already constructed and would not be modified.

Due to the substantial lower emissions from cars and trucks, the determining factor for the design of the ventilation system was no longer the normal comfort ventilation but nowadays the ventilation system design is determined by safety considerations in case of fire incidents. Basically this results in higher air volumes and correspondingly square higher pressures. The physical consequences of this change in design criteria and the experiences gained during construction are discussed in this paper.

2. PARTIES INVOLVED

In October 2008 the contract for the Engineering, Supply, Installation, Commissioning and Testing of the ventilation system of the A10 - Tauern Tunnel was awarded by the ASFINAG, Autobahnen- und Schnellstraßen-Finanzierungs-Aktiengesellschaft to Zitron Nederland B.V.

Customer:
ASFINAG
Asfinag Bau Management GmbH

Site supervision (Örtliche Bauaufsicht, ÖBA):
IDS Beratende Ingenieure GmbH

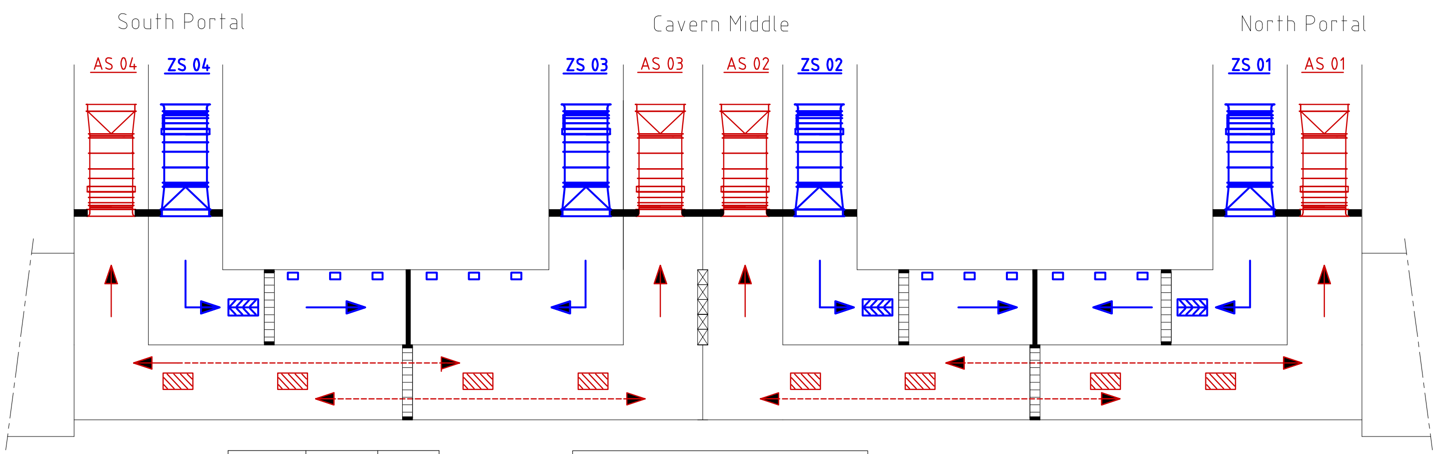
Begleitende Kontrolle (BK):
Hopferwieser Consult Ziviltechniker GmbH

Ventilation design:
FVT - Forschungsgesellschaft für Verbrennungskraftmaschinen und Thermodynamik m.b.H.

Ventilation system review:
ILF Beratende Ingenieure GmbH

3. CONTRACTUAL REVIEW OF VENTILATION SYSTEM DESIGN

The ventilation system of the Tauern tunnel is represented in Fig. 1:



	Q m³/s	dp Pa	Pmot. kW
AS01	165	3100	700
AS02	160	2825	700
AS03	160	2825	700
AS04	160	3250	700
ZS01	150	1625	350
ZS02	130	1875	350
ZS03	130	1875	350
ZS04	150	1625	350

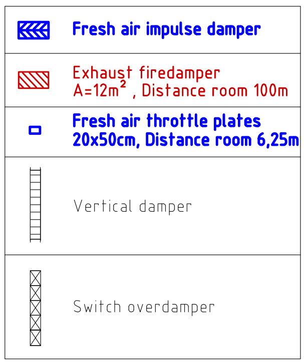


Fig. 1: Ventilation system

As a part of the contract, the ventilation system design [1] has been reviewed [2]. According to the Austrian RVS 09.02.31 the meteorological influences (barometric pressures and wind influences) need to be considered in the calculation of system pressure differentials. For the design review, meteorological data were obtained from the Zentralanstalt für Meteorologie und Geodynamik, the Austrian meteorological institute (ZAMG).

The meteorological conditions deviated from the data from a neighbouring tunnel which were used in the system design. The main consequence was that higher pressure differentials at the portals had to be taken into consideration:

Table 1: Meteorological influences, ZAMG

Percentile value	Processing of the Pressure differences at the portals		Processing of the Shaft Natural Draught	
	NP – SP	SP – NP	Shaft-Draught Up	Shaft-Draught Down
	Pa	Pa	Pa	Pa
80- Percentile	148	85	423	92
85- Percentile	170	114	462	103
90- Percentile	199	142	506	116
95- Percentile	236	182	553	133
98- Percentile	282	219	600	144
Maximum	511	417	693	168

The higher portal pressure differentials caused doubt on the capability of the system to control the longitudinal velocity in the tunnel in case of a fire incident. This problem was solved by installing an additional, so-called reversible fresh air impulse damper close to the middle in both tubes.

The lesson learned in this case is that the design review needs to be carried out immediately after contract award. It is not just a formality but can result in changes of fan selection and drive motor sizing, equipment which determines the delivery time of the ventilation system.

4. LIMITATIONS AS A RESULT OF EXISTING FAN ROOM AND VENTILATION DUCT DIMENSIONS.

<u>Exhaust fan configuration:</u>

The limitations caused by the existing fan rooms and ducts influenced the construction of the supply and exhaust fan units. The large exhaust air volume (160 m^3/s per fan) through a relatively small duct in the vicinity of the fans (2,2 x 2,2 m), results in high velocities (33 m/s), causing pressure losses which are significantly higher than newly designed tunnels, where duct velocities are limited to 15 to 20 m^3/s.

The normal, aerodynamically optimised fan construction consisting of inlet bell, fan casing and diffuser requires a length of approx. 9 m. The available length of the Tauern tunnel fan room was 6 m.

Apart from the higher system pressure losses, the limited length and small ducts have also a negative effect on the fan related losses and on the in- and outlet conditions.

The inlet conditions for the exhaust fans were geometrically and aerodynamically optimised using CFD, with the assistance of ILF, Fig. 2 and 3.

The optimisation resulted in 5 to 10% lower power consumption depending on operating point and fan application.

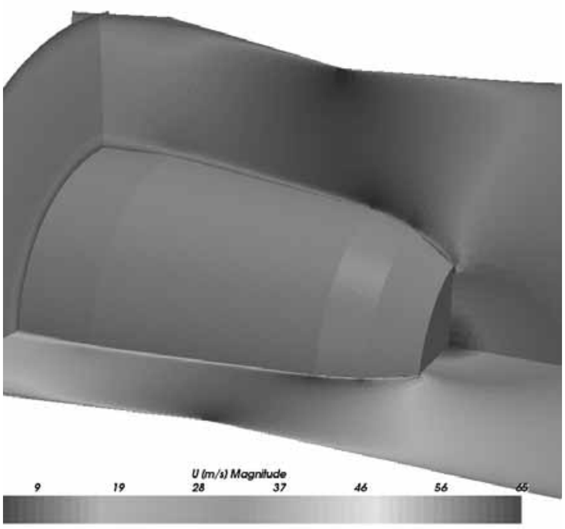


Fig. 2: optimised inlet condition

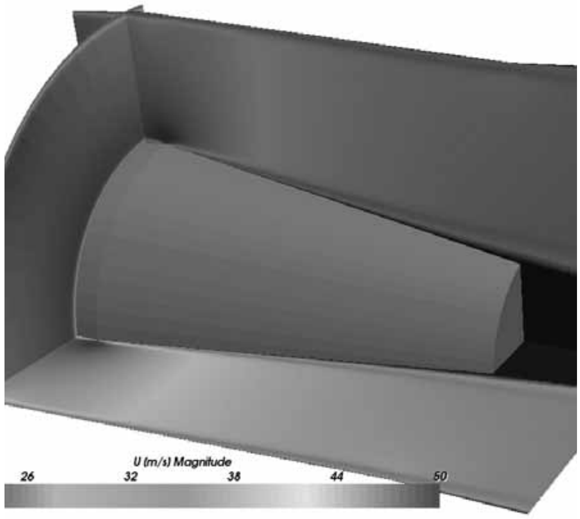


Fig. 3: optimised diffuser shape

Further power savings would only have been possible after enlargement of the ventilation ducts and fan rooms. As an example we compare the exhaust fan configuration and power consumption of the Tauern tunnel with an optimised fan room- and duct lay out, Fig. 4 and 5.

<u>TAUERN</u>
Length of fan room: 6000 mm.
Duct suction side.: 2.200 x 2.200 mm.
Duct pressure side.: 2.200 x 2.200 mm.

<u>OPTIMUM</u>
Length of fan room: 9.000 mm.
Duct suction side.: 3.000 x 3.000 mm.
Duct pressure side.: 3.000 x 3.000 mm.

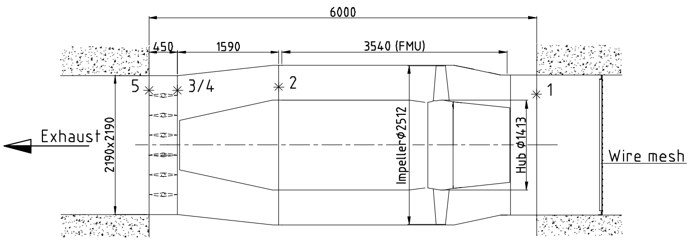


Fig. 4: Tauern exhaust fan configuration

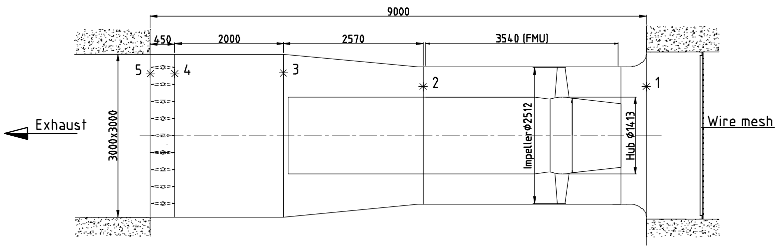


Fig. 5: Optimal fan configuration

The lower air velocities and the significantly higher dynamic pressure recovery by the diffuser are shown in the table 2.

Table 2: Fan power consumption related to fan related losses, Tauern vs. Optimal configuration

Tauern Exhaust Fan (Impellerdiameter 2510 mm.)							Optimum Duct lay-out				
Component	Volume m3/s	Duct m2.	v m/s	P-dyn. Pa	ζ [-]	**ΔP Pa**	Duct m2.	v m/s	P-dyn. Pa	ζ [-]	**ΔP Pa**
<u>Inlet part:</u>											
Screen	160	4,84	33,06	639,30	0,10	**63,93**	9,00	17,78	184,89	0,10	**18,49**
Inlet piece	160	4,84	33,06	639,30	0,05	**31,97**	9,00	17,78	184,89	0,09	**16,64**
<u>Discharge duct / Diffuser:</u>											
Inlet	160	3,38	47,36	1312,22			3,38	47,36	1312,22		
Outlet	160	3,27	48,89	1398,25			4,61	34,67	703,26		
Efficiency / factor	160				0,15	**12,90**				0,15	**91,34**
<u>Impuls losses</u> 3>4											
With innerpipe	160	3,71	43,13	1088,28			5,05	31,67	586,87		
Without innerpipe	160	4,84	33,06	639,30		**60,89**	6,18	25,88	391,87		**20,13**
Fan isolation damper	160	3,71	43,13	1088,28	0,25	**272,07**	9,00	17,78	184,89	0,25	**46,22**
Total Fan pressure losses						**441,76**					**192,82**
In- and outlet concrete duct losses (based on assumption of 1,5 x dynamic loss)						**958,95**					**277,33**
Total losses						**1400,71**					**470,15**
Fan Power at 85% efficiency						**263,66**					**88,50**

<u>Auxiliary equipment:</u>

Due to location and limited size of the fan rooms, the auxiliary components such as electrical panels, auxiliary cooling- and hydraulic units cannot be situated directly next to the fans, which means that additional provisions had to be made. Additional oil leakage units were installed, lay out and installation of auxiliary cooling air ducts, hydraulic oil tubing and supply- and sensor cabling was more complicated and time consuming, Fig 6 and 7:

Fig. 6: Hydraulic oil tubing

Fig. 7: Auxiliary cooling air ducts

5. ACCEPTANCE TESTS

The main supply and exhaust fans have been full size tested to demonstrate the required air volumes, pressure rise and energy consumption. Based on the test results the expected annual energy consumption has been confirmed. The fan test results provide a solid basis for site acceptance tests in terms of leakage and overall system performance. For accurate air volume measurements, nozzles were mounted in the exhaust duct, Fig. 8.

Fig. 8: Measuring nozzle in exhaust duct

The leakage test revealed high leakage volumes. This required renewal of the sealing and improvement of the tightness of the joints in the concrete exhaust- and supply-air ducts as well as improving the sealing flanges around the existing dampers, in the existing tunnel.

The fire test revealed that in the event of a fire incident in combination with a high natural draught in the tunnel, it may be recommendable to use 2 exhaust fans, instead of 1, for exhaust of the smoke out of the tunnel. In that particular case 1 or 2 more fire dampers should be opened.
This was recommended by the BMVIT (Bundesministerium for Innovation and Technology) and its consultant HBI.

6. CROSS PASSAGE VENTILATION

Ventilation of the cross safety passages between the tunnel tubes.

In case of a fire, the cross safety passages must be kept free of smoke. This is realised by an over-pressure of approx. 50 Pa, generated by the fan placed at the non-incident traffic tube side of the passage. To keep the possibility to manually open and close the cross passage doors with reasonable force, the over-pressure should not be in excess of 50 Pa.
When the cross passage doors are opened, the fans need to be accelerated to maintain the 50 Pa over- pressure. With an opened cross passage door the air volume must be increased to a level which results in 2,5 m/s air speed through the opened cross passage door. Upon closing of the cross passage door, the fan speed must be decelerated to reduce the pressure rise caused by closing the cross passage door.
The relatively long time required to accelerate and decelerate the fans is a disadvantage of this process, the system reacts relatively slow on opening and closing the doors. This disadvantage is also found at other cross passage ventilation systems.

To overcome this disadvantage we see following possibilities:

- Use of slide doors

The advantage of a sliding door is that it is possible to open these with a limited force, also at higher over-pressures. In Switzerland we have seen cross passages with sliding doors. The response time of the system is still somewhat slow, but the influence of the force required to open the doors is limited.

- Use over-pressure dampers.

The best option to keep the over-pressure in the cross passage more or less constant is the use of pressure relief dampers. The size of these dampers should be the same as the area of the doors. In this case the response time of the system on closing and opening cross passage doors is reduced significantly (example Wattkopftunnel, Germany)
Aspects like available space and economic considerations may prevent the use of sliding doors and pressure relief dampers

7. FAN STALL PREVENTION

The fresh air for the 4 supply fans is sucked from a common fresh air duct, the 4 exhaust fans blow into a common exhaust duct. This may result in fan stall during starting additional fans or increasing air volume of the fans. The fans are equipped with a stall measuring device, therefore it is possible to measure the stall line of supply and extract fans the fans at site.
To not only determine but actually prevent fan stall from occurring, electrical contractor Dürr Austria has installed an active fan stall prevention routine, which operates as shown in Fig.9:

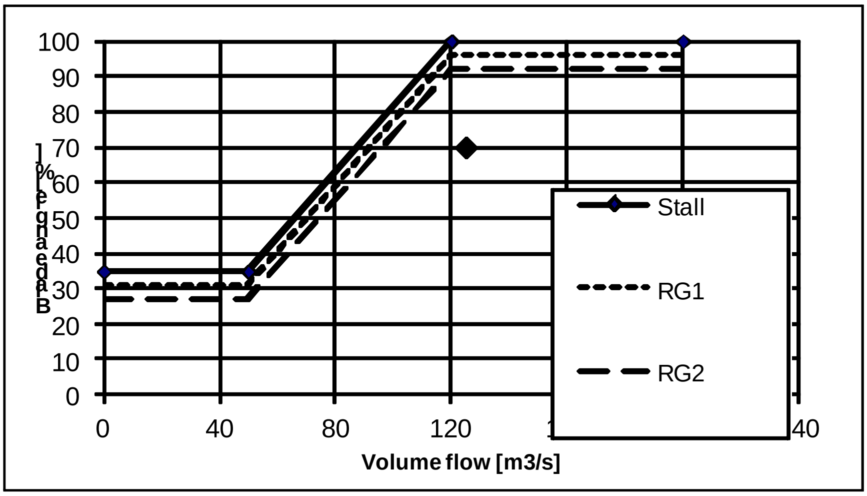


Fig. 9: Air volume vs. % of full blade angle

If the operating point of the fan is below the line RG2 the blade angle is increased when a higher volume is required.

If the operating point is above the RG2 line the blade angle will not be increased when a higher volume is required.

When de volume flow is reduced (due to a higher volume of other fans) and the operating point is above the RG1 line, than the blade angle is reduced by 3 degrees. After 30 seconds the system checks again if the operating point is still above the RG1 line, when that is the case the blade angle is reduced again.

When the operating point is above the stall line, the fan will be stopped (only during normal operation).

8. COMMERCIAL ASPECTS

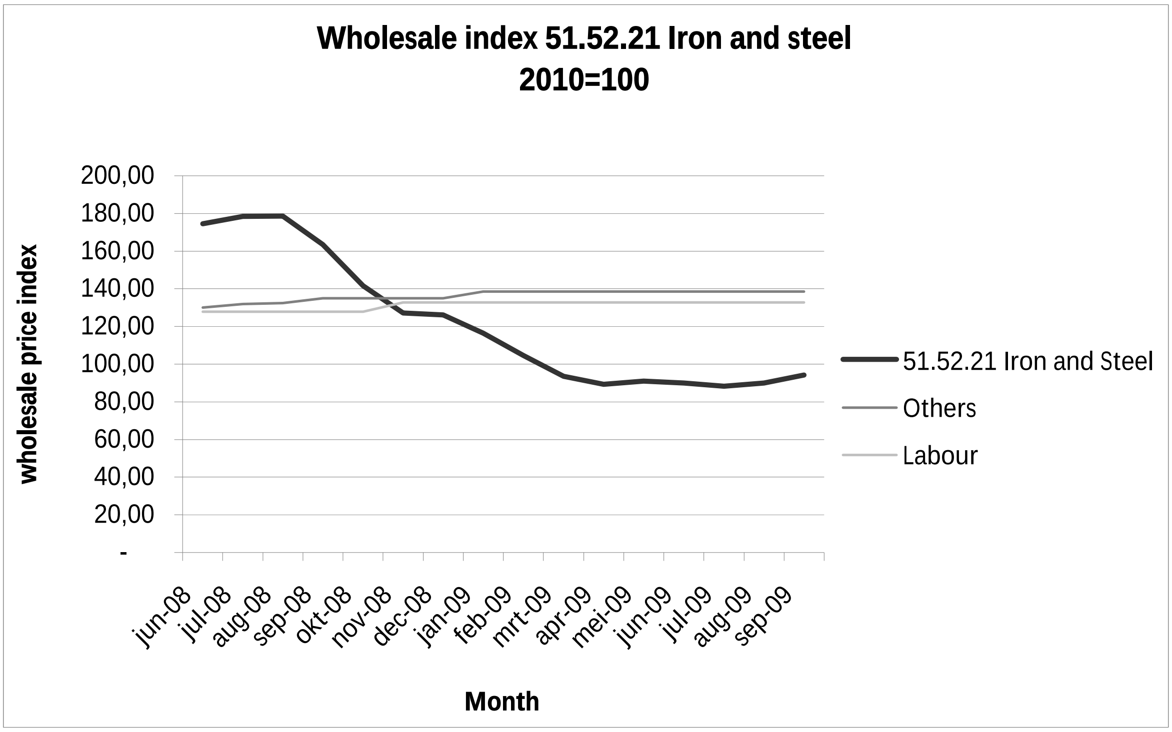
Contracts like the Tauern tunnel ventilation system supply are subject to a price escalation formula in which the final price is determined based on the value of indexes for labour and material.

The prices in the contract are based on the submission date of the tender, which was June 30, 2008.

In the period 2005 to 2008 the material prices had increased substantially because of the economic boom and high demand from high growth rate countries like China and India.

The second half of 2008 the world economy came into a recession, due to the financial crisis in the USA which spread later to Europe. As a result the material prices went down dramatically, table 3.

Table 3: Price index for iron and steel, resulting indexes for labour and others



source: Statistik Austria

Example:

Price basis	June 2008	Due date Sept. 2009
Labour:	127,78	132,69
Others:		
Labour:	130,02	138,50
Material:	174,60	94,20

Calculation:

	Price Split-up %	Po without esc. %	Lo / Mo	Ldd / Mdd	Price factor	Pdd with esc. %
labour	20	20	127.78	132.69	1.04	20.77
Others						
Wages	48	48	130.02	138.50	1.07	51.13
Material	32	32	174.60	94.20	0.54	17.26
		100				**89.16**

Under normal market conditions prices which are subject to a price escalation formula will slightly rise during the construction period. For the Tauern Project the final price decreased with more than 10% between tender submission date and invoice date. A main-contractor can mitigate this deficit by negotiating lower prices with sub-contractors based on lower material prices or by agreeing the same price escalation formula for sub-contracted supplies.

However, a substantial part of the risk of negative price variation will remain with the main contractor.

9. LOCAL PARTICIPATION

Local participation in facilitating and assisting with local assembly, installation, removal and re-cycling, supply of steel construction work, such as platforms, stairs, ramps, as well as ducts, railings and other construction parts have proven to be vital for a smooth site erection and installation.

Another advantage of the involvement of local contractors is that local fitters for assembly and installation work can gain experience with a tunnel ventilation system.

Especially when staff of local sub-contractors are invited to join at commissioning, testing and the instruction sessions, they become specialist service fitters for the ventilation equipment.
So in case of a failure or damage, it is possible to have an engineer in place, for the first diagnoses, within a very short notice period. The specialist local staff can also be employed for service and maintenance under supervision of a specialist from the factory, making this more cost effective than sending a full team with associated cost for travelling costs and lodging.

10. CONCLUSIONS AND RECOMMENDATIONS

Design review

It is essential that the design review takes place immediately after contract award as the Tauern project has shown that it is not a mere formality but can have significant consequences on selection an sizing of ventilation system components.

Fan room and – duct dimensions

Allowing for sufficient space for fans and ventilation components will reduce capital cost and energy consumption.

Acceptance tests

Carrying out site tests is not only required to prove system performance but can also reveal further optimisation possibilities.

Cross passage ventilation

More attention should be given to the response time for pressurizing cross passages.

Active fan stall prevention

Processing the data from air volume and fan stall measuring device enables active stall prevention which is advantageous for fan durability and ventilation system reliability.

Price escalation

Price escalation formula's can, in unusual circumstances result in lower final equipment prices.

Main-contractors should take this into consideration during tender preparation, agree same conditions with sub-contractors. Customers may allow for limits in price variation to limit overall economic risk for longer term contracts.

REFERENCES:

[1] P.J. Sturm and M. Bacher, Institute for Internal Combustion Engines and Thermodynamics (2008); Design of the ventilation system of the Tauerntunnel.
.

[2] B. Höpperger, ILF Consulting Engineers (2008); Review calculations of the ventilation system Tauerntunnel.

ENERGY EFFICIENCY – ABB MATHEMATICAL MODEL FOR TUNNEL VENTILATION CONTROL

D. Červar; BINA Istra Operation and Maintenance Ltd, Croatia
V. Jakobović; ABB Ltd, Croatia

ABSTRACT

An advanced system of tunnel ventilation control was put into operation at the end of 2009 in tunnel Učka. The ventilation control system is based on ABB's predictive fuzzy logic mathematical model. The first year of operation is analyzed and compared with ten-year averages. Operation based on mathematical model resulted in reliable control of pollutant concentration within given levels, reduced number of on- and off-switching of ventilators, increased lifetime of ventilators and electrical switching equipment, savings in maintenance costs and increase of tunnel safety. Significant savings of electrical power consumption are achieved as well as increase of energy efficiency.

Keywords: *tunnel, tunnel Učka, ventilation, fuzzy logic, mathematical model, control system, energy efficiency*

1. INTRODUCTION

Tunnel Učka is an important transport link of the peninsula of Istria and the rest of Croatia. The tunnel construction began in 1976 and opened in 1981. Since 1995 Bina-Istra d.d. has had concession for the tunnel.

Tunnel Učka is 5,062 m long. Traffic runs in both directions along one lane in each direction.

Two smaller tunnels "Zrinščak I" (196 m) and "Zrinščak II" (45 m) and viaduct, together with the main tunnel, make one unit controlled remotely from the control centre located in a building on the Istrian side of the tunnel.

During the past period the concessionaire asked for two security checks of the tunnel (see Tomašević G., *Modernisation of Učka Tunnel*, 2010, [3]) , the first in 1996 and the second one in 2005 to get recommendations that will raise the level of safety in the tunnel. Thereby, consultants considered the following:

- Directive 2004/54/EC on minimum safety requirements for tunnels in the *Trans-European Road Network,*
- *European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR),*
- Regulation RABT 02/2002 – *Guidelines for equipment and operation of tunnels* (Germany),
- Regulation RVS – *Guidelines and Regulations for Road Construction* (Austria),
- Recommendations of *Permanent International Association of Road Congresses* (PIARC) and other relevant studies.

During recent years, respecting these recommendations, extensive modernization of many technical systems in tunnel Učka was conducted and is still undergoing. As the final phase of modernization of ventilation, two software modules were introduced in the remote control system:

- The ventilation control in normal mode, based on a predictive mathematical model and *fuzzy* logic.
- The ventilation control in emergency (fire) mode

Algorithm and implementation of the **ventilation control in normal mode**, results obtained and analysis of energy savings in the first year of operation i.e. in 2010 are also described in this herein.

2. VENTILATION SYSTEM OF TUNEL UČKA

The ventilation system of tunnel Učka is of longitudinal type and consists of 144 jet-fans arranged in 48 fan groups. Each group comprises of three jet-fans powered by electric motors suspended from the tunnel ceiling. Jet-fans are unidirectional, i.e. they always operate in one direction (operation direction cannot be changed). They are arranged so that groups operate alternately in one or other direction. Fan groups are not evenly spaced along the tunnel tubes, but are grouped toward the tunnel, so that there are no jet-fans in the central part of the tunnel.

The power of built-in fan motors is 30 kW. Ventilation is supplied from six substations 20/0, 4 kV located inside the tunnel (TS2 - TS7), which are, via two external substations 20/0, 4 kV, TS1 (Istria) and TS8 (Kvarner) connected to the power distribution network. Each substation in the tunnel supplies eight fan groups. Depending on needs, by control of MV distribution, all the jet-fans can be supplied from the grid from the Istrian or Kvarner side. In normal conditions, each network supplies half of the tunnel.

Ventilation is controlled from the control centre through remote control, and during maintenance jet-fans can also be controlled from the local electrical cabinet

3. MATHEMATICAL MODEL FOR VENTILATION CONTROL

Pollution resulting from the traffic of vehicles driven by internal combustion engine, carbon monoxide (CO), soot and nitrogen oxides (NOx), create particular difficulties in tunnels.

- Natural ventilation is generally insufficient, and therefore mechanical tunnel ventilation system should be installed in order to keep the level of pollution within the given limits.
- Besides controlling the pollution concentration, mechanical system plays a role in preventing the spread of fire and fire fighting in case of an emergency situations
- A specific case is the control of air flow velocity to increase safety in normal operation, e.g. regulation of air flow velocity in transport of hazardous substances in conditions of strong natural flow of large, i.e. *bura* (strong north wind).

In most of modern tunnels (depending on the tunnel length, traffic intensity, etc.) mechanical ventilation systems are installed which are classified in two basic types - longitudinal and transverse. Ventilation is controlled from the control centre via the remote control. In general, ventilation control i.e. switching-on and -off of individual jet-fans, or fan power control, can be made in "manual mode" (operator in control centre) or with the help of a software module for automatic ventilation control.

In "conventional" automatic control system (Figure 1) the pollutant concentrations, i.e. the concentration levels of carbon monoxide (CO), opacity ("visibility") and nitrogen oxides (NOx) are taken into account as variables used as the basis for control in the control loop.

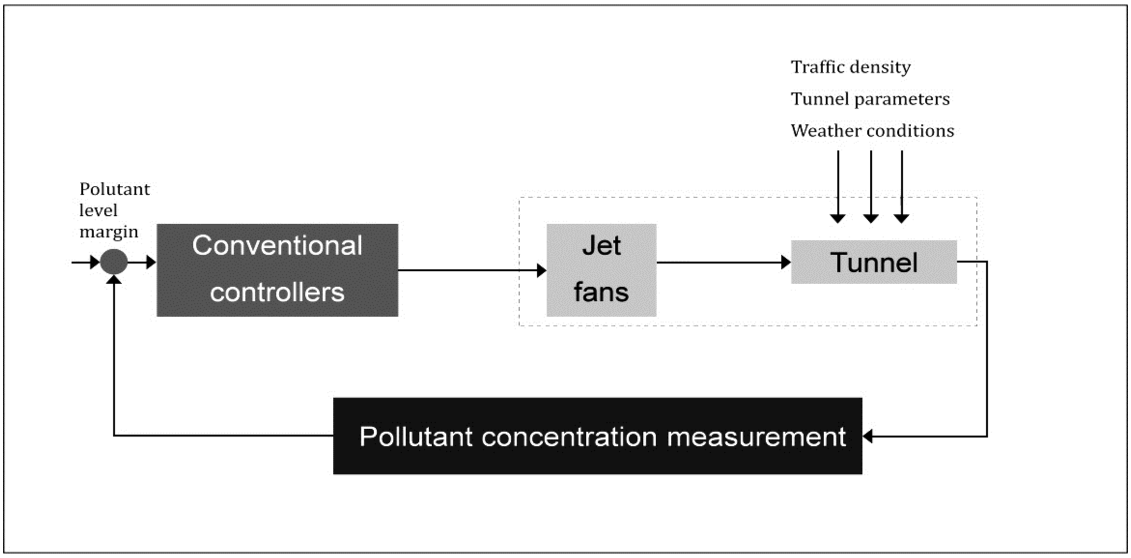


Figure 1: Control loop of conventional ventilation control

The advanced algorithm (see Bogdan S.; Birgmajer B.: *Model Predictive Fuzzy Control of Longitudinal Ventilation System in a Road Tunnel*, 2006, [1]) based on predictive mathematical model and *fuzzy* logic (Figure 2) takes into account the tunnel parameters (shape, cross section, differences in elevation of tunnel portals etc.), the current weather conditions (pressure, temperature, air speed and direction), and current traffic condition (direction, intensity, speed and class of vehicles). Mathematical modelling provides prediction of pollutants concentrations and fresh air requirements, and thereby is advantageous over the "conventional" algorithm of automatic control. The algorithm also takes into account the actual measured current values of pollutant concentrations (CO, visibility, NOx) in the tunnel.

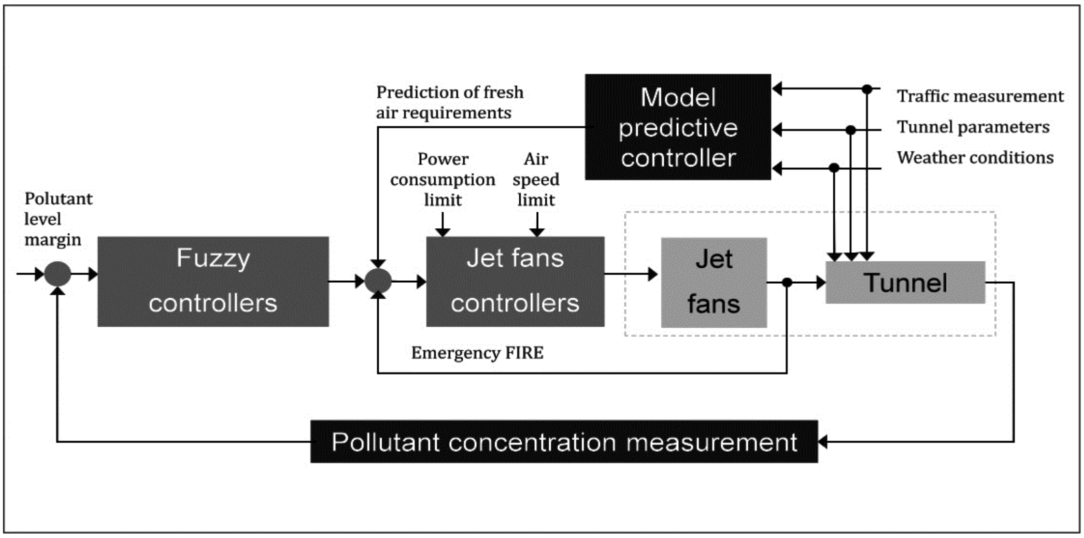


Figure 2: Mathematical model of tunnel ventilation control

By analyzing both models of control using simulation software for the same given conditions the advantages of mathematical models in relation to the "conventional" model of ventilation control is seen (Figure 3):

- control of pollutant concentration within predefined limits with saving of energy,
- reduced number of on- and off-switching of jet-fans, i.e. increased lifetime of jet-fans and electrical switching equipment and savings in maintenance costs,
- increase of tunnel safety.

During control using the mathematical model, smaller number of jet-fans is switched on and lower peak air velocity is achieved, which is of particular advantage in case of emergency situation (fire), because in such situation switch over to mode with small air velocity required to establish smoke stratification in the tunnel will be faster.

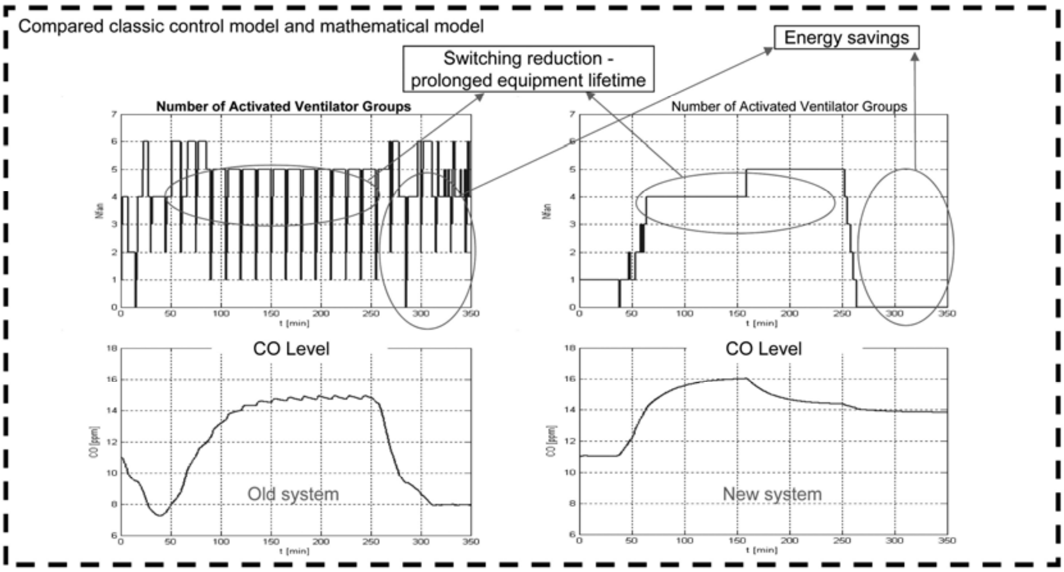


Figure 3: Comparison of conventional and mathematical model of tunnel ventilation control

4. MODERNIZATION AND ADDS-ON OF VENTILATION SYSTEM

During modernization and add-on of the remote control system for ventilation control in 2005 using the mathematical model, tests and measurements of the tunnel parameters were carried out, and functioning of mathematical model was made. However, significant adds-on and modernization of the ventilation system had to be done before that.

In 2007 *The ventilation study* (see Drakulić, M.; Lozica, M.; Herve, F.; Binacchi, M. and others, *The ventilation study of Učka Tunnel*, 2007, [2]) was made to upgrade the system. A group of authors engaged in preparation of the study collected data on the existing equipment, examined the ventilation system and gave guidelines for modernization of existing equipment. Simultaneously, the Preliminary design of remote control system add-on was made, aimed to modernization, expansion and the planned admission of new subsystems in the tunnel.

The remote control system of tunnel Učka is based on DCS (*Distributed Control System*) ABB System 800xA, and it integrates monitoring and control with all the subsystem in the tunnel: power supply, ventilation, lighting, traffic signalization, fire alarm, SOS telephones, etc.

Completion of this modernization and adds-on created conditions for implementation of predictive mathematical model of ventilation control in normal mode, and algorithm for air flow control in emergency (fire) mode as well.

5. IMPLEMENTATION OF MATHEMATICAL MODEL IN TUNNEL UČKA

Design and implementation of mathematical model of ventilation control began in 2005 as part of modernization and add-on of remote control. In late 2009, completion of reconstruction of ventilation equipment ensured all the preconditions and so, after preliminary tests were done, the system was put into trial operation in December of the same year. The software module of mathematical model is designed as a component of remote control.

The input parameters for predictive mathematical model of tunnel Učka are:

- tunnel physical parameters, taken from project documentation and determined by testing and measurements at the system start-up,
- measurement of carbon monoxide (CO), visibility and air speed at five acquisition station in tunnel,
- measurement of atmospheric pressure at tunnel portals,
- measurements from traffic counters - four traffic counters in tunnel and two traffic counters installed at six kilometres before tunnel.

Besides the basic requirement of ventilation control, i.e. keeping pollutant concentration within defined limits, the concessionaire required the following:

- equalization of power load per both power supply networks, during operation roughly the same number of jet-fans is supplied from the Istrian and Kvarner side;
- load equalization at all substations, i.e. during operation roughly the same number of active jet-fans at all substations;
- equalization of the fan operating hours over longer period i.e. during exploitation all the jet-fans have roughly equal number of operating hours.

During trial period and the first year of mathematical model of ventilation control at tunnel Učka, it was shown that all requirements are met, with simultaneous significant increase of energy efficiency and energy savings.

6. ENERGY SAVING IN THE FIRST YEAR OF EXPLOITATION

By following up the consumption, substantial savings in electricity consumption (Figure 4) were recorded already in the first months of operation. Comparison of the average energy consumption per a vehicle in 2010 with the previous ten-year period - from 2000 to 2009 shows substantial decline in consumption in 2010. It should be noted that the total power consumption of tunnel Učka is being followed up, which includes: lighting, consumption of the building, installed systems, and ventilation. The consumption of lighting, building and installed systems that is mostly constant throughout the day and year, i.e. it does not change significantly compared to the daily and seasonal changes in traffic through the tunnel, while consumption of the ventilation system depends highly on the traffic through the tunnel. Data on total electricity consumption, trend of total number of vehicles, ratio of heavy and light vehicles, and data on average energy consumption per a vehicle (kWh / vehicle) at annual level in the period from 2000 to 2010 is presented in -> *Table 1.*

Saving in the average consumption (total) of energy per a vehicle for 2010 compared to the previous ten-year period amounts to 16.89 %.

Financial indicators of savings are also very significant. Taking the average consumption per a vehicle in the previous ten year period and the traffic realized in 2010 as a starting point, the estimated financial savings amount to 16.28%

It should be noted that the savings are achieved during the day when the traffic is increased, and electricity is more expensive, and higher financial savings are to be expected with rising annual traffic levels. Also, as a significant result of the applied model is equalization of consumption per supply networks and reduction in subscribed demand which will further contribute to savings and reducing the financial cost.

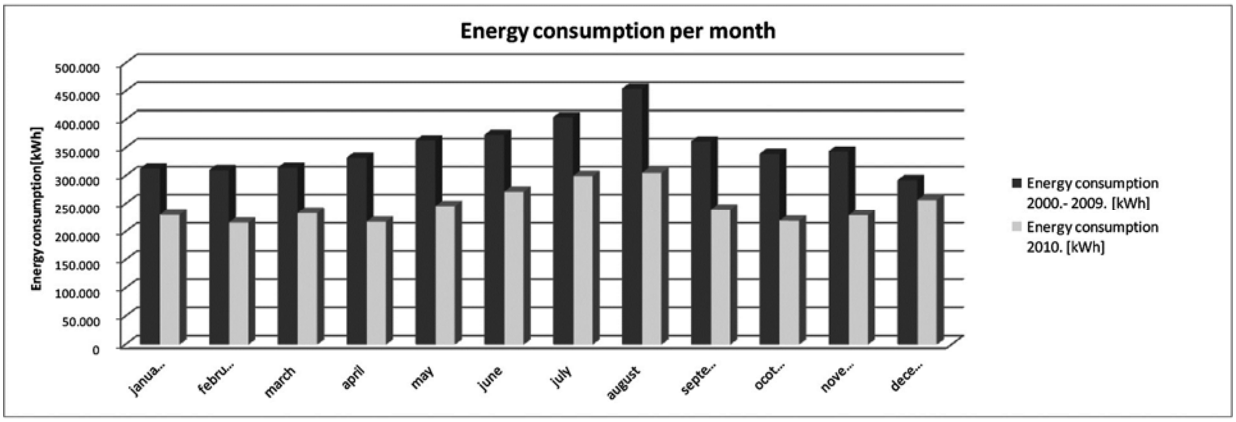


Figure 4: Energy consumption per month - a comparison of average energy consumption from year 2000 until 2009 compared with year 2010

Table 1: Trends in the number of vehicles, the relationship between heavy and light vehicles, and total energy consumption in the period from year 2000 to 2010

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
I	1 610 433	1 718 815	1 786 891	1 871 356	2 063 164	2 036 864	2 170 110	2 358 850	2 357 546	2 319 438	2 215 666
II	175 119	199 731	217 967	225 403	261 729	268 754	280 368	297 123	299 460	271 179	266 855
III	174 470	192 171	201 443	212 362	216 638	196 869	202 368	212 571	208 934	188 214	178 794
IV	95 816	107 509	113 953	124 433	140 579	141 060	143 259	155 009	156 834	148 205	138 342
TOTAL	2 055 838	2 218 226	2 320 254	2 433 554	2 682 110	2 643 547	2 796 256	3 023 553	3 022 774	2 927 036	2 799 657
Light vehicles	1 785 552	1 918 546	2 004 858	2 096 759	2 324 893	2 305 618	2 450 478	2 655 973	2 657 006	2 590 617	2 482 521
Heavy vehicles	270 286	299 680	315 396	336 795	357 217	337 929	345 778	367 580	365 768	336 419	317 136
Heavy/Light vehicle (%)	15,14	15,62	15,73	16,06	15,36	14,66	14,11	13,84	13,77	12,99	12,77
Energy (kWh)	4 189 709	4 304 993	4 673 424	4 148 368	4 228 985	4 073 334	4 423 493	4 027 845	4 169 258	3 738 675	2 964 599
kWh/vehicle	2,04	1,94	2,01	1,70	1,58	1,54	1,58	1,33	1,38	1,28	1,06

Note: energy consumption is overall consumption including ventilation, lighting, control building, etc.

7. EVALUATION OF THE EFFECTIVENESS OF MATHEMATICAL MODEL

The analysis performed has shown the efficiency of mathematical model and cost savings in relation to total consumption. Looking at a part of energy consumption influenced by the applied model of control, i.e. energy consumption by the ventilation system, energy efficiency of the mathematical model can be expressed as the ratio of energy savings and energy consumption of the ventilation system.

$$\eta = \frac{\Delta Ev}{Ev} \qquad (1)$$

where:

ΔEv – energy saving achieved by mathematical model

Ev – energy consumption of ventilation system

The mean value of saving in energy consumption per a vehicle for all months in 2010 compared to the ten-year average which is 16.89% is used as the value of efficiency. The share of consumption of the ventilation system (estimate) is 50.87% of total energy consumption, and efficiency of the mathematical model is:

$\eta = 33\ \%$

8. CONCLUSION

Mathematical modelling provides prediction of pollutant concentrations, providing significant advantages over "conventional" algorithm for automatic control. The result of mathematical model is:

- reliable pollutant concentration control within predefined limits,
- number of on- and off-switching of jet-fans, i.e. increased lifetime of jet-fans and electrical switching equipment and savings in maintenance costs,
- savings in maintenance costs,
- increase of tunnel safety (by reducing peak velocity of air flow),
- significant saving in electricity and
- increase of energy efficiency.

In hierarchical control level, mathematical model of tunnel ventilation control is a separate unit superior to the basic functions of the Control and Monitoring System, and it can be applied as Add-on in other tunnels, too.

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DETERMINATION OF VENTILATION EFFICIENCY IN ROAD TUNNELS BY USING TRACER METHODS

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ABSTRACT

This paper reports recent findings from applying tracer methods for the determination of ventilation efficiency and reference velocities in different Swiss tunnels.

Fast tracer concentration measurement devices and a mass flow controller were applied together successfully. This has led to the successful validation of the pulsed emission tracer method with the constant emission tracer method in three Swiss tunnels. This new method was further enhanced with a complete evaluation procedure to express measurement uncertainty.

The pulsed emission tracer method was validated with the constant emission tracer method in three Swiss tunnels and further enhanced with a complete budget to express measurement uncertainty.

The constant emission tracer method was and will be applied again in 2012 as reference in a long time measurement campaign that validates velocity measurement devices in two Swiss tunnels (Bözberg AG and Flüelen UR). Future work will include testing the feasibility of using an alternative tracer gas such as $C_2H_4F_2$ instead of SF_6.

Keywords: ventilation efficiency, tracer methods, volume flow of air, velocity measurements

1. INTRODUCTION

Since 2002 the constant emission tracer method has been used by scientists and engineers of the Centre for Integrated Building Technology at the Lucerne University of Applied Sciences and Arts (LUASA) to determine volume flow and leakage in exhaust ducts of twenty-two road tunnels in Switzerland and Europe. Economic considerations initiated the authors of this paper to investigate an alternative tracer method which needs less tracer gas with equal or more precise results as the constant emission method. This new method was tested embedded in a project of the Swiss Federal Roads Office (FEDRO) (see Buchmann, 2010, [1]). These investigations have led to a new method called pulsed emission tracer gas method.

2. CONSTANT AND PULSED EMISSION TRACER GAS METHOD

Both methods are described in detail in Frei & Kägi, 2010, [2] and are illustrated in **Figure 1**. The present paper gives only a briefly overview. For the development and application of the pulsed emission method a new generation of fast measurement devices and mass flow controllers was essential. Non Dispersive Infrared Spectroscopy (NDIR) and Fourier Transformation Infrared Spectroscopy (FTIR) together with thermal mass flow controllers are now used in field applications. But even highly sophisticated thermal mass flow controllers had to be improved to really measure “mass flow” and nothing else. The mentioned equipment is able to measure concentrations and control flows of tracer gases like sulphur hexafluoride (SF_6), nitrous oxide (N_2O), and 1.1-difluorethane ($C_2H_4F_2$).

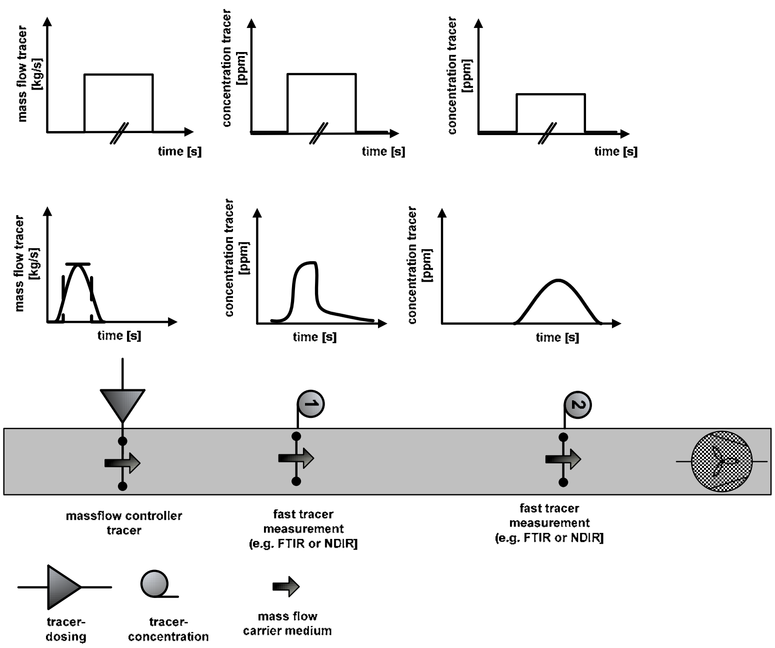

Figure 1: Experimental set-up of the constant and pulsed emission tracer method in exhaust ducts

3. VALIDATION OF THE PULSED EMISSION TRACER GAS METHOD

First experiments with the pulsed emission method were gathered in road tunnels Kirchenwald (2008), Aescher (2009), and Islisberg (2009) (see **Figure 2**). Single- and multipoint-sampling strategies showed good agreement and therefore excellent mixing even shortly after dosing can be concluded.

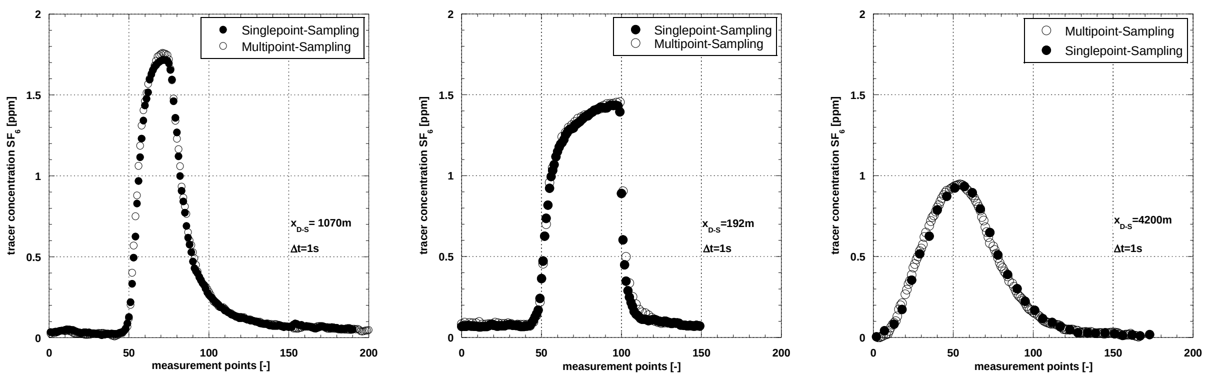

Figure 2: Tracer gas pulses downstream in exhaust ducts of road tunnels. From left to right: Kirchenwald, Aescher, Islisberg (according to Frei & Kägi, 2010, [2]).

Further on important pulse-design and pulse-integration-tools were developed with LabView® in a LUASA R& D project in 2010.

As mentioned in Frei & Kägi, 2010, [2] a comparison and validation of experimental results obtained by constant and pulse tracer method had to be realised.

Table 1: Experimental results obtained by constant and pulsed emission method in exhaust ducts of three Swiss tunnels.

	Kirchenwald tunnel	**Aescher tunnel**	**Islisberg tunnel**
pulsed emission (pe) singlepoint	concentration integral = 64.4s	concentration integral = 66.6s	concentration integral = 71.3s
	mass flow of air =196.8 kg/s	mass flow of air =198.8 kg/s	mass flow of air =117.5 kg/s
pulsed emission (pe) multipoint	concentration integral = 64.6s	concentration integral = 69.0s	concentration integral = 72.0s
	mass flow of air =195.9 kg/s	mass flow of air =229.4 kg/s	mass flow of air =113.5 kg/s
constant emission (ce)	mass flow of air =211.6 kg/s	mass flow of air =217.0 kg/s	mass flow of air =117.1 kg/s
deviation $\overline{pe}$ / ce	7.2 %	1.3 %	1.4 %
deviation singlepoint to multipoint	0.5 %	13.3 %	3.5 %

- Deviation between the pulsed and constant emission method is comparably small with the exception of Kirchenwald tunnel. In this tunnel pulsed emission tracer method was applied the first time by LUASA. Uncertainties caused by dosing a tracer gas in a new way led to this deviation.
- Deviation between singlepoint- and multipoint-sampling is remarkable in Aescher tunnel caused by a short mixing length (196 m).

Furthermore the measurement uncertainty of the pulsed emission tracer method according to ISO-standards had to be defined. For this reason a complete uncertainty budget according to the guide to expression of measurement uncertainty (see GUM, 1995, [3]) was developed. **Figure 3** shows the uncertainty budget for the pulsed emission method measurement in Islisberg tunnel (singlepoint). Mass flow of the carrier fluid in this case was (117.5 ± 4.9) kg/s or 117.5 kg/s ± 4.2% (95% confidence interval)

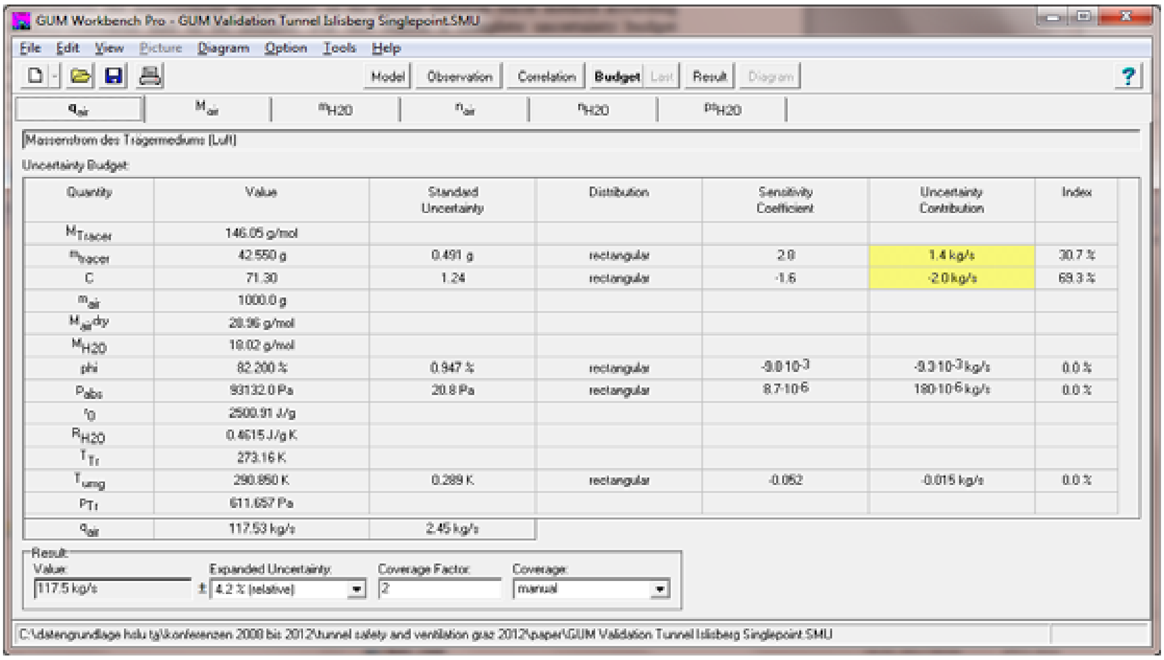

Figure 3: Budget for measurement uncertainty according to the GUM, 1995, [3].

4. RECENT APPLICATIONS OF TRACER METHODS IN SWISS TUNNELS

4.1. Determination of ventilation efficiency in tunnel Mappo-Morettina TI

The Swiss tunnel Mappo-Morettina near Locarno TI has a total length of 5530 m with two sections Mappo and Morettina. This tunnel has separate exhaust and supply air ducts. LUASA determined leakages and the ventilation efficiency in spring 2011 during two night-closures in both sections. The results will cause an intensive duct tightening campaign to lower leakages and enhance ventilation efficiency.

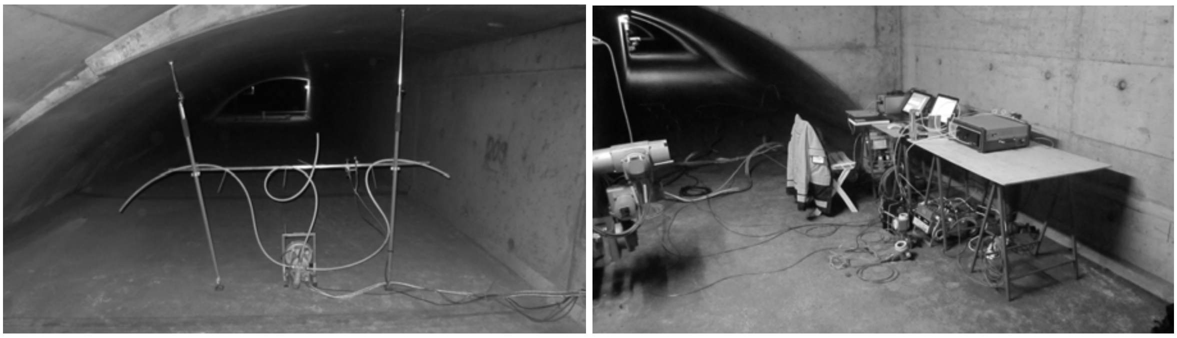

Figure 4: Multipoint-sampling in exhaust duct (left) and measurement devices in supply duct at measurement site MS2 (right).

LUASA applied the constant and pulsed emission tracer method downstream in the exhaust-duct at two measurement sites (MS1 and MS2). Distances from the dosing station was less than 100 m for MS1 and approximately 2300 m for MS2. The measurements have proved that the pulse emission tracer method has the ability for a fast approximation on leakages, mean velocities (derived from distance and delay time), and short circuits. Lessons learnt from tunnel Mappo-Morettina are the following: A rectangular pulse generation for short mixing lengths less than 100 m has to be avoided, otherwise deviation between constant and pulsed emission can exceed 10%. A rectangular pulse generation does not influence deviation at measurement site 2 (under 5%). Further considerations to enhance the pulsed emission method to operate with an alternative tracer gas like 1.1-Difluorethane ($C_2H_4F_2$) are under way.

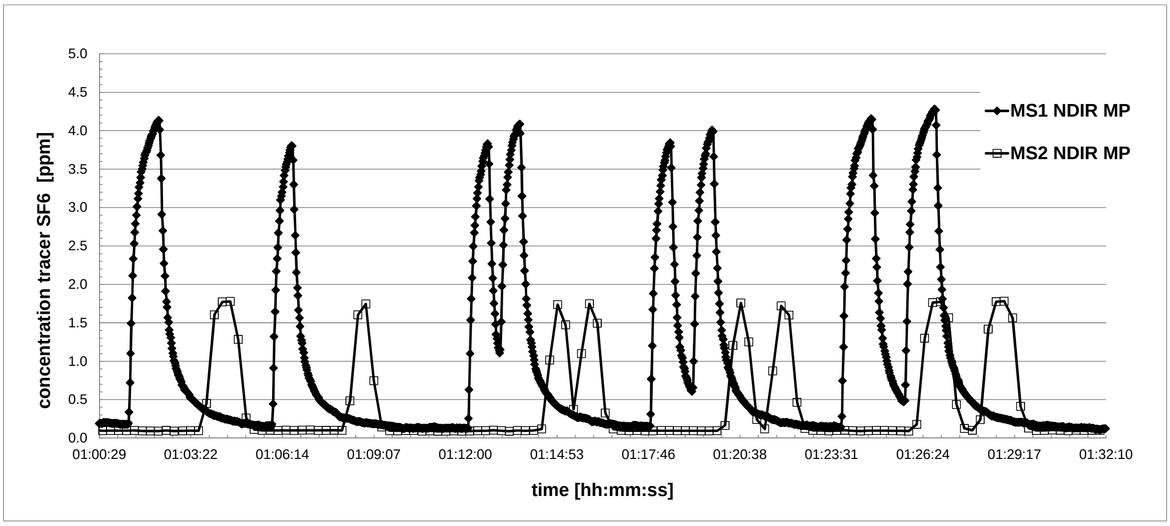

Figure 5: Series of pulses downstream at measurement sites 1 and 2 in Morettina section.

4.2. Determination of reference velocities in tunnel Flüelen UR and Bözberg AG

A long-time measurement campaign concerning the measurement of air velocities in road tunnels was initiated in autumn 2011 by FEDRO (contractor Lombardi). Manufacturers of air velocity measurement equipment installed their devices for long-time measurements and data processing in two Swiss road tunnels Flüelen UR and Bözberg AG. Data is collected and stored in time steps of 10 seconds. Every day a backup of 24-hours measurements is sent by GSM router to Lombardi for data processing and interpretation. Possible long-time shifts and a dependence on the installation point of the devices are observed by engineers of Lombardi.

LUASA were asked to provide verification data using the constant emission tracer method. Mean air velocities can be derived from volume air flow and cross-section area. In the current FEDRO project reference mean velocities derived from measured volume air flows by using the constant emission tracer method were to be determined. Measurements under different traffic conditions have been conducted successfully in January 2012. A second series of reference measurements is planned for autumn 2012. Experience from dosing and sampling under traffic conditions will boost the ability to apply the pulsed emission method not only in exhaust ducts, but also in tunnel tubes.

Figure 6: Dosing of tracer gas SF_6 with small ventilators near the north portal in tunnel Flüelen UR.

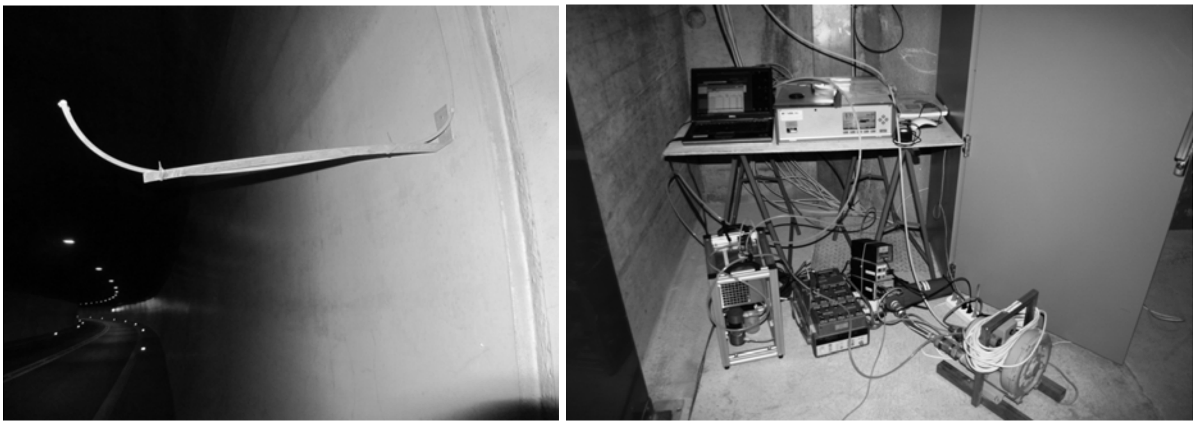

Figure 7: Part of multipoint-sampling in tunnel Flüelen UR (left) and measurement devices in a cross-passage (right).

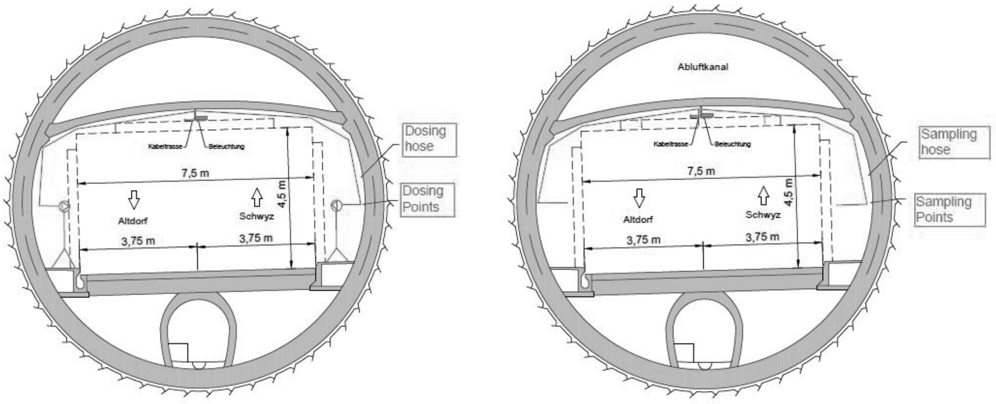

Figure 8: Dosing and multipoint-sampling of tracer gas SF6 in tunnel Flüelen UR.

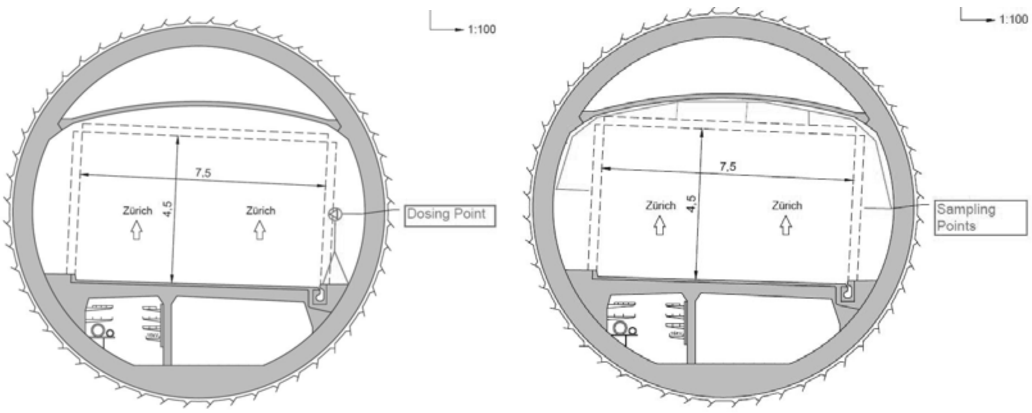

Figure 9: Dosing and multipoint-sampling of tracer gas SF6 in tunnel Bözberg AG.

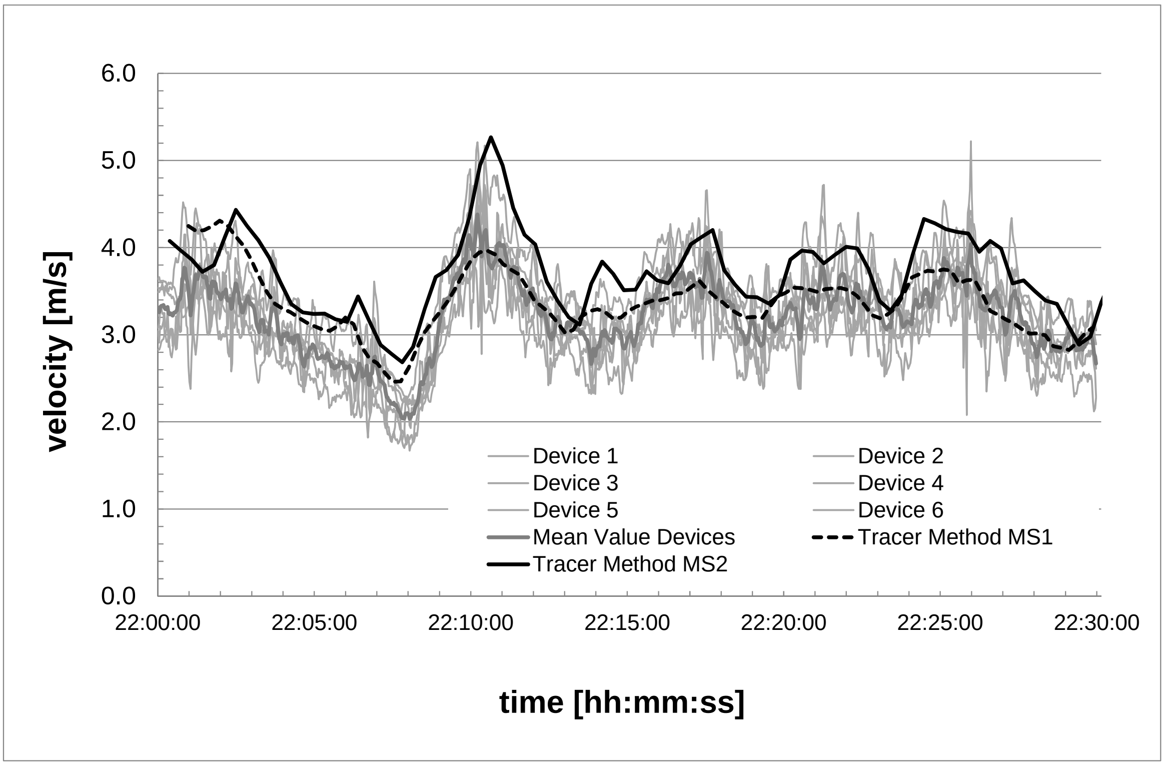

Figure 10: First results from measured local und derived reference mean velocities.

5. CONCLUSION AND OUTLOOK

Comparison measurements of the constant und pulsed emission tracer methods showed good agreement for each single measurement site in exhaust ducts of three Swiss tunnels.

In the exhaust ducts of the Mappo-Morettina tunnel the pulsed emission tracer method delivered results comparable to the constant emission tracer method for all measurement sites. Both methods are equally adapted for ventilation efficiency validation in ducts.

The constant emission tracer method has shown its ability to serve as reference method for velocity measurements in tunnel tubes under traffic conditions.

The enhancement of the constant and pulsed emission tracer method by using an alternative tracer gas like 1.1-difluorethane ($C_2H_4F_2$) is planned for coming measurement campaigns.

The application of the pulsed emission tracer method to measure volume air flows in tunnel tubes under traffic conditions is under consideration by the authors of this paper.

6. ACKNOWLEDGEMENTS

We would like to thank Marco Bettelini (Amberg), Urs Grässlin (Lombardi), Andrea Weber Marin, and René Hüsler (both LUASA) for their continuous scientific and financial support.

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COMPENSATORY EFFECTY OF FIXED FIRE FIGHTING SYSTEMS IN TUNNELS

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ABSTRACT

During the last years, more and more tunnels are equipped with fixed fire suppression systems (FFFS). Obviously the purpose of the systems somehow differs for each tunnel, but in up to now they are used to increase the level of safety.

The research project SOLIT², a consortium of FOGTEC, STUVA, BUNG, Ruhr University and TÜV Süd, followed a different approach. Major aim of the project was to identify compensatory measures by FFFS in tunnels aiming for technical easier and more cost-effective solutions, but ensuring the same or even a better level of safety.

In 2011 a large scale fire test program was carried out by the German Institute of Fire Brigades and IFAB on behalf of the SOLIT² consortium. The paper will focus on the interaction of water mist systems with longitudinal and semi-transversal ventilation systems. Based on tests with a severe truck fire load as well as pool fires up to 100 MW it was possible to show that with a combination of both systems it was possible to reduce the ventilation power by up to 70% achieving the same effects.

The paper gives an overview of possible compensatory effects of fixed fire suppression systems and will give some advice regarding minimum requirements for the design of tunnel safety systems by using compensatory effects.

Keywords: ventilation, FFFS, fire protection, fire tests, compensation, SOLIT²

1. INTRODUCTION

The beneficial effects of fire suppression systems in tunnels are well known and were studied extensively during the last years. However, the evaluation of test data from full scale fire tests and further data already showed that more benefits can be achieved by FFFS as simply increasing the level of safety. The research project SOLIT², funded by the German government studied during the last 2 years the possibilities of compensating accepted and well established safety measures by using FFFS in tunnels. Furthermore tools were developed to check the level of safety of various combinations of safety measures as well as to evaluate and compare the life-cycle-costs of these systems. Further information about the SOLIT² project can be found at www.solit.info.

2. FIXED FIRE FIGHTING SYSTEMS IN TUNNELS – STATE OF THE ART

During the last years several tunnels throughout Europe where equipped with fixed fire fighting systems (FFFS), mainly based on water mist technology. Just recently, the new tube of the New Tyne Crossing was opened after an extensive testing and training program with the water mist system that is installed in the tunnel. Within Europe more than 35 km of tunnel are equipped with FFFS but these systems can be seen in most cases as ad-on safety measure. They were installed to increase the level of safety but were not required according to rules or standards. Referring to the opinion of many experts the benefits of these systems are obvious. According to the work of several research projects, e.g. UPTUN or SOLIT, the main aims of these systems are [1]:

- Protect the tunnel structure and minimize the damages on the tunnel
- Hampering fire spread to adjacent objects, e.g. other trucks
- Facilitate the work of the rescue services
- Improvement of the self-rescue conditions for people inside the tunnel

Figure 1: Spray test with a water mist system in the New Tyne Crossing

The layout basis for all systems are full scale fire tests with severe truck fire loads as it were used during the SOLIT research project or e.g. for the New Tyne Crossing

General recommendations for the system layout and minimum technical requirements can be found in the UPTUN guidance R251 [2] as well as in the latest version of the NFPA 502. Also PIARC recently published some recommendations for FFFS in tunnels [3].

3. COMPENSATION OF SAFETY MEASURES

3.1. GENERAL

In general, compensation describes the possibility to achieve the same effect by using different methods. Looking at safety concepts for road tunnels and other underground facilities the way how safety systems are designed is changing more and more from a prescriptive based methodology by simply applying standards and fixed rules to a more performance based approach. This development leads to a much higher flexibility in design but gives also higher responsibility and requirements for the design process.

Furthermore, with a performance based approach it is possible to also customize safety systems to the special risks that can be found in the specific tunnel or building.

More complex underground structures and complex tunnel systems but also higher requirements on safety increased the costs for safety systems and in particular fire fighting systems during the last years. When it comes to refurbishment of existing tunnels, an upgrade of safety systems is often technical extensive or even impossible, but in most cases extremely expensive. In buildings the compensation of structural fire protection measures where the implementation is difficult technical, expensive or against design aspects is common practise.

The idea of compensatory effects can be summarized as increasing the level of safety with same costs or keep the equal level of safety with same costs.

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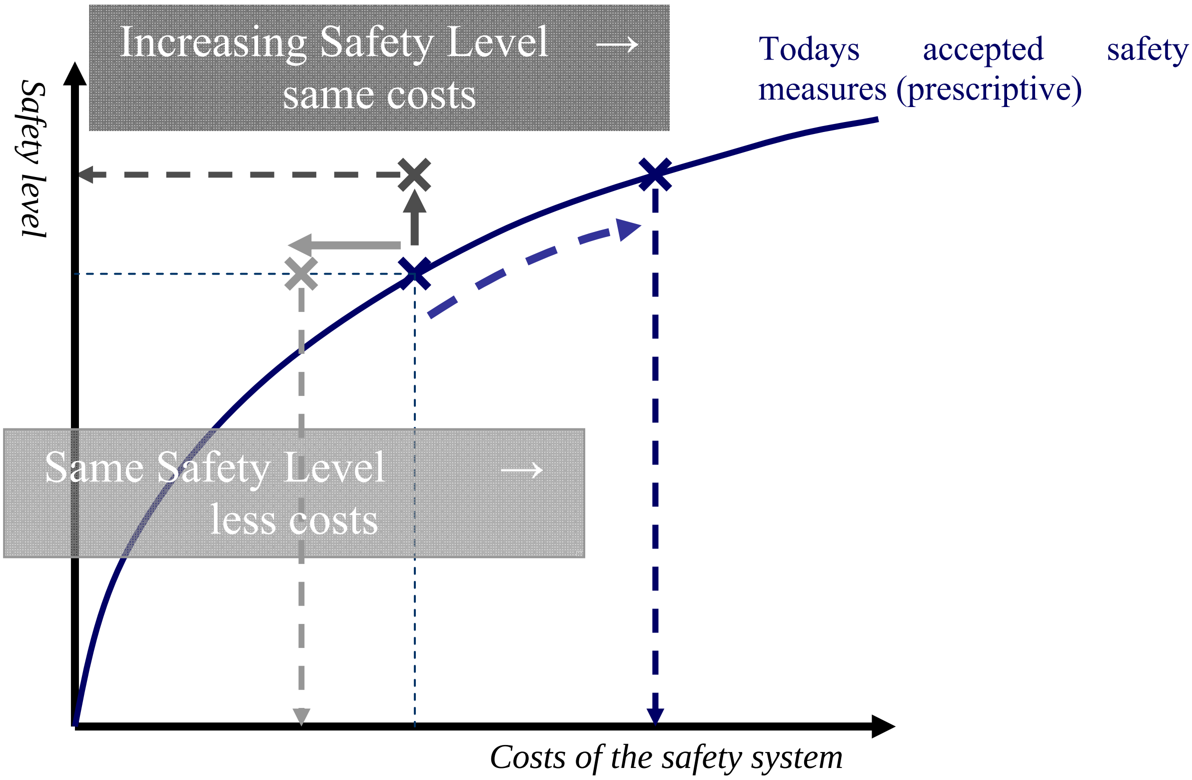

Figure 2: Correlation between the safety level and the costs of a safety system [4]

In the following chapters, possible compensation methods are described. The effects are based on the SOLIT² full scale fire test program which was carried out in summer 2011.

3.2. STRUCTURAL FIRE PROTECTION

Real fire accidents in tunnels showed that within a short period of time, high temperatures up to 1200°C might occur. This also reflects in the standard time-temperature curves for testing material such as the RWS-curve or the ZTV-Ing-curve. Applying these temperatures over a long period of time on structural elements, this will lead to extreme damages which might also risk the stability of such structural elements. In any case the repair works that are necessary after fires, even smaller ones, are extensive, time consuming and expensive.

One of the major effects of FFFS in tunnels is the cooling of the environment. Compared to standard deluge or foam systems, water mist systems are having a much higher cooling potential. Even if the fire size is not reduced by the FFFS, as most fires are inside the compartments or covered, the temperature level inside the tunnel is reduced significantly. The effects of water mist systems regarding temperature management can be summarized as follows:

- The zone of higher temperatures (> 200°C) is limited only to the fire source itself. Usually the spread of the fire is also hampered so that the fire zone can be limited to the initial vehicle.
- Directly above the fire load inside the flame zone (e.g. for truck fires if the load is burning), in some small areas temperatures of 600°-900°C may occur. These temperatures were only observed locally and for a short period of time.

Using the results of specific FFFS from real full scale fire tests with representative fire loads, the time-temperature curves which defines the requirements for structural elements can be modifies. The absolute height of the temperature is reduced, the radiant heat impacting structural elements is significantly less and the exposure time is much shorter than in standard time-temperature curves.

Basically, this means that the requirements on passive fire protection linings or boards are reduced significantly or they can be even avoided. Moreover, the repair works on the concrete structure of tunnels in case of incidents is also much less.

3.3. VENTILATION

Already during the fire tests within the UPTUN and SOLIT projects the positive effect of FFFS on the ventilation where observed. During the SOLIT^2 fire tests program the effects of

Figure 3: Smoke layer shortly after ignition and after activation of the FFFS

various FFFS on the ventilation program were evaluated. For this purpose, pool fires with sizes of 30, 60 and 100 MW were used as the smoke production is extremely high and smoke management effects can be studied. For the ventilation a longitudinal ventilation system as well as a semi-transversal ventilation system was used. The systems were calculated dimensioned to be effective for fires of 30 MW which means that the longitudinal ventilation systems avoids back-layering and the semi-transversal system should keep a smoke free layer of at least 2 m.

During free burning tests it turned out that the semi-transversal ventilation system, although designed correctly and working in normal mode, was hardly able to keep the smoke free layer. It should be taken into account that the conditions in the test tunnel were almost ideal as there were no obstacles or any other situations that my effect the smoke layer negatively.

During the fire tests with FFFS it turned out that in combination with activating the FFFS the same effectiveness of the ventilation and smoke extraction system can be achieved with a 100 MW fire. That means that the longitudinal air velocity designed for a free burning 30 MW fire was able to prevent back-layering for a 100 MW fire in combination with a FFFS. For the semi-transversal ventilation system an analogue effect was observed.

Although the SOLIT² consortium is still evaluating the test data, these positive effects are most likely based on the enormous cooling effect of the water mist and therefore a volume reduction of the smoke.

Of course, there is an interaction of the smoke layer and the activated FFFS. In the area where the FFFS is activated, there is a mixture of smoke and the water mist and therefore the smoke layering is partly disturbed. But, as described before, it is a question of future research and studies if a smoke free area as intended can be created in case of real bigger fires.

The reduction of visibility in the area of the activated FFFS was not considered as a problem as it is still enough to orientate and to find illuminated exits signs.

4. FURTHER EFFECTS

The chapters before are describing the main effects regarding compensation of elements of the tunnel safety system by using FFFS. Applying FFFS in a tunnel of course give further beneficial effects.

Due to the significantly reduced temperatures and because fire spread is reduced, damages in the tunnel are also reduced. This further leads to a significantly reduced down time in case of an incident as well as reduced costs for the repair works.

A major beneficial effect can be seen for the fire brigades. An active FFFS allows fire brigades to enter the fire zone quickly and with a very limited risk compared to a free burning fire. In no case during more than 100 large scale fire test steam production that might cause a risk were reported, although the fire men were in a distance to the fire of less than 5 m.

As soon as the fire brigade is close to the fire zone, the fire can be extinguished quickly. This also leads to an enormous reduction in damages to the tunnel.

5. REQUIREMENTS AND PROCEDURES

The performance based approach of designing and effective safety systems for tunnels and underground stations is always based on a profound risk analysis. After that it is up to the designer to combine the various safety measures to create a holistic safety system for each specific tunnel or underground facility. Depending on the special requirements and conditions it might be beneficial to compensate well accepted safety measures as described above.

However, it is always essential to proof the effectiveness of the new combination of measures to show, that at least a same level of safety can be achieved with the new safety system. Of course this procedure must be well documented and approved by independent bodies.

In particular if technical systems are used as safety systems, it should be ensured that these systems have an acceptable reliability. This not only should apply for FFFS but also for all other technical systems acting as safety systems in a tunnel, such as ventilation, communication and data transfer. For such systems RAMS analysis as well as SIL levels should be applied.

6. OUTLOOK

The SOLIT² research program ends in spring 2012. As part of the work of the consortium a technical engineering guidance will be produced to explain the procedures during compensation of elements of tunnel safety systems. The SOLIT² engineering guidance will also include minimum requirements on the performance of FFFS as well as on the reliability, maintainability and safety of technical elements. Furthermore it will give advice how life cycle costs are correctly evaluated for various combinations of elements of the tunnel safety system. This is essential to not only evaluate various technical solutions based on their efficiency but also on costs.

This document will be public available in summer 2012.

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FLEXIBLE DEVICES FOR SMOKE CONTROL IN ROAD TUNNELS

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ABSTRACT

This paper summarizes the investigations carried out for systematically assessing the applicability of flexible devices for smoke control in road tunnels. After a thorough investigation of previous efforts, all possible applications of flexible devices in existing and new road tunnel were systematically evaluated. Permeable devices for controlling the longitudinal air velocity are being used in one tunnel in Austria. Three additional types of applications emerged from this screening process, which appear both technically feasible and practically interesting: closure of tunnel entrances by tight or permeable devices, to be applied to short, steep tunnel with natural ventilation, and smoke curtains in longitudinally ventilated tunnels with either bidirectional traffic or unidirectional traffic with high congestion frequency. The findings for smoke curtains, which allow for an excellent control of smoke propagation with low longitudinal air velocity, are particularly promising and are illustrated in some detail.

Keywords: smoke control, road tunnel, fire compartment, smoke curtain, smoke barrier

1. INTRODUCTION AND OBJECTIVES

Flexible devices for sub-dividing large rooms into fire compartments are commonly used in large buildings. They can be used for preventing fire and smoke propagation in case of fire emergency while preserving a great flexibility for building exploitation. A Swiss national research project was launched for investigating the use of similar devices for controlling smoke propagation in existing and new road tunnels.

The issue of fire compartmentalization has been discussed in the past as an innovative approach for fire and smoke control in road tunnels. The specific objectives, the physical principles involved and the resulting physical realization depend on the tunnel configuration considered. In principle the physical scope is very wide and ranges from the pure control of longitudinal air velocity (as investigated in previous efforts in Austria, discussed in the following chapter of this paper) to fire-compartment building, with the objective of oxygen depletion (self consuming fire) and direct prevention of smoke propagation. Fire compartmentalization can moreover enhance fire extinction using water-mist systems (Bettelini & Seifert, 2009, [2]). These effects follow the fire extinction principles of the “fire triangle”.

A number of different devices, including massive doors, water or air jets and many more could be used in a similar manner for achieving congruent objectives. The field of investigation had to be narrowed for preventing an excessive dispersion of energies. The scope of this research project was therefore restricted to flexible, solid devices. Its focus was moreover more on physical principles than on specific constructive characteristics. Based on the results, the development effort needed for providing suitable devices shall be left to the market. Conversely, with respect to tunnel configuration maximum generality was striven for, including single and double-tube tunnels, fluid traffic and congestion, natural or mechanical ventilation, cut-and-cover and excavated tunnels, existing and new tunnels.

The key objectives of the research was the identification and assessment of the most promising configurations in term of prevention of loss of human life, reduction of material damages and minimization of tunnel unavailability in case of fire.

2. PREVIOUS INVESTIGATIONS

Results from previous investigations were gathered by means of a comprehensive literature study and of questions sent to 11 leading international experts in the field of tunnel ventilation and safety. The results were very satisfactory and allowed for a full overview of previous investigations and experiences.

The most important and best known application of flexible devices for reducing the longitudinal velocity of air in fire incidents is described in Öttl et al. (2002, [6]). The devices considered consist of a number of strips formed by a fire-resistant textile, which can very effectively reduce the longitudinal air velocity in the tunnel while allowing for the transit of vehicles and persons. The investigation, which also included full-scale tests in the tunnel Roppen (Henn & Sturm, 2010, [4]), resulted in the installation in the Austrian tunnel Roppen (double-tube with unidirectional traffic, 5’069 m, concentrated smoke extraction in case of fire) and in the commercialization of the devices (system FIREcurtains by Aigner Tunnel Technology).

Further investigations were carried out for an inflatable tunnel plug in a real-scale tunnel fire test during the UPTUN project (Bergmeister, 2005, [1]). The goal was to isolate the fire in short tunnel sections. The tunnel barrier efficiently reduced smoke concentration outside the fire section. Complete sealing of the fire compartment was not possible. However, this kind of confinement of the fire leads to the formation of a highly flammable gas mixture in the compartment and, as Bergmeister (2005, [1]) recognized, “…this would increase the risk of an explosively burst of the plug with all consequences” (backdraught). The same concept, building of fire compartments with the aim to extinguish the fire, was experimentally investigated by Kohl. He observed that, after closing the barriers of the fire compartment, fire power increased for a short time, before being drastically reduced, due to lack of oxygen (Kohl et al., 2005, [5]). Although a fixed construction was used to seal the fire compartment, fire caused damage to the structure, which enabled some fresh air to penetrate into the compartment.

3. NEEDS AND OPPORTUNITIES

3.1. Safety needs in road tunnels

The main safety issues in road tunnels arise from fire scenarios. Tunnels of a certain length normally have a powerful ventilation system for extracting or controlling longitudinal smoke propagation. Shorter tunnels have mainly longitudinal ventilation or only natural ventilation. As showed by several incidents in the recent past (e.g. Mont Blanc, Gotthard and Viamala), incomplete control of smoke propagation can lead to dramatic problems for self-rescue of the tunnel users and for intervention. Particularly unfavorable conditions are generally observed in short tunnel with high longitudinal slope (Bettelini & Seifert, 2010, [3]).

A systematic preliminary screening was conducted for all practical tunnel types, traffic conditions and ventilation systems. The main goal was the identification of the situations, for which the greatest needs for innovative solutions arise. Based on this, it was decided to focus on the following configurations:

- Short tunnels with natural ventilation and high longitudinal slope, where high longitudinal air velocities arise because of the “stack effect”.

- Short, steep tunnels with longitudinal ventilation (uni- & bi-directional traffic), where mastering the longitudinal air velocity is frequently extremely difficult (jet fans in the smoke, complex regulation of longitudinal air velocity based on measurements of uncertain accuracy because of the presence of smoke).
- Tunnels with smoke extraction systems but insufficient control of longitudinal air velocity, where smoke extraction alone does not allow for a sufficient control of smoke propagation because of the excessive longitudinal air velocity.

Additional needs arising from insufficient ventilation power or wrong design in existing tunnels are unfortunately not uncommon but shall not be considered specifically, since they call in most cases for very specific solutions. For the application of different types of flexible devices in tunnels the key issues to be accounted for are:

- Aerodynamic characteristics (influencing fire development, preventing smoke destratification, influencing smoke propagation, etc.).
- Self-rescue conditions for tunnel users (fire and smoke compartmentalization without endangering the tunnel users during self-rescue).
- Conditions for intervention (favorable conditions for rescue and fire fighting, flexible intervention options and constraints, self-protection conditions for fire services).

3.2. Physical effects and safety implications

The following physical principles could be exploited by means of different devices:

- Reduction of longitudinal air velocity. This is important for all tunnels where vehicles are trapped on both sides of the fire (bidirectional or unidirectional congested traffic) and where high longitudinal airflows could be expected (e.g. stack effect in case of large longitudinal slope or large meteorological pressure differences on Alpine tunnels), independently on the ventilation system.
- Partial smoke blockage by means of smoke curtains in the upper part of the tunnel profile. Unlike common application of smoke curtains e.g. in train or metro stations, the focus is here on the reduction of the critical velocity.
- Form a barrier for smoke confinement, on one or on both sides of the fire.
- Form a closed compartment around the fires for fire extinction by oxygen depletion.

Most practical devices act on more than one way. Some degree of blockage of longitudinal air velocity is e.g. clearly provided by almost all practical systems. Similarly, some level of oxygen depletion is provided by several devices. It is nevertheless important distinguishing between main and side effects, for a proper identification of the characteristics of the best possible device for every potential application.

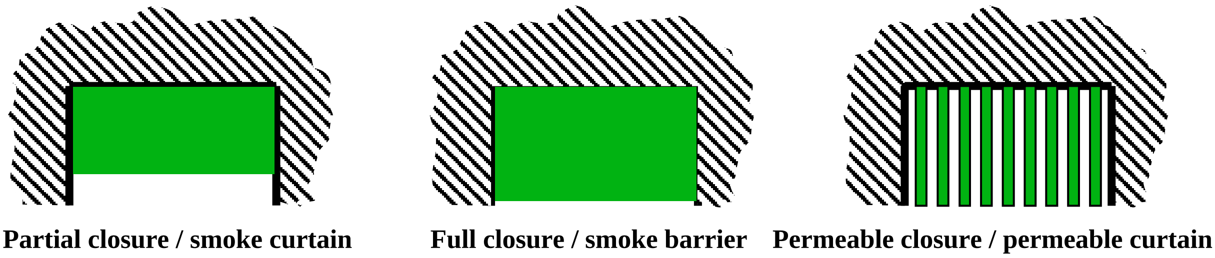

Figure 1: The basic devices considered.

A number of disadvantages and potential risks had to be accounted for from the beginning. The most obvious is physical blockage, which hinders the transit of persons and vehicles. Smoke barriers typically improve the conditions on one side, while higher smoke concentrations or some degree of stratification loss could be expected on the other one. This is particularly important during the self-rescue phase but has important consequences also for intervention. As a general guidance for the project it was decided that no device is acceptable if self rescue is not possible for all users in the tunnel. Thus all devices and combinations, which are not in line with the principle of a fair chance of survival for all users during the self-rescue phase, were rejected.

3.3. Investigation methodology

The investigation was carried out in two steps:

- Detailed investigation of the aerodynamic characteristics of all devices, for assessing their suitability and effectiveness in terms of control of smoke propagation and survivability conditions.
- Discussion of all safety-relevant issues, including self-rescue and intervention.

The investigation was carried out by means of a combination of one-dimensional (1D) and three-dimensional (3D) analysis.

3.4. Preliminary investigations of potentially useful applications

Useful applications must be effective, practically relevant and feasible with reasonable cost. Thus a systematic, preliminary screening of all possible combinations was carried out for different tunnel configuration, traffic conditions and ventilation systems. Attention was focused on issues, which can't be entirely mastered by conventional means, first of all tunnel ventilation. This includes e.g. short, steep tunnels with either natural or longitudinal ventilation. As shown by Bettelini and Seifert (2010, [3]) smoke propagation in such tunnel can't be effectively mastered by means of conventional ventilation systems.

The preliminary investigations showed among others that the option of realizing air-tight fire compartments is not feasible, because of the practical difficulties (highly tight closures at very short distances would be required), limited effectiveness (if the compartments are not very small and well sealed) and of safety consideration (self-rescue issues and risk of backdraught during intervention).

Based on the preliminary investigations it was concluded that the most relevant applications of flexible devices in road tunnels are the following ones:

- Permeable curtains or smoke barriers for naturally-ventilated tunnels with bidirectional or unidirectional traffic with high risk of congestion (application at the portals or in the tunnel) for reducing the longitudinal air velocity.
- Smoke curtain for longitudinally ventilated tunnels with bidirectional or unidirectional traffic with high risk of congestion. The smoke curtains are used for reducing the critical velocity and allow for an excellent control of smoke propagation with small longitudinal air velocities.
- Control of longitudinal velocity in long tunnel with smoke extraction. These devices have already been investigated in great detail in earlier studies and did not call for additional efforts within this project.

In this paper we will focus on the second application, more innovative and interesting from the point of view of tunnel ventilation. A few representative results are presented in the following chapter.

4. AERODYNAMICS AND SMOKE PROPAGATIONS

Representative "pilot" tunnels were selected for investigating aerodynamics and smoke propagation. Their key characteristics are:

- Portal permeable or total closure: length 500 m, "horseshoe" profile, cross section 56 m^2, longitudinal slope 3%, natural ventilation.
- Partial closure: length 650 m, "horseshoe" profile, cross section 56 m^2, vanishing longitudinal slope, longitudinal ventilation with jet fans.

A large number of simulations have been carried out for many relevant configurations. The findings will be illustrated based on smoke curtains with longitudinal ventilation. For all other devices only the main findings and general conclusions will be presented in the final chapters of this paper. The considered scenario was as follows:

- 30 MW fire in tunnel center, which is reached after 5 min
- Detection of fire after 1 min
- Activation of ventilation and curtains after 1.5 min, complete closure of curtains after 2 min
- Vehicles in the tunnel: 14 cars and 1 lorry on every lane.

Smoke curtains are lowered from the ceiling to a minimum height of 2 m above floor, which represents an obstacle only for buses, lorries and HGV. Persons and cars can still pass the curtains without any difficulty.

Smoke propagation in tunnels with bidirectional traffic and longitudinal ventilation is in most cases difficult to control. Key issues are the ventilation direction, the high longitudinal velocities necessary for suppressing backlayering, (roughly 3 m/s), which would disturb smoke stratifications and drastically worsen the conditions downstream of the smoke source, and the danger of direct smoke destratification by the jet fans. A common approach in such situations is to establish a longitudinal airflow of 1-1.5 m/s in the direction of the initial flow. This ventilation regime allows to keep smoke stratification and to slightly influence smoke propagation but is, in most cases, far from optimum.

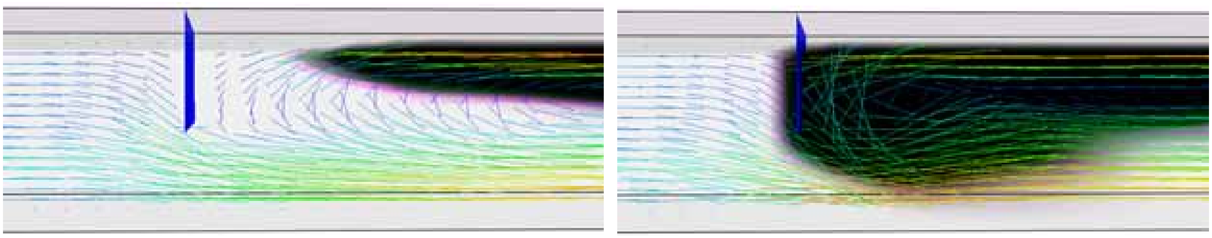

Figure 2: Visualization of smoke layer behavior at the smoke curtain.

The new investigations showed that the curtains, if installed upstream of a fire, represent a very effective barrier against smoke backlayering, since the critical velocity is locally significantly reduced by the smoke curtains. The effect of the curtain on the smoke layer is illustrated in Figure 2. Drawback of the installation is that downstream smoke stratification is disturbed.

A combined system of smoke curtains and longitudinal ventilation can prevent backlayering with a longitudinal airflow of about 0.5 m/s. Smoke curtains show the tendency to smoke destratification, but have the ability to keep a wide range of the tunnel free of smoke.

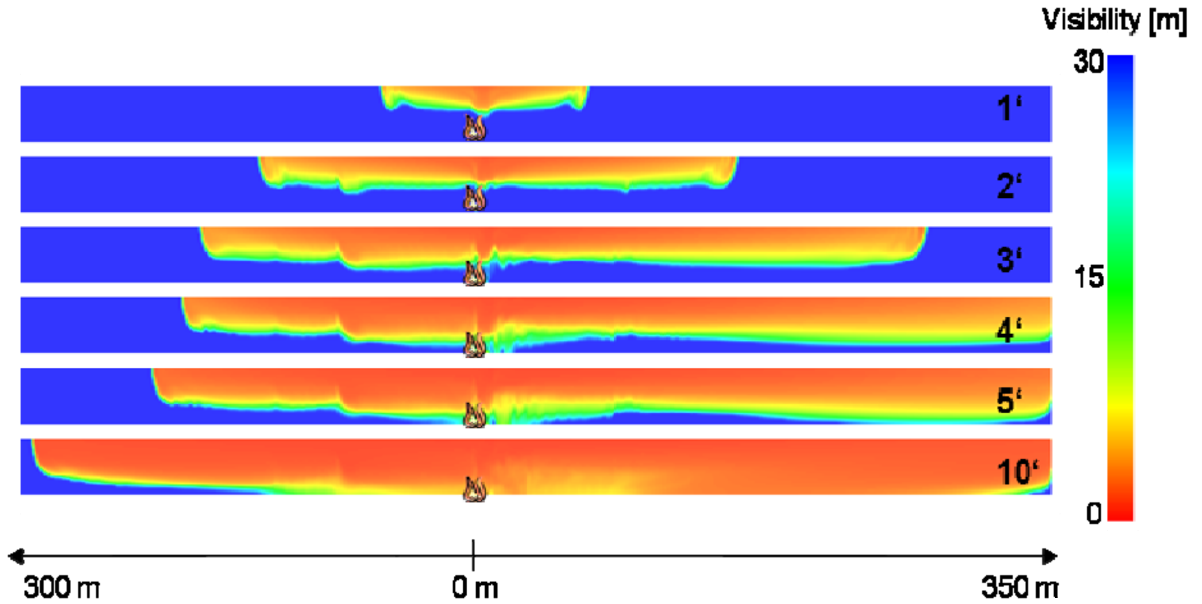

Figure 3: Evolution of visibility conditions in a longitudinally ventilated tunnel (30 MW fire, longitudinal air velocity 1 m/s, no smoke curtains).

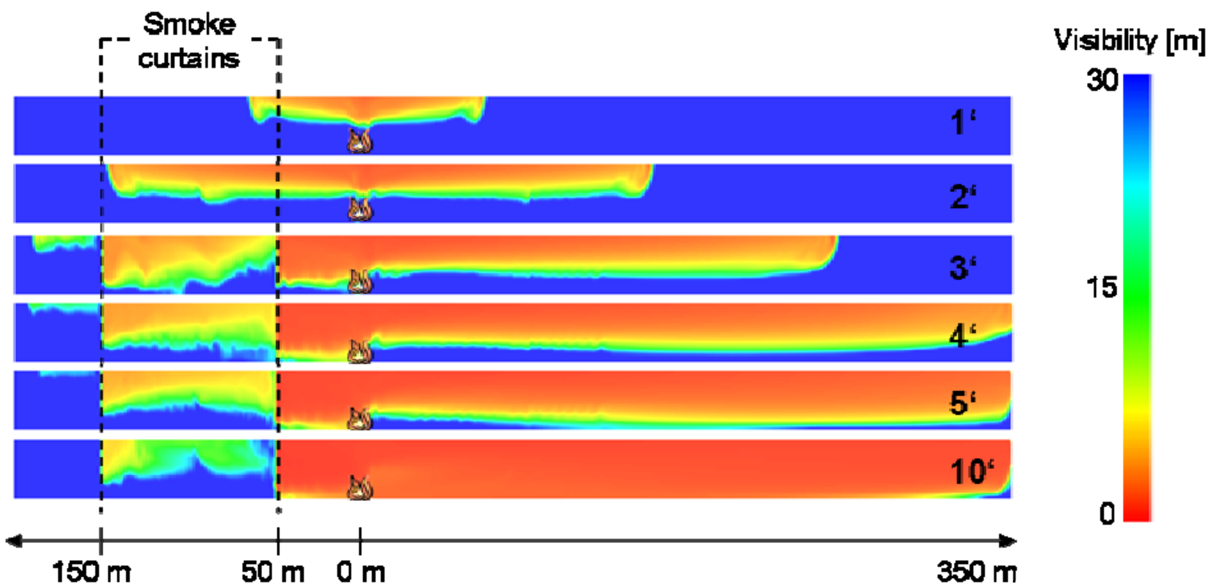

Figure 4: Evolution of visibility conditions for a combined ventilation concept consisting of longitudinal ventilation and smoke curtains (30 MW fire, longitudinal air velocity 0.5 m/s).

Figure 3 presents the simulation results for the purely longitudinal ventilated tunnel. Ventilation was activated 1.5 min after fire ignition, enabling airflow from left to right with a velocity of 1 m/s. As expected, smoke stratification is quite stable and backlayering can not be prevented. Figure 4 illustrates visibility conditions for the same tunnel activating two smoke curtains and longitudinal ventilation with 0.5 m/s for smoke control. Upstream, smoke propagation is effectively limited by the smoke curtains. Downstream, smoke stratification is disturbed by the smoke curtains' recirculation. This significantly worsens the condition between smoke curtain and fire location.

Comparing the two ventilation concepts, purely longitudinal and longitudinal ventilation combined with smoke curtains, a clear advantage for the self rescue phase is not observable for the investigated conditions. Since under these conditions, according to simulation results, smoke stratification is quite stable, this situation does not represent a major problem for the self-rescue phase. However one should be aware that even small disturbances (traffic signs, moving vehicles, lay-bys etc.) could easily lead to a disastrous smoke destratification. Moreover, smoke curtains limit smoke spreading upstream of the incident location. This represents a clear advantage for rescue and intervention forces, which could get close to the fire under favourable conditions and clear view, without change of the ventilation regime.

5. SAFETY ISSUES

The different types of devices lead to specific safety-related issues, which need to be addressed carefully for any application. Only a few key issues are addressed herein.

5.1. Devices control

Clear specifications for the activation of these devices need to be defined. The general goal is a rapid activation in case of fire. Smoke curtains are fairly uncritical, since small vehicles and persons can pass them unhindered. In principle they can be activated very rapidly after fire detection and automatic activation could be envisaged.

Permeable or impermeable full closure systems are far more critical because of the potentially dangerous interactions with moving vehicles. Traffic accidents and damages to the devices could easily results from a sudden, unexpected closure while the traffic is still running. In short tunnels this can be easily prevented by a reasonable waiting time before closure, of the order of 30 to 60 seconds. More generally, a visual verification (CCTV) will be needed before device activation. Additional supporting measures, such as specific signalization (e.g. additional traffic lights, VMP, barriers, possibly loudspeakers) could be necessary for preventing dangerous secondary incidents. Moreover the performance of fully closing devices may drastically deteriorate if vehicles are located under the device.

In general it must be pointed out that the installation of flexible devices will require the installation of additional tunnel equipment, which will increase the overall costs. This is particularly true for short tunnels with natural ventilation, where in most cases only limited equipment is in place, which in many cases does not include e.g. fire detection or CCTV.

5.2. Implications for self-rescue

As a basic principle, all tunnel users must be able to leave the tunnel with their vehicles or attaining safe heavens on foot. Any device which does not allow for a fair chance of rescue to all tunnels users is not acceptable.

Escaping tunnel users need to go through such a device without great efforts. This requirement is entirely satisfied by smoke curtains and excellent solutions can be found for permeable closures, as demonstrated by Aigner’s FIREcurtains. In the case of full closing devices specific solutions are needed, which block smoke and air propagation but allow for person’s passage (e.g. clear marked doors or highly flexible parts of the structure, such as lamellae). Normal “doors” without locks might be possible if smoke tightness is not necessary. Such devices might be fairly complex and expensive and acceptability by the tunnel users will certainly represent an important issue.

5.3. Implications for intervention

Flexible devices being lowered down to create some sort of compartmentalization may cause concentrations of hot smoke and combustion gases behind the device. When approaching to the smoke barrier, fire fighters have to be very careful because the sudden availability of oxygen could cause a dangerous flashover. Smoke barriers, permeable curtains or the accumulated smoke behind them can close the view towards the fire site. On the other hand such devices can also represent an important element of protection for fire fighters (thermal & smoke protection). The intervention conditions at the upstream side of the fire site are generally much better with such a device in place. Protecting devices like smoke curtains can enable fire fighters to approach easier and to use special intervention tactics or means (e.g. use of fire fighting supporting machines like the LUF60 with radio-commanded capabilities to work in front of the fire team and cool down the environment).

6. CONCLUSIONS AND OUTLOOK

A systematic investigation on the use of flexible devices for controlling smoke and fire propagation in road tunnels was carried out. The results showed that flexible devices have a significant potential for contribute solving some safety-relevant issues, which can't be tackled using conventional tunnel equipments, such as ventilation. The following applications were identified as excellent candidates for additional investigations:

- Permeable curtains or smoke barriers for naturally-ventilated tunnels with bidirectional or unidirectional traffic with high risk of congestion (application at the portals or within the tunnel) for reducing the longitudinal air velocity.
- Smoke curtain within longitudinally-ventilated tunnels with bidirectional or unidirectional traffic with high risk of congestion for reducing the critical velocity.
- Permeable curtains in long tunnels with smoke extraction and insufficient control of longitudinal air velocity.

The investigations conducted to date were focused on aerodynamics, smoke propagation and user interaction. Costs and benefits will be investigated next.

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VENTILATION AND DISTANCE OF EMERGENCY EXITS IN STEEP BI-DIRECTIONAL TUNNELS

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ABSTRACT

Experience from occurrences of fires in road tunnels shows that victims are usually found within a few hundred metres of the scene of the incident. The fatal consequences of a fire in a tunnel measuring only a few hundred metres can be comparable to those resulting from a fire in a long tunnel. In tunnels with considerable slope the hazard for tunnel users increases due to rapid smoke dispersion. In addition to an efficient alarm system, successful self-rescue requires tunnel users to be provided with measures that enable them to reach an emergency exit. When it comes to short, steep, bi-directional tunnels, the aerodynamic approach to avoiding or slowing down smoke dispersion reaches its limits. Longitudinal ventilation systems can cause additional danger by worsening visibility conditions. The largely passive safety system consisting of a parallel safety gallery featuring short distances between emergency exits promises great benefits in terms of safety in these particular constructions. But even here, the question is raised as to determining an appropriate distance.

Key words: Tunnel safety, distance of emergency exits, short and steep tunnels

1. INTRODUCTION

In countries with stringent exhaust regulations, even bi-directional tunnels of several kilometres in length can be navigated without requiring any mechanical ventilation. The purpose of built-in tunnel ventilation is often solely to contain vehicle fires. In the past, this has led to the installation of longitudinal ventilation systems in short, bi-directional tunnels even though the systems display only limited suitability for this purpose. Even today, national guidelines recommend the use of longitudinal ventilation for short, bi-directional tunnels despite the generally questionable benefit. The aerodynamic alternative featuring an extraction system is extremely costly, disproportionately so for short tunnels, both in terms of investment and maintenance.

The problem is clearly illustrated in tunnels with considerable slope. The special problems arising from those circumstances have been previously described in [10], [11].

In the following, requirements are outlined and approaches are described for determining the distance of emergency exits.

2. REQUIREMENTS

The requirements are illustrated on the basis of the EU-directive [1] as well as Swiss [2], Austrian [3] and German [4] guidelines and the standard [6].

2.1. Ventilation system

According to various guidelines, the ranges shown in Figure 1 for the primary ventilation systems natural ventilation, longitudinal ventilation and extraction are possible for bi-directional tunnels. Depending on the future traffic situation in a time frame of 10 to 15 years, the higher or the lower limits apply.

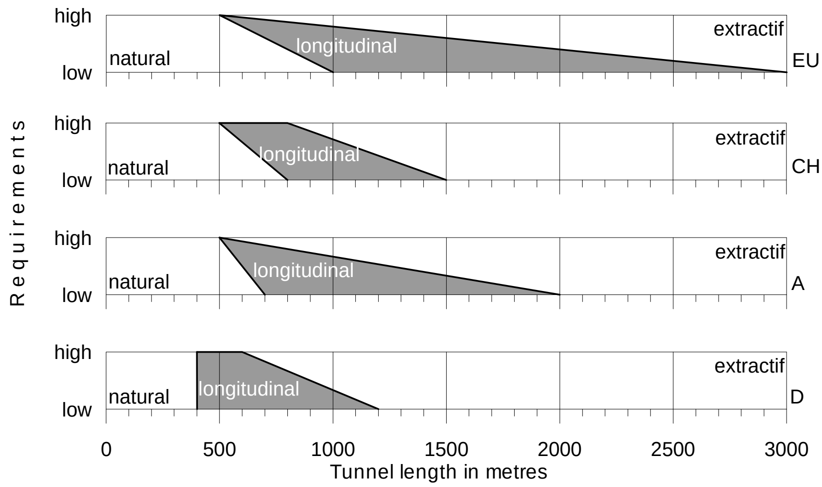

Figure 1: Examples of longitudinal ranges for the use of ventilation systems in bi-directional tunnels

Despite the obvious difference in the specifications at first glance, commonalities can be found:

- The total length of tunnels with natural ventilation lies within the range of the specifications for a maximum distance of emergency exits (section 2.3).
- In tunnels with high requirements, the range with longitudinal ventilation is strongly limited. According to EU and Austrian guidelines, the possibility of longitudinal ventilation is to be ruled out depending on the situation.

2.2. Slope

In accordance with the EU-directive, slopes of greater than 5 % are not permitted in new tunnels unless geographical conditions make it unavoidable. Special measures must be taken for tunnels with a gradient greater than 3 %.

The indications in the Swiss guideline [2] apply to tunnels up to 5 %. For steeper tunnels, separate considerations are required to ensure compliance with required safety standards.

According to the RVS, a detailed risk analysis must be performed for tunnels with slopes greater than 3 %. Special considerations are also necessary as regards smoke dispersion and accidents.

Pursuant to RABT, special measures must be taken for tunnels with a gradient greater than 3 %. Slopes greater than 5 % are to be avoided.

On the basis of aerodynamic calculations and in accordance with the provisions in the guidelines laid out in [1], [3] and [4], a small slope is assumed to be up to 1.5 % and a steep slope starts at 3 %.

2.3. Distance of emergency exits

The EU-directive stipulates a maximum distance of emergency exits of 500 m. To reach the minimum safety standard, the distance of the emergency exits can be reduced.

The distances of emergency exits for tunnels in Switzerland are stipulated in the SIA standard [6]. The data is limited to slopes up to 5 %.

The standard distinguishes between emergency exits in a parallel safety gallery and safety galleries leading directly to the open. This distinction is based on the fact that emergency exits leading directly to the open are generally significantly more cost-intensive in terms of investment and maintenance.

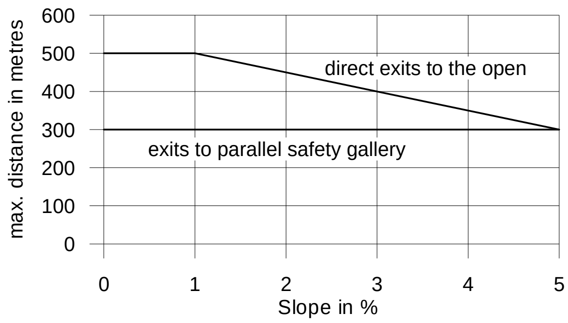

Figure 2: Distance of emergency exits as a function of slope for bi-directional tunnels according to [6]

Statistically speaking, about twice as many accidents per vehicle kilometres occur in bi-directional tunnels compared to tunnels with one-way traffic. For the latter a maximum distance of 300 m between emergency exits is stipulated. The specification for bi-directional tunnels and safety galleries leading directly to the open thus contains a rudimentary cost-benefit trade-off.

According to the Austrian Road Tunnel Safety Law, STSG, [7], and in accordance with the wording of the EU-directive, the maximum distance between emergency exits may not exceed 500 m.

In the RABT, the maximum distance between emergency exits is 300 m.

2.4. Emergency bays

The EU-directive stipulates 150 m as the maximum distance of emergency bays for new tunnels and 250 m for existing tunnels.

For bi-directional tunnels in Switzerland, niches for SOS equipment must be located on alternating sides every 150 m in accordance with the SIA standard. Hydrants are to be placed at the same distance and generally on one side.

In accordance with RVS, the distance of emergency bays may not exceed 150 m. In the case of tunnels in risk classes I and II as well as tunnels not subject to the STSG, the distance may be up to 250 m.

According to RABT, there must be emergency bays on one side of the tunnel at least every 150 m.

The cited guidelines are thus consistent in their stipulation of the 150 m regulatory distance.

2.5. Detection

A video system or automatic fire detection system must be installed in accordance with the EU-directive. There are no requirements pertaining to response times.

The Swiss guideline stipulates that new and refurbished tunnels are to be equipped with smoke detectors. Bi-directional tunnels feature smoke detectors every 100 m. A response time of 60 s is targeted.

In accordance with the RVS, a fire detection facility must be operated in tunnels if a ventilation system is present. When it comes to standard fires, the guideline stipulates response times of 90 s until the alarm at a rate of flow of less than 3 m/s or 150 s at 3 m/s or greater. In addition, a reliable alarm must be guaranteed as early as the smouldering phase. Video analysis for smoke detection is to be considered.

In accordance with RABT, tunnels with a ventilation system must also run a fire detection installation. Thermal line sensors are to be used. Opacity metres are to be comprised for fire detection (pre-alarm). Infrared cameras and suitable video devices may be permitted instead of fire detectors.

The requirements placed on detection systems are considerably different. The effectiveness and reliability of the Swiss approach with smoke detectors has already proven itself.

3. PROBLEM SHORT, STEEP, BI-DIRECTIONAL TUNNELS

In the alpine and prealpine region of the Swiss road network there is a significant number of tunnels with slopes of 3 % and greater. For example, the grade of the tunnels of the Gotthard ramps with a total height difference of 700 m is up to 5 %. The bypass route is the bi-directional A13 motorway via San Bernardino. Its north ramp in particular features a series of short, steep tunnels.

In what follows the authors focus on short, steep tunnels with slopes of 5 % or greater and lengths of up to 1.2 km. The longer Crapteig tunnel, located adjacent to the Viamala, Bärenburg and Rofla tunnels, is also quoted.

Table 1: Examples of bi-directional, steep tunnels

Tunnel	Grade	Length[1)]	ADT 2012	Speed limit	Ventilation	Emergency exits
Viamala	5.3 %	756 m	9'000	80 km/h	Longitudinal	PSG[4)] planned
Bärenburg	6.6 %	1031 m	9'000	80 km/h	Longitudinal	PSG planned
Rofla	5.6 %	1087 m	9'000	80 km/h	Longitudinal	PSG planned
Crapteig	6.5 %	2117 m	9'000	80 km/h	Extraction	PSG planned
Fieud	5.4 %	795 m	4'400[2)]	80 km/h	Longitudinal	Planned (2)
Soliwald[3)]	6.8 %	560 m	6'500	40 km/h	Natural	Planned (2)
Marzoli	11.0 %	870 m	2'700[2)]	80 km/h	Natural	None
Silvaplana	8.3 %	750 m	3'000	60 km/h	Natural	6, Δ = 125 m

1) including short, adjacent galleries
2) only accessible in the summer period
3) curve radius: 75 m
4) PSG: parallel safety gallery

Experience drawn from actual vehicle fires shows that the greatest danger to tunnel users comes from fires resulting from accidents with rapid heat development. In such cases, the fire spreads with smoke and buoyancy development within minutes. The available response time of tunnel users is very short and there is little time for self-rescue including alerting, orientation, reaction and escape. When the slope is significant the sequence is severely accelerated. During the Viamala tunnel fire in 2006, the buoyancy driven flow upward through the tunnel was reported to be around 7 m/s after the longitudinal ventilation was shut down. Some people fleeing to the upper portal on foot were overtaken by the smoke.

4. AERODYNAMIC APPROACH

The advantage of longitudinal ventilation in terms of safety in bi-directional tunnels is limited because the smoke can only move within the tunnel. An advantage comes with a fire near the portal and a rapid ventilation response, when the smoke can be blown out of the portal. Very rapid detection and automatic control are prerequisites in this case but the risk of an inadequate response is considerable.

As the slope increases, the buoyancy drastically reduces the available time for a useful ventilation response in a short bi-directional tunnel. In addition, the installable thrust is limited [10] in short tunnels. Smoke detectors are to be used to avoid operating jet fans in smoky sections, especially in tunnels without extraction.

Calculations have shown that when it comes to the geometry of the Fieud, Viamala, Rofla and Bärenburg tunnels, longitudinal ventilation no longer meets the requirements of the guideline [2]. However, jet fans installed by the upper portal might eject smoke developing near the lower portal. This decreases the effective buoyancy in the tunnel, gaining time for self-rescue. In the event of a powerful fire near the lower portal, these fans can slow down the upward flow. However, we must assume that even with the indirect effect of the jet fans on the smoke-filled zone, any existing smoke layer would be destroyed.

The effect of a decrease in the longitudinal flow can also be achieved using adjustable curtains (see [12]).

Systems featuring smoke extraction by way of adjustable dampers have been proven in steep tunnels (Gotschna tunnel, length 4 km, slope 5 %). To control smoke dispersion, sufficient thrust and large exhaust air flows have to be installed. When it comes to short tunnels, the issues of feasibility and suitability are raised.

5. RISK ANALYSIS AND STANDARD

Risk analyses are a useful tool for determining a balanced use of limited funds. In accordance with the requirement in the EU-directive, a number of national methods were developed and now serve as a basis for the equipping of safety installations. The EU's objective of defining a standardised method has not yet been met though.

Different fundamental questions arise when applying risk analyses and the ensuing determination of the cost effectiveness of individual measures. Examples include:

- Object-specific adaptation
  On the one hand, a number of predetermined criteria are assessed on an object-specific basis and then integrated into the model. On the other hand, specific features hardly fit the rigid framework. Examples of this include the curviness and the traffic character: It can be assumed that the curviness of the tunnel was the crucial factor in the fatal event in the Viamala tunnel in 2006. On tourist routes with a high percentage of coaches and fully occupied cars (e.g. families with children) it must be assumed that self-rescue is difficult. Including such features is not appropriate for the method as the homogeneity and required comparability are then lost.
- Modelling
  Modelling the sequence of events during an incident often depicts reality in an optimistic way. If, in addition, the same methods are applied as were used, for example, when designing the ventilation, the result may be idealised and inappropriate. Risks and thus the consequences of incidents may be underestimated.
- Differences in the assessment of criteria
  An example would be the amount assigned to a fatality when calculating the cost effectiveness of a specific safety measure. In different analyses, values in the range of a factor of 3 were used. This directly affects the result.

Up until a few years ago, safety devices were dimensioned exclusively according to standard specifications. Following the fire in the Gotthard tunnel in 2001 Switzerland formulated the arguable somewhat optimistic policy that in the case of an incident every tunnel user should be given a *fair chance* to get himself to a safe area. In this case it is fairer to use the risk-based method which identifies that in certain scenarios fatalities are inevitable. The standard-oriented approaches applied already contained certain risk-based approaches. In hindsight it is clear that the cost-benefit ratio was not optimal and often still is not. In our opinion, the objective must be to use cost-benefit analyses to specify standards that approach the intended purpose and will be appropriately applied in an object-specific manner. In conjunction with risk assessments, this will enable more efficient use of the limited funds available. However, this process will still take some time. It is important to understand that optimum results cannot be achieved by using standard *or* risk-based methods alone but rather by using both methods together. The PIARC Technical Committee C4, Working Group 4 [13] also arrived at this consensus.

6. PRAGMATIC APPROACH

When constructing new tunnels in Switzerland, the specifications outlined in the publication of the SIA standard in 2004 are observed as regards the distance of the emergency exits (see Figure 2). 300 m is used as the standard distance between emergency exits. For the short, steep bi-directional tunnels now in need of retrofitting, deviations from this standard solution will need to be made.

6.1. Principles

The proposed pragmatic approach for steep tunnels is based on the following principles:

- Comparable safety standard to a tunnel with a slope of 3 % (section 2.2)
- Standardised distances which are easy for tunnel users to understand and remember
- Coordination of emergency exits with other safety devices as far as practicable
- Possibility to deviate from the specific requirements of the guideline when designing the ventilation
- Quick detection for signalisation, alarm and other reflexes

6.2. Viamala, Rofla and Bärenburg tunnels with parallel safety galleries

Parallel safety galleries are planned for the Viamala, Rofla and Bärenburg tunnels as well as for the longer Crapteig tunnel. Using so-called scenario analyses based on a tunnel in compliance with the guideline at a 5 % slope, a maximum distance of 260 m between emergency exits was determined for these tunnels. The cost of constructing the short links between the parallel safety gallery and the tunnel is approximately 5 % of the total cost of constructing the parallel safety gallery.

Based on the principles outlined in section 6.1, which correspond to the specifications in the EU-directive (section 2.3), the authors recommend aiming for 150 m between exits in these tunnels. The results are summarised in Table 2.

Table 2: Effect of the recommended approach on the distance of emergency exits and on the cost of the parallel safety galleries

	Original planning		Recommendation		Additional cost kCHF, %
Tunnel	Emergency exits	Distance	Emergency exits	Distance	
Viamala	2	252 m	4	150 m	500, +5 %
Bärenburg	3	258 m	6	150 m	750, +5 %
Rofla	4	217 m	6	150 m	500, +3 %

The three tunnels feature longitudinal ventilation and jet fans distributed over the length of the tunnel. A reassessment of these ventilations should be carried out separately from the considerations regarding the emergency exits.

6.3. Costoni di Fieud tunnel with safety gallery leading directly to the open

Another study, which applied the BAST method for safety assessment [14] to the Fieud tunnel, also arrived at a distance of approximately 250 m. However, the basic conditions are extremely different in terms of traffic for this tunnel on top of Gotthard Pass (open only in the summer period, hypothetical increase in traffic following refurbishment of Gotthard road tunnel, coach traffic, but no further heavy-duty traffic) and safety galleries leading directly to the open. Based on BAST, the sum of CHF 15 million was used for a fatality. The result was an additional emergency exit leading directly to the open and the renouncement on the existing, insufficient longitudinal ventilation.

Including other accompanying and in part temporary safety measures, the recommended distance of the two emergency exits seems justifiable.

6.4. Crapteig tunnel with extraction

The ventilation of the Crapteig tunnel will be refurbished and equipped with a powerful extraction system in compliance with the guidelines. In addition, a 2 km long parallel safety gallery will be constructed. The costs of these measures are in total around CHF 45 million.

The construction is found on the San Bernardino route with the Viamala, Rofla and Bärenburg tunnels. Despite the powerful ventilation that will be installed in the very steep tunnel Crapteig, arguments for homogeneity and understandability of the distances of emergency exits should still be highlighted.

Table 3: Effect of the recommended approach on the distance of emergency exits and on the cost of the parallel safety gallery

	Original planning		Recommendation		Additional cost kCHF, %
Tunnel	Emergency exits	Distance	Emergency exits	Distance	
Viamala	8	241 m	13	150 m	1250, +4 %

7. CONCLUSIONS

Based on the concerns described and in agreement with the guidelines of the EU, Austria and Germany, the authors recommend that the distance between emergency exits in short, steep, bi-directional tunnels with a slope above 5 % and with a length up to 1200 metres should be usually 150 m. By considering remarkable, object-specific features other distances might result on behalf of risk-analysis approaches. For constructions requiring long safety galleries leading directly to the open, larger distances may be permitted. Suitable measures should be used to observe the safety standard of a tunnel with 3 % slope and a distance between emergency exits of 300 metres.

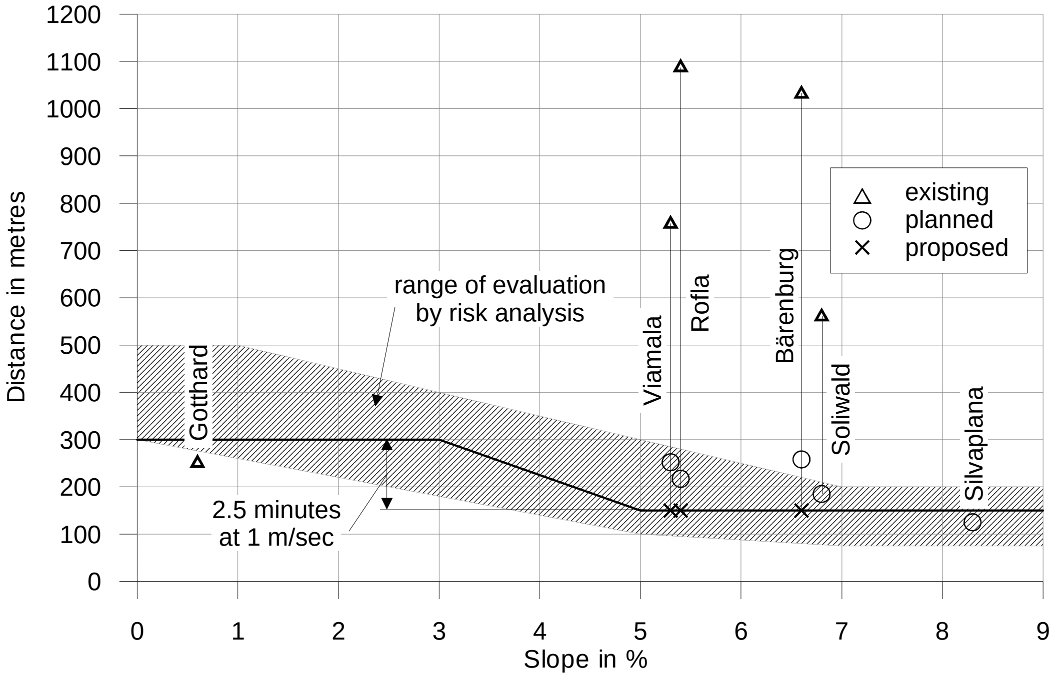

Figure 3: Proposed "guideline" and range for risk analysis for the distance between emergency exits in tunnels with bi-directional traffic displaying the described tunnels

The design of the systems and assessment of safety should take into consideration the particular, object-specific features of the tunnel.

With special tunnel geometries in particular, designs adhering to guideline specifications, standards or cost-benefit analyses should be critically questioned, justified and adapted if necessary. The generally formulated requirements should be used as a guiding, not hindering force for the art of engineering. Appropriate safety and economic solutions take precedence over pure legal considerations following the letter of the requirements.

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