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- New Developments in Tunnel Safety –

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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 great success of the 2002 conference led to follow up meetings being organized biennial.
Since 2002 the conference has been accompanied by an exhibition. The growing interest in such exhibitions has since forced us to leave the confines of University campus and move to the roomier facilities of the trade fair centre.
Another change concerns the conference topics. While the first conferences were strongly influenced by the tunnel incidents in the late 90'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 local 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.
Austria has a lot of tunnels crossing the Alps. They have several common features: all are quite long, have a complex ventilation system, and have only one bore. Many of the older 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, for example, the characteristics of the first tube, the location of existing ventilation shafts, escape routes, etc. 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 name of Univ.- Prof. Dr. Karl Pucher is strongly associated with tunnels in the Austrian Alps as well as all over the world. He was involved in much of their design, as well as in consultancy work related to ventilation and safety problems. Unfortunately, Karl Pucher, having reached his 76th year of life, passed away in March 2008. His work focussed strongly on the development of new ideas and approaches in ventilation and fire safety as well as on defining appropriate guidelines at national and international levels. Karl was not only a brilliant scientist and engineer, he was also a man who was willing to put people first. All this can be seen in the condolatory statements submitted by colleagues and friends. A small selection of such statements is given below.

The death of Karl Pucher not only means that we have all lost an outstanding expert in tunnel ventilation, it also means that I have lost a dear friend. Karl pioneered the development of tunnel ventilation at our institute. A major strength here was his ability to apply theoretical knowledge of fluid mechanics to practical settings. He was very much liked by both colleagues and students. He supervised many doctoral students, some of whom have since become valuable members of our institute and who continue to develop his work. Our institute owes Karl Pucher a major debt of gratitude (Rudolf Pischinger, Austria).

Karl Pucher was for many years a significant figure (factor) in the global efforts to understand the technical issues surrounding the application of tunnel ventilation to smoke control in the world's road tunnels. I worked with Karl, on PIARC activities related to road tunnel smoke control, beginning over 15 years ago and found him to have outstanding technical skills. Besides being a well recognised expert on tunnel ventilation and tunnel smoke control Karl was always the consummate gentleman (Art Bendelius, USA).

With Karl's passing we have lost one of the "grand old men" of tunnel ventilation whose inputs and innovation form the basis of our profession as it is today. Things we all take for granted were thought of and developed by those like Karl. I had the pleasure of being involved in a few projects with Karl both before and after his retirement and his contributions were, as ever, vital. His advice was always free and open and his enthusiasm for his subject was infectious as anybody who worked with him will know. Goodbye Karl, it was an honour to have known you (John Day, Switzerland).

I'd like to express my very deepest regret at the passing away of Professor Karl Pucher. I learned a tremendous amount from him concerning aerodynamic theory and tunnel ventilation in recent decades. It pains me to realize that we will no longer be able to meet at any place in this world. Not only for me, but also for many other Japanese engineers working in the field of tunnel ventilation, Professor Pucher was a highly respected European teacher.
My deepest regrets (Yoshikazu OTA; Japan).

Professor Karl Pucher will be fondly remembered within the Australian tunnel ventilation fraternity for his scholarly works, practical eye and gentlemanly manner. Only now is the world recognizing the importance of his early ventilation efficiency work while his experiments in relation to vehicle exhaust particle agglomeration remain even more important today than when they were first published. But aside from his technical excellence he was also honourable in his dealings, amicable in his disposition and willing to share his thoughts and experiences. He was regarded and will be remembered as a leader in his field and a model to young engineers (Arnold Dix; Australia).

The recent loss of our colleague and friend Karl Pucher was a matter of great sadness for us. We very much treasured his substantial knowledge in all fields of ventilation and fire safety in traffic tunnels. His ability to remain calm and collegial, even during heated moments of critical argumentation was much admired. We also appreciated the many occasions when we could simply be together and talk about general topics of daily life. We like to remember all his sound presentations and explanations of the equipment in the Plabutsch Tunnel and in other major tunnel projects in Austria and other parts of the world. I personally met Karl Pucher for the last time two years ago on the occasion of the 3rd international conference on tunnel safety and ventilation, and we made a private excursion into the wonderful surroundings of Graz to enjoy the excellent Styrian wine and food. We will never forget our friend Karl Pucher and will continue to hold his memory in the highest esteem (Alfred Haack, Germany).

I am grieved by the death of Professor Pucher. I first met Karl Pucher at the Tunnel Committee of PIARC in Marrakech (1991). It is with pleasure that I remember the very good and successful work, he performed in the field of ventilation and vehicle emissions in road tunnels, particularly that undertaken for the international community of PIARC.
I was honoured by his friendship and will retain very good memories of Professor Pucher and of the work we did together (Vincenzo Ferro, Italy).

The life and work of Professor Karl Pucher were very closely tied to the topic of ventilation in road tunnels. His field of activity covered fundamental research on road tunnel planning with respect to both basic operational considerations as well as emergencies, i.e. fire. He was engaged in the first fire tests in the Zwenberg Tunnel, and in the planning and operational activities for the first long, cross-alpine tunnels in Austria. He was also involved in developments to improve transverse ventilation systems by using exhaust dampers for extraction . As a result of his rich experience Professor Karl Pucher played a leading role in the drafting of official standards and regulations concerning the planning of road tunnel ventilation systems. Such regulations still remain the basis for both Austrian and international tunnel projects. We at AG Tunnelbau der Forschungsgesellschaft Straße-Schiene-Verkehr, thank Professor Karl Pucher for all his work and will continue to hold him in fond memory. (Rudolf Hörhan, Austria).

With the above in mind, suffice it to say that many of the presentations in the present conference continue to follow the paths laid down by the work of Karl Pucher. As a sign of our respect, and in order to honour his memory, we devote the 4th Conference of Tunnel Ventilation and Safety to him.

Peter J. Sturm Helmut Eichlseder
Graz, April 2008

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"TUNNEL SAFETY AND VENTILATION"
Graz, April 21 – 23, 2008

POSTERPRESENTATIONS

EARLY EXPERIENCE WITH THE ROAD TUNNEL SAFETY LAW

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Innovation and Technology

ABSTRACT

This report deals with the application of the EU Directive 2004/54/EC in Austria under the Road Tunnel Safety Law. Appropriated procedures for the approval of tunnel preliminary drafts and the putting into operation of tunnels guarantee that the minimum requirements are fulfilled according to the Road Tunnel Safety Law 54/2006 and the technical state-of-the art defined in the Austrian code for the planning and operation of tunnels. Existing tunnels were subject to a first evaluation the data from which together with the safety documentation of the respective tunnel served as a basis for the preparation of a report discussing the level of the fulfilment for the requirements set by the Road Tunnel Safety Law. In the meantime safety reports have been prepared for all motorway and expressway tunnels longer than 500m whether they are in the planning stage, under construction or in operation.

1. INTRODUCTION

The Austrian Road Tunnel Safety Law STSG 54/2006 has been in force since May 2006 and represents an important basis for the planning, construction and maintenance of Austrian roadway tunnels. The implementation of this law is based on the EU Directive 2004/54/EG issued by the European Parliament and the Council on 29 April 2004 which deals with the minimum requirements for the safety of tunnels within the Trans-European roadway network aiming at setting standardised minimum requirements for the safety of European road tunnels. Hence, the guideline contains both regulations regarding minimum requirements for safety facilities and regulations regarding the unification of the design and the providing of notes and information for all European road tunnels in order to unify and simplify the necessary procedures for tunnel users. This concerns primarily facilities serving the purpose of self-rescue, such as indication signs for escape routes, lay bays, emergency phones or fire extinguishers. In Austria the use of these traffic and emergency signs is regulated in the amendment of the road traffic law (STVO) and the road tunnel safety law.

Minimum safety requirements for tunnels longer than 500m are defined by a set of minimum requirement for safety design equipment, by general safety parameters and by operation procedure specifications. In cases of special tunnel characteristics a risk analysis ought to be carried out to establish whether additional safety measures or supplementary safety equipment are necessary to ensure an equivalent safety level.
The safety of a tunnel not only depends on the safety equipment used but also on operational aspects, on the initial and continuing training of operational staff, and road use behaviour. That is the reason why the law for tunnel safety in Austria, in accordance with the related EU Directive, provides a set of organisational measures and procedures to ensure the uniform safety of tunnels.

2. PROCEDURES FOLLOWING THE AUSTRIAN ROAD TUNNEL SAFETY LAW

The Austrian Road Tunnel Safety Law provides several protocols to set minimum safety requirements for tunnels during the planning and operational stage. Regarding the Austrian law, procedures are carried out for the approval of the design before any construction work

begins and for the approval of the tunnel before opening the roadway for public use. These procedures also apply in cases of substantial modification work on existing tunnels, as this may significantly alter part of the constituent components from the safety documentation. When the procedures following the Austrian law for tunnel safety are finished a decision document is prepared which includes conditions and penalties if necessary.
Concerning the EU Directive, special attention was given to the compliance of existing tunnels with the specified requirements set by the Directive within a target date which is set for Austria as 30 April 2019, as Austria is home to a high percentage of tunnels in the Trans-European roadway network. The European Commission required a report of the plan for the refurbishment of all existing tunnels with regard to the EU Directive before 30 April 2007. To comply with these requirements, last year the Austrian administrative authority carried out the first assessment of 59 motorway and expressway tunnels longer than 500m, following the Austrian law for tunnel safety. The report was very thoroughly prepared with review of safety documentation and inspection of each tunnel.

In Austria the implementation of safety requirements focuses mainly on the construction of the second tunnel tube, which has been and will be managed completely by the ASFINAG instead of the very expensive measure. Figure 1 shows a list of the tunnels on motorways and expressways in Austria, which are already built, are under construction or are in the planning stage.

Tunnel	Road	Length of the Tunnel [m]	Second Tube opening date /status
Selzthal	A09	958	04/2000
Gräbern	A02	2145	10/2003
Amberg	A14	2967	12/2003
Plabutsch	A09	10085	01/2004
Herzogberg	A02	1956	06/2006
Assingberg	A02	251	01/2007
Lainberg	A09	2208	02/2008
Ganzstein	S06	2100	08/2008
Tauern	A10	6546	under construction
Katschberg	A10	5418	under construction
Roppen	A12	5100	under construction
Pfänder	A14	6700	under construction
Bosruck	A09	5425	planning stage
Perjen	S16	2990	planning stage
Total		54.849	

Figure 1: Roadway tunnels on motorways and expressways with an added second tunnel tube

Furthermore, a main measure of the implementation work is the construction of emergency exits at a maximum distance of 500m, normally connected to an emergency tunnel. In the past many tunnels, especially bidirectional tunnels with a transverse ventilation system, have had no emergency exits.

As after more than 20 years, most electric equipment in the tunnel has normally reached its maximum functional lifespan, the corrective maintenance and upgrading to the technical-state-of-the-art of the first tunnel tube leads to significant extra costs in addition to the high costs for the construction of the second tunnel tube.

3. SAFETY DOCUMENTATION

The safety assessment of a road tunnel according to the Austrian law for tunnel safety is based specifically on the safety documentation of the tunnel in question. The requirements of the safety documentation are different depending on the respective project stage. In the design stage, the safety documentation focuses on the description of infrastructure and traffic, whereas during the operation stage the usage aspects gain importance. According to the state of ongoing project development, the information grows in detail. The safety documentation should be comprised of living documents which are continuously developed und upgraded, including changes in tunnel infrastructure and traffic data, as well as important findings based on experience.

Since then, safety documentation was prepared for each tunnel longer than 500m in the Austrian motorway network, which contains all safety-related information about the respective tunnel.

Recommendations for the content of safety documentation have been prepared by ILF Engineering Consultants (Linz) and consist of the following main topics:

- Introduction
- Description of the position of the tunnel in relation to the roadway network
- Description of the tunnel infrastructure and access to tunnel (lanes, cross sections, gradients, emergency exits, etc.)
- Description of the traffic situation, including the transport of dangerous goods and information on tunnel operation
- Specific hazard investigation: checking the safety parameters complying with the requirements of the Austrian law titled “Safety in Road Tunnels”
- Risk analysis according to the Austrian law titled “Safety in Road Tunnels” shall be carried out if the tunnel has special characteristics for defined safety parameters
- Description of additional measures or supplementary equipment, if they are necessary to ensure the level of tunnel safety
- Organisation of and resources for operation and maintenance
- Emergency response plan
- Feedback from experience, especially in the operational stage

The specific risk analysis is represented in the form of a table in which the singular points of the infrastructure-related measures according to the Road Tunnel Safety Law are listed. This table includes a column in which, using different colours, it is indicated whether the requirements of the respective criteria are fulfilled, not fulfilled or not applicable. If a safety parameter is not fulfilled, alternative measures must be proposed and evaluated. Additionally, it must be defined if these alternative measures are of preventive or damage limiting character and to what extent they contribute to risk minimization. Preventive alternative measures are for example increase of light intensity, reduction of maximum allowable speed and continuous observation of speed limit adherence. Damage limiting measures are the taking into account of the possibility of large fire loads, especially in case of higher large vehicle volumes as well as additional measures regarding the alarm and emergency plans.

Additionally the Austrian Road Tunnel Safety law requires an expert’s report regarding all safety parameters and all additional measures to ensure the compliance with the Austrian Road Tunnel Safety law incorporating the state-of-the-art of tunnel safety.

The experts should evaluate the plausibility and the interconnectedness of all safety relevant measures. In doing this, the specific risks of the respective tunnel must be demonstrated and discussed. According to law the safety officer must also prepare a statement regarding the safety of the tunnel in question, as he should know all details of and events occurring in the tunnel.
The safety standard for most Austrian tunnel structures is far higher than that required by the Road Tunnel Safety Law, as many details of tunnel design representing the technical-state-of-the-art are set by the Austrian Guidelines. As example one can refer to the high requirements for automatic processes as used for fire detection, ventilation control and emergency management, which significantly contribute to risk minimization in case of an incident.

4. RISK ANALYSIS

The EU Directive on road tunnel safety requires every member state to develop a method for a risk analysis at the national level. The tunnel risk model TuRisMo has already been completed in Austria and the description of this model, including some case studies, has been published in [1] of the Austrian Association for Research on Road-Rail-Transport. A report on the Austrian model has been presented at the 3rd Symposium in Graz from 15 - 17 May 2006.

The TuRisMo focuses on frequently occurring mechanical incidents and also fire incidents involving small and medium fires. The model can be used for a wide variety of different applications, such as safety assessment of new or existing tunnels, support of the decision-making process for selection of safety measures (new tunnels) or upgrading measures for existing tunnels, including the defining of priorities for upgrade measures, etc.

The risk analysis aims to investigate the risk for tunnel users (personal injury and fatalities). As a relevant reference value, the societal risk (fatalities per year) of the tunnel is calculated by combining incident frequencies and related values for defined scenarios in the event tree. The estimation of the probabilities in the event tree comes from statistical data, experience, the estimation of the related values on statistical data of mechanical incidents and simulations of fire scenarios.
The development of a risk assessment for the transport of dangerous goods is nearly complete. See section 5.

The EU Directive and the Austrian Road Tunnel Safety law allows limited exemptions for several requirements, on the condition that the same safety level can be gained via alternative risk reduction measures. For this reason, the Austrian TuRisMo provides a relative comparison of the risk of the tunnel investigated with the risk of a reference tunnel. A tunnel of the same length, type and traffic characteristic which fully complies with the minimum safety requirements per the “Austrian Road Tunnel Safety” regulation is used as a reference case. The mismatches identified can be assessed in terms of risk. Alternative measures to offset the exceptions can be evaluated; the risk reducing effects of the alternative safety measures can be investigated in a similar way. The assessment of safety measures can then be completed carrying out a cost-effectiveness analysis.

The method has been successfully applied for several tunnels in the Austrian motorway network having special characteristics.

On the basis of further tunnel incident data collection, evaluations of different scenarios can and will also be carried out in the future with regard to the event tree and damage extent analysis.

5. ASSESSMENT OF DANGEROUS GOODS TRANSPORT

With regard to the Road Tunnel Safety Law in Austria and the EC Directive 2004/54/EC, risks of the transport of dangerous goods (DG) in road tunnels are to be thoroughly examined within the scope of tunnel safety documentation.

In Austria these investigations have progressed quite far. Today experts are in the stage of detailed evaluation and are developing a multistage strategy to assess the risk of DG transport in roadway tunnels. These investigations are carried out using the DG QRAM model of OECD/PIARC.

Early in the investigations, it was necessary to gather very precise data about the amount and kind of the DG transported - hence elevations of DG transports were carried out in 12 areas from different main Austrian traffic routes. Summarizing all investigations of DG transports and analysing them according to ADR-classes, a subdivision was generated as shown in Fig. 2.

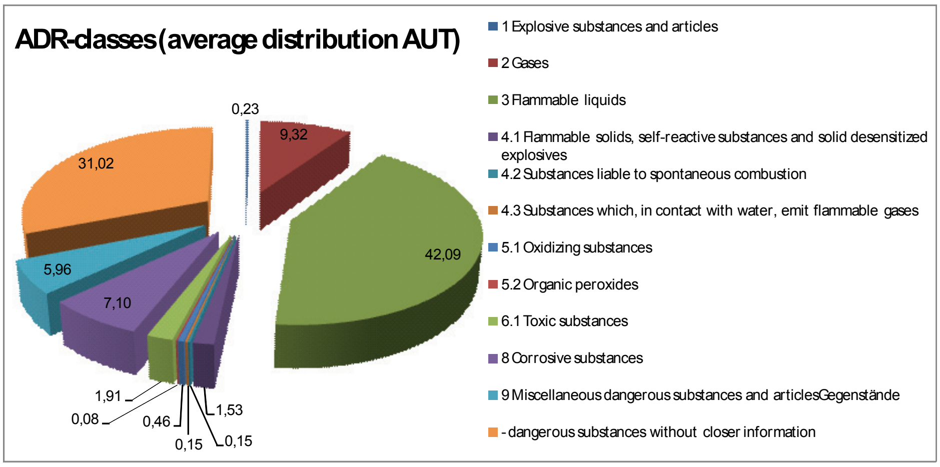

Figure 2: Allocation danger good transports according to ADR-classes (AUT)

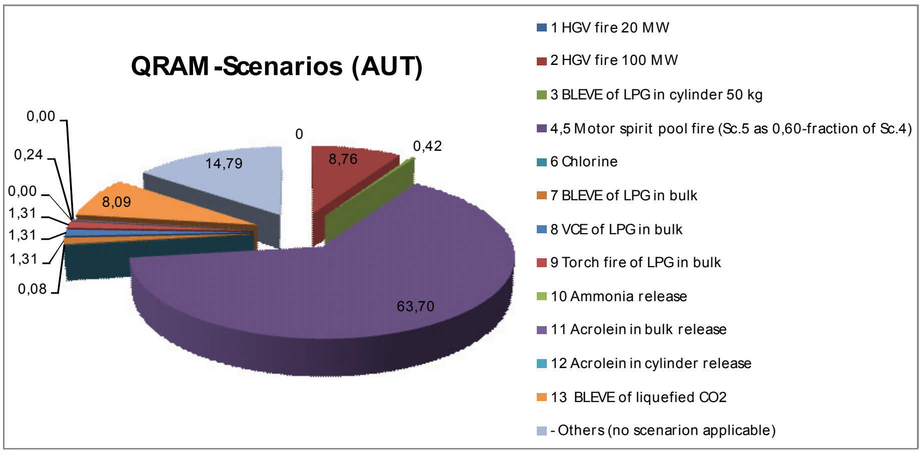

Figure 3: Allocation to the accident scenarios according to DG QRAM model

Consequently, the allocation of investigated DG had to be assigned to the predefined accident scenarios (using the QRAM-model) based on hazard numbers, available lists or complementary searches of the specific material qualities (see Fig. 3).

With the evaluated data from each cross section a sensitivity investigation was carried out via application of DG-QRAM. A comparable reference tunnel (same direction traffic, length 1,500 m, 20,000 vehicles/day) was used to try to ascertain which DG distribution or which accident scenarios have the greatest influence on the result of the risk analysis (i.e. expected value). In addition it was checked as to whether a standardized DG distribution is applicable for a simple procedure for risk evaluation in Austria.

Today a whole strategy for risk evaluation of DG transports in roadway tunnels is in the final stages of preparation. As a first step in this strategy, a simplified assessment procedure had to be implemented. Thus a systematic calculation of the risks for specifically chosen reference tunnels began. In addition to the derivation of a standardized DG distribution for Austria, the different possible input data variants (tunnel length, ventilation system, kind and strength of traffic, share of large vehicles, etc.) were taken into account.

By determining agreed-on relevance criteria (e.g. expected value, F/N-curve) a first assessment can be made for any tunnel referring to the results of the systematic calculations for the investigated reference tunnels. If the defined flag criteria are met, more detailed investigations of the tunnel concerned must be undertaken.

The recent assessment strategy for a simple procedure to assess DG transport in road tunnels should be applied as a practical tool for use in reaching compliance with the EU Directive 2004/54/EC and the requirements given by the ADR.

6. COLLECTION AND ANALYSIS OF INCIDENTS

Collection and analysis of events are essential for the risk assessment of a tunnel and for the improvement of safety measures. Due to the great number of tunnels in Austria and the depth of accident data, the TiRisMo has been done based on Austrian data and experience.
Data was collected from accidents involving personal injury in motorway and expressway tunnels for the years 1999–2003. The collection and analysis of incidents is now also completed for incidents occurring between 2004 and 2007. Relevant data for incidents in tunnels between 2004 and 2005 has been collected and an in-depth analysis has been carried out using police and court files. For the period from 2006 to 2007 data from the newly developed tunnel database has had to be corrected inserting official accident statistics.

The EU Directive requires reports on fires in tunnels and on accidents which clearly affect the safety of road users in tunnels, and on the frequency and causes of such incidents. For this reason, the Ministry of Transport, Innovation and Technology commissioned the Austrian Road Safety Board to develop a tunnel incident database. The ASFINAG provided the company server for this database and personnel for data entry in the tunnel control centers. The tunnel incident database contains data regarding tunnels on motorways and expressways as well as data for reportable events in tunnels. The data have been recorded since 1/1/2006 in the tunnel control centers, according to the requirements of the EU Directive and with respect to future research.

Accidents involving personal injury in tunnels are analysed according to point of origin, accident type and cause. The investigation by the Austrian Road Safety Board has shown that in tunnels with bi-directional and unidirectional traffic, the highest accident rate is in the portal area. In tunnels with bi-directional traffic, the accident rate in the areas just outside the entrance is higher than in the interior zone of the tunnel. For this reason, the new Austrian database includes the following detailed specification for incident locations:

- Area within 250 m outside the portal
- Entrance area (0m to 150m inside tunnel)
- Portal
- Interior zone (more than 150 m inside the tunnel)
- Area more than 250m outside the portal

Figure 4 shows the personal injury accident rate in the different zones outside and inside a tunnel

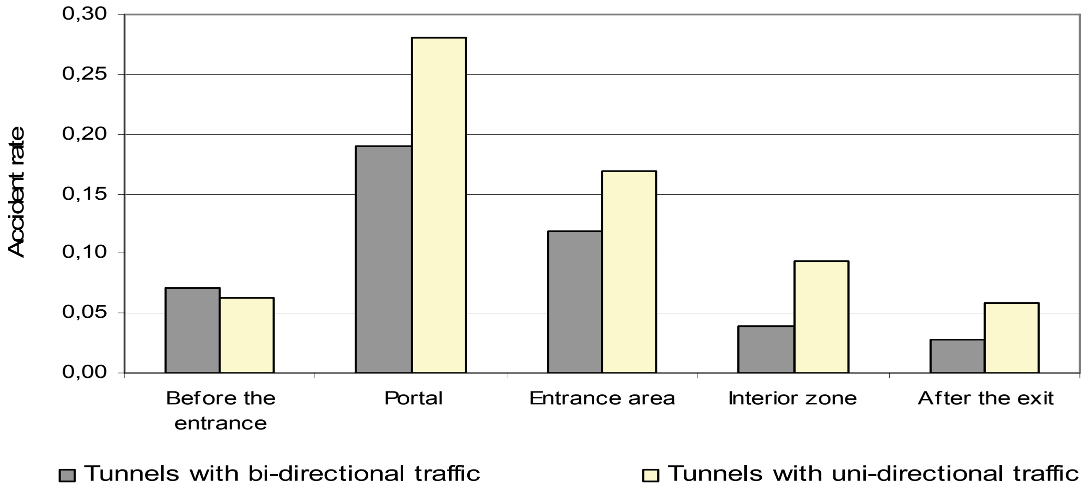

Figure 4: Personal injury accident rate [PIA/1 million vehicle-kilometres] in tunnels with bi-directional traffic and unidirectional traffic by point of origin of the accident (1999-2007)

Accidents involving damage to property and without personal injury are also recorded in the new Austrian database because they have a high impact on road safety. The trends in future incident rates can only be analysed once data become available.

Over the last two years, a total of 130 accidents involving personal injury, 334 accidents involving damage to property and 16 fires occurred in Austrian tunnels on motorways and expressways. The highest share of all incidents in tunnels are accidents involving damage to property (69.7%), followed by 27.1% accidents involving personal injury. Fires are comparatively rare in tunnels.

7. CONCLUSIONS

The application of the Road Tunnel Safety Law allows onto compare the risks of different roadway tunnels in a new way. It is based on a safety report containing a description of all safety-relevant parameters as well as a risk analysis and evaluation. Hence, both all infrastructure-related and operation-related measures may be evaluated with regard to their risk minimizing effects and planned appropriately. This reviewing method is completely new with respect to the arrangements of safety equipment and may lead to a new methodology in this field. However, this is realizable only under the precondition that the risk-oriented evaluation, which contrasts with the current exclusively prescriptive view, is widely applied and accepted.

8. REFERENCES

[1] RVS 09.03.11 Methodology of Risk-Analysis (2008)

EVOLVING NEEDS OF TUNNEL VENTILATION IN A CHANGING WORLD

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ABSTRACT

The role of road-tunnel ventilation has changed during the last decades. While in former years tunnel ventilation was responsible for providing an acceptable environment for tunnel users passing through the tunnel during normal operation conditions [30], nowadays the support of rescue conditions during a fire is dominating. The introduction of the fire case into the ventilation design resulted in increased demands and led to a remarkably increase in extraction volumes and ventilation powers. Ventilation control which in former years focused on maintaining the in-tunnel air quality has now become a very complex tool in order to fulfil the requirements for supporting self-rescue possibilities in case of an incident.

A second issue, which becomes increasingly important, is the environmental impact caused by the polluted tunnel air. Portals and air exchange stations in built-up areas call for intelligent control of the air flows and even in some special cases for exhaust-air treatment systems. For tunnels with severe air-quality constraints at the tunnel portals, significant ventilation power is required.

Keywords: road tunnels, ventilation design

1. INTRODUCTION

Tunnels form an enclosed compartment in which an environment has to be provided for tunnel users in order to allow for a safe and secure passage. These demands result in two prime requirements, namely:

- ensuring adequate air quality during the passage in normal operation, and
- improve egress conditions in case of fire.

While the first aspect has been the focus of ventilation design since pollutant emissions became a major issue in tunnels, the latter was initially treated with lower priority but was brought to attention in the 1960’s [20], 70’s [21] and 80’s [6], [29]. Moreover, this became a major topic after the fire disaster in Montblanc and Tauern road tunnels.

Although also considered in the 1980ies ([6], [29]), during the last decades focus has intensified on the impact of the polluted tunnel air on the environment. Especially in major cities, road traffic has been diverged using road tunnels in order to improve the quality of life within the cities and keeping traffic moving at a sufficient and functional level. However, tunnels have portals and sometimes ventilation shafts. At such locations, pollutant emissions might result in air-quality problems, which call for a specific design of the ventilation system, air-exchange stations and sometimes even using filtration systems.

The primary focus on managing air quality inside the tunnel has been replaced by the demands on fire safety and environmental concerns.

2. DESIGN PARAMETERS

2.1. In-tunnel air quality

In-tunnel air quality is responsible for ensuring a safe travel through the tunnel. Conventionally, this safety aspect is ensured by controlling two airborne pollutants. One represents the influence on the human health and the other one the visibility in the tunnel. For a long time, carbon monoxide (CO) was considered to be the main pollutant to be controlled in a tunnel in order to avoid health problems. Emissions of particles from vehicle exhaust and road abrasion (as well as tyre and break wear) restrict visibility inside the tunnel. In order to provide sufficient visual range, ventilation has to provide the required dilution with fresh air. While in former years, the fresh-air requirement was driven by the dilution needed to keep the CO concentration at acceptable levels, nowadays in most cases for tunnels at lower altitudes, visibility is the more stringent parameter. This is due to the strong reduction of CO in vehicle exhaust. On one hand, particle emissions per vehicle have been reduced but on the other hand, the number of diesel passenger cars has increased in many countries. At present, the consideration of the so called non-exhaust particles originating from road-surface abrasion, tyre and break wear as well as caused by dirt carried into the tunnel is more critical in terms of particle emissions. These non-exhaust particles are emitted by all vehicles and not only by diesel cars. Nowadays, non-exhaust particles are responsible for the majority of the fresh-air dilution required in order to respect the limits for visibility.

Threshold values for in-tunnel air quality and visibility have been defined in international guidelines such as PIARC (e.g. [2], [4], [5], [6]) which are in most cases recommendations or at national level binding threshold values (e.g. [13], [15], [16], [29], [46]).

There has been no radical change during the last decades in threshold values. CO levels for demanding a tunnel closure were reduced from 200 ppm to 120 ppm or even to 100 ppm; operation levels were reduced from 120 ppm to 80 ppm and in a few countries even to 30 ppm. CO concentrations of 20 ppm to 30 ppm are the typical maximum values for a working environment i.e. permitting exposure to this concentration level during 8 hours. However, as mentioned above, in most tunnel designs, the CO concentration is often no longer determining for the dimensioning of the ventilation system (except in tunnels with almost no diesel powered vehicles or located at high altitudes).

The criterion concerning the visible range has changed little over the years. The extinction values of $k = 0{,}012\ km^{-1}$ for requiring tunnel closure and $k = 0{,}007\ km^{-1}$ as a typical threshold value for normal operation have not been changed. A major change in the calculation procedure was the inclusion of the non-exhaust particle emissions in the fresh-air demand calculations. This was necessary as the exhaust emissions of particles have been reduced due to technological improvements in the diesel engines but the resuspension of road dust inside the tunnel remains on a constant level. Nowadays, this so called non-exhaust particle emissions are about the same amount as the exhaust ones. In future, the non-exhaust particles will dominate the visibility situation inside a tunnel. Extensive work on this issue has been performed during the PIARC working cycle 1997 to 2002 [5].

Vehicle exhaust contains several other gasses than CO that are toxic and can influence human health. Nevertheless, most countries continue to use CO as representative for the toxicity level. The reduction in permissible CO concentrations can be seen as a reaction in order to ensure adequately low toxicity levels. Some countries, however, have decided to implement a threshold value also for nitrogen-oxides (NO_x, NO_2) concentrations inside the tunnel ([4], [10], [46]). However, it has to be mentioned that the effect of nitrogen oxides is rather an ambient air issue than of concern for the in-tunnel air quality. Measurements of concentrations of CO are simpler and more reliable than measurements of any species of NO_X.

2.2. Ambient air quality

Road tunnels play an important role in managing traffic in built-up areas. The removal of vehicles from the surface to subsurface levels improves the air quality in the vicinity of former congested open roads. As the emissions are now contained inside a tunnel, the concentrations of certain compounds increase and concerns about ambient air quality in the surrounding of tunnel portals and air-exchange stations have to be considered. In order to overcome such problems, detailed examinations of technical and non-technical solutions have to be examined. However, technical solutions have a significant impact on the size and operation costs of the tunnel-ventilation system. In most cases, the restriction of portal emissions has highest priority. This fact calls for exhaust-air extractions close to exit portals etc. and in some cases even needs the installation of filtration systems.

Polluted tunnel air exiting the portals causes higher air-pollution levels over an area in the region of 200 m length and 50 m width. Beyond this zone, the impact of the tunnel in terms of ambient air quality is hardly distinguishable. Nowadays, particulate matter PM_{10} and NO_2 are the two components that dominate exceedance of the ambient air-quality criteria. Some countries adopt a cost benefit analysis including examining the exposure levels in order to determine whether or not such situations are acceptable. Other legislations demand by default that if the air-quality is already at its limit, almost no worsening is acceptable e.g. the portal emissions are restricted. In this case, the conventional solution is to use a vertical stack in order to expel large tunnel-air quantities at high flow velocities of minimum 10 m/s into the atmosphere. In such cases the impact of tunnel air is almost negligible.

Imposing certain ambient air-quality criteria should ideally be coupled with measurements of the ambient air quality. However, even with local measurements it might be legally difficult to determine whether or not the design and the operation of the tunnel-ventilation system fulfil their objectives. Therefore, the official requirement could be that no net-portal outflow may occur at any time. Fulfilment of such a requirement is easier to prove but inevitably results in very high energy consumptions.

Filters that reduce particulate matter have been installed in several tunnels [28], [31]. However, filtration of gases, e.g. NO_2, has been tested but it is yet unclear whether or not this technology is adequately mature for use in a tunnel environment. Often filtration cannot replace the requirement for a ventilation stack, as only a few components of the tunnel air may be reduced and other compounds still need to be expelled vertically into the atmosphere.

2.3. Fire case

The most demanding changes during the last decades concerned the requirements for ventilation in case of an incident and in particular for fires. Although the fire case was content of intensive investigations in the 1960's (Ofenegg, [20]), 1970's (Zwenbergtunnel, [21]) and a major test series in 1993 to 1995 (Memorial tunnel) [22], ventilation design was driven by "normal" operation. Tests within the EUREKA 499 – Firetun project [23] gave additional valuable information about heat loads and smoke-production rates. This is also reflected in the content of the several PIARC guidelines to this topic [1], [3], [7], [8], [9] as well as in the European Directive on Minimum Safety Requirements for Tunnels in the Trans-European Road Network [12].

For a long time, the typical design fire was 20 MW with a smoke-production rate of 60 m^3/s. The corresponding typical extraction rate was 80 m^3/s. This amount had to be extracted over a distance of one kilometre [29]. Still based on a truck fire, the design fire was subsequently increased to 30 MW with a corresponding smoke-production rate of 80 m^3/s. This is still the design fire in Switzerland [16]. When designing the tunnel-ventilation system, Austria assumes a heat-release rate of either 30 MW or 50 MW. In Germany [13], however, the design fire depends on average number of truck kilometres a tube experiences per day, resulting in design fires of 30 MW, 50 MW or 100 MW with corresponding smoke-production rates of 80 m^3/s, 120 m^3/s or 200 m^3/s. Norway specifies heat-release rates of 20 MW, 50 MW or 100 MW depending on the tunnel class corresponding to the risk level [46].

In case of smoke extraction, the earlier methods were typically based on using slots located in a false ceiling above the traffic space every, say, 10 m. During normal operation, fresh-air was often injected through the same slots and in case of fire, the fans reversed (reversible semi-transverse ventilation). Reversing the flow can take several minutes, which is a critical time for the survival chances during the self-rescuing phase. Using reversible fans for smoke extraction is therefore no longer a preferred method. Moreover, due to the long extraction zone, the extraction rate near the fire is relatively weak. In conjunction with improvements in fire-detection techniques, modern methods use remote-controlled dampers so that the smoke can be extracted close to the fire. Fire detection is in most cases based on linear heat detectors and independent smoke detectors. Visibility and CO sensors can also be used for smoke detection [45].

These changes are also reflected in the evolution of the Austrian guideline RVS 09.02.31 [14], which is the pertinent one for ventilation design in Austria. From 1997, the ventilation requirement was adapted in order to cater for the needs of smoke control in case of a fire. For transverse ventilation systems the major change was the substitution of the small exhaust air openings by remote controlled dampers with large cross sections (up to 10 m^2) located at distances of up to 100 m. Instead of the former uniform extraction of smoke over a long distance, a powerful massive point extraction in case of a fire was introduced. The extraction capacity was initially fixed to 80 m^3/s (reference density 1.2 kg/m^3). In 2001, the minimum extraction capacity was increased to 120 m^3/s. Leakage rates for ducts and dampers were specified in the acceptance tests. In 2007, the design criteria were further tightened so that the volume flow of the fans has to include the 120 m^3/s and twice the amount of allowable leakage rates. This results in increased volume flows and ventilation power.

In Switzerland, the smoke extraction rate is defined as 3 m/s to 4 m/s times the tunnel cross section [16], i.e. some 150 to 200 m^3/s. In Germany, however, the minimum extraction rate is 150% of the smoke-production rate [13].

For longitudinal ventilation in Austria, it was defined that the fans have to provide a minimum velocity of 1.5 m/s, and a minimum flow rate of 80 m^3/s. In 2001, this flow rate was increased to 120 m^3/s.

The principle of the longitudinal smoke management in Switzerland and Germany is to ensure the critical velocity[1] for unidirectional tunnels. In this case, the Swiss design guideline [16] specifies a critical velocity of 3 m/s. However for tunnels with bidirectional traffic, the dimensioning is conducted for various scenarios for a longitudinal velocity of 1.5 m/s.

The impact of demanding the critical velocity is shown for tunnel inclinations of 0 % to -4 % in **Figure 1**.

With the application of numerical simulations including calculations of the transient flow behaviour during fire scenarios, intermediate states are nowadays also being considered, see [34]. This leads to the conclusion that cross passages between two tunnel tubes have to be closed with doors, although stationary computations would show that this is not indispensable.

Moreover, in the case of tunnels with several tubes, it must be ensured that the non-incident tubes are under higher pressures than the incidence tube with the fire, so that the escape routes are kept free from smoke. However, the overpressure has to be kept below a certain level in

[1] Ensuring the critical velocity, smoke is always driven in direction of the flow and no backlayering[2] occurs.

order to allow for an easy opening of the egress doors, otherwise special provisions for the doors have to be considered. For some tunnels, intermediate states need considering when designing the over-pressurisation system of the non-incident tube incorporating the events in the incidence tube [37].

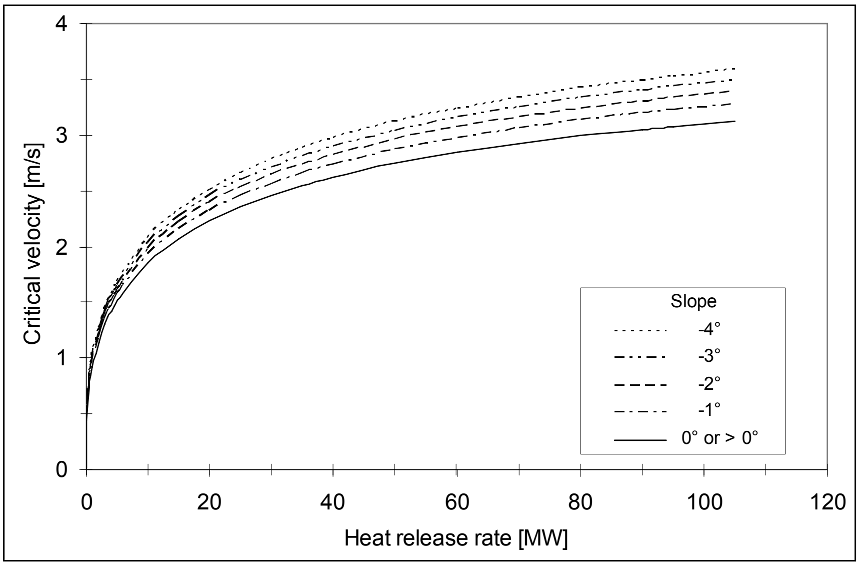

Figure 1: Critical velocity for a typical 60 m2 tunnel with slopes between -4 % and 0°%.

3. VENTILATION CONTROL

The ventilation control is embedded in the SCADA (supervisory control and data acquisition) system and it is paramount that a clear hierarchy is defined in particular in modern automatic control systems. This hierarchy also defines the priority of actions e.g. when two different methods detects a fire, see [38] and [39]. A key decision is when and how to react to a second fire detection.

The implementation of specific fire-case guidelines regarding ventilation as well as the implementation of massive smoke extraction in semi- and full transverse ventilation systems has called for the use of automatic control of the ventilation systems. There is a large difference between steering ventilation and closed-loop controllers. While steering is based on a simple activation procedure, closed-loop control systems set the activation, monitor the effects, and feed back the monitored information in order to specify further actions.

3.1. Normal operation

The methods used to compute the fresh-air demand are in general based on hourly averaged traffic scenarios. Due to the very low emissions of the vehicles, this may lead to very low fresh-air demands. Dimensioning the ventilation system in order to meet such demands only, might cause too bad air quality during peak time operation. Therefore, time-scales have to be considered [42], [43]. The ventilation time scales during normal operation are in the order of minutes. As a pragmatic approach, a minimum longitudinal velocity that is also used for the dimensioning can be required [16].

Sometimes, normal operation also considers other safety relevant aspects such as ventilation in order to reduce the risk of steaming up of wind screens [33] or fog entering the portals [39]. Moreover, it is occasionally warranted to ensure a certain minimum flow in order to prevent flow reversals or short circuits that can occur e.g. before a fire has been detected.

3.2. Ambient air-quality constraints

Control routines are sometimes defined in order to minimise impact on the ambient air-quality. If the requirement is that no net air flow may exit any portal at any time, this is a challenging task. The piston effect of the driving vehicles is the major force in the system and this has to be balanced typically by optimising extraction rates and the use of jet fans. When the tunnel is equipped with additional entrance and exit ramps, the balancing is difficult but achievable [32]. For such purposes, considerable testing time and resources can be saved by using dynamic numerical modelling in order to mimic the tunnel responses for the testing of the control system [32].

3.3. Fire case

National guidelines like [13], [14], [16] and PIARC [11] enforce or recommend certain strategies on how to use a ventilation system in the case of a fire. Common to them all is that in case of fire in a tunnel with bidirectional traffic or with congested traffic, the air speed shall be kept at a low level, in order to optimise the conditions for self rescue in both directions away from the fire, particularly within the first phase of egress. Only in case of unidirectional traffic without a congested situation, a higher air speed might be favourable. This means that in the first case (bidirectional or congested traffic), an air speed of some 1 m/s to 1.5 m/s has to be maintained [44], while in the case of unidirectional traffic without congestion, the target speed is between 2 m/s and the critical velocity in order to prevent back layering of smoke[2].

In longitudinal ventilated tunnels, the achievement of the target air velocity has the highest priority. **Figure 2** shows the ventilation concept. In transverse (semi- or full) ventilated tunnels, a highly efficient smoke extraction is the main objective. **Figure 3** shows the concept for such a tunnel. When the tunnel is operated with bidirectional traffic, the ventilation shall provide an equal amount of flow from both sides towards the extraction zone i.e. the open damper(s). In case of unidirectional traffic, more air is normally extracted from the fire side than from the downstream side. Consequently, smoke and fresh air is extracted from the fire side and only fresh air from the other side. This apparent drawback has to be accepted, as during the period from the onset of the fire until full smoke extraction, smoke has flown downstream of the extraction zone. This smoke has to be retrieved back to the extraction zone in order to obtain a smoke-free zone i.e. to create a safe haven beyond the smoke-extraction zone.

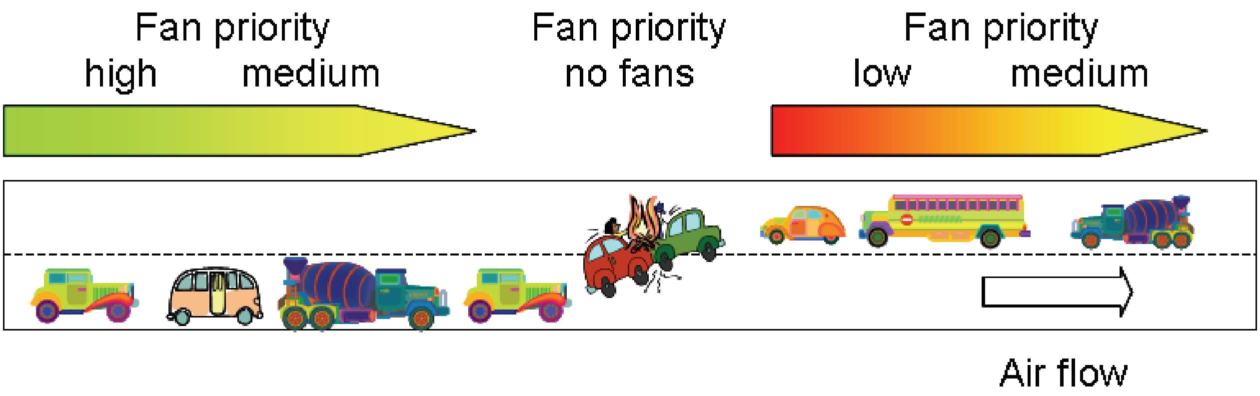

Figure 2: Ventilation philosophy for longitudinally ventilated tunnels with bidirectional traffic

This complex smoke movement requires a closed-loop controlled ventilation system. Consequently, quick and reliable sensors to monitor the smoke/air movement inside the tunnel and a well balanced "controller" which operates the ventilation system automatically

[2] In case of smoke backlayering, some smoke flows against the main direction of the flow. Consequently, smoke is spread to both sides of the fire.

are required. The aim of the control system is to bring as quickly as possible the actual velocity value to the range of the target value and to maintain this in a stable manner. **Figure 4** shows the controller performance. In order to achieve such a situation, an infinitely adjustable input of the force (thrust) would be needed. This would call for speed controlled fans, which in most cases are not available and also not required. Hence, a stepwise approach is often the solution in particular for systems with jet fans. In some scenarios, exceeding the target value is to be avoided.

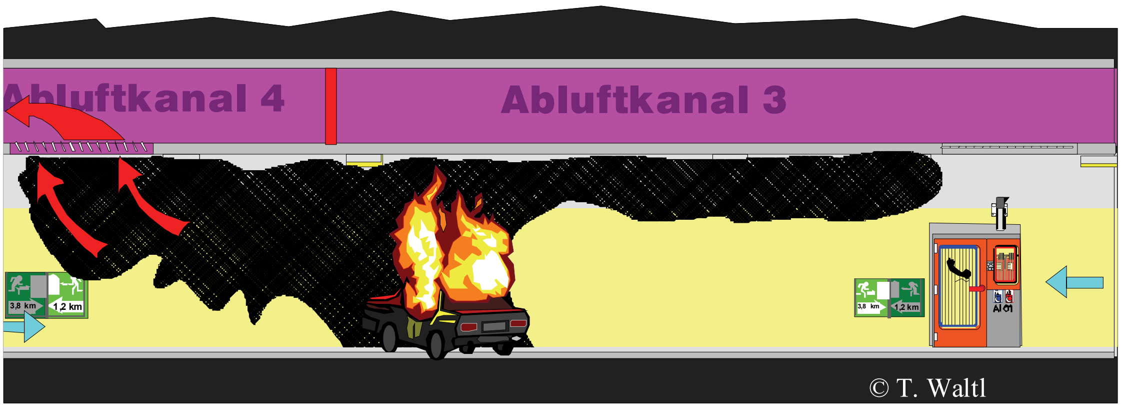

Figure 3: Ventilation philosophy for transverse ventilated tunnels

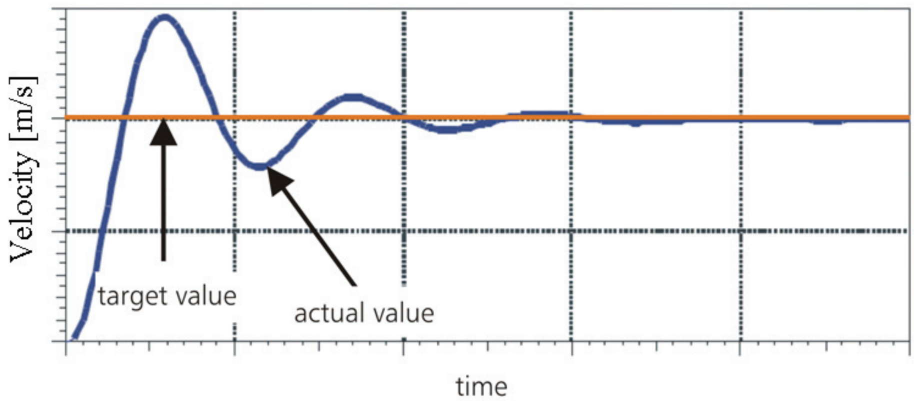

Figure 4: Behaviour in case of a closed loop control

4. REQUIREMENTS TO FANS AND DAMPERS

The consideration of fires in a tunnel influences the requirements to the mechanical equipment. This mainly concerns the resistance to high temperatures. While in former years no specific temperature requirement was expressed, the German guideline RABT (1994 version) and the Austrian Guideline RVS 9.261 (1997 version) required a heat resistance of 250°C during 90 minutes for all fans which could be operated in hot smoke (i.e. jet fans and exhaust air axial fans). Moreover, RABT (1994) already required a temperature resistance of 400°C during 90 minutes for fans that extracted smoke directly from the traffic space. The new RVS 9.02.31 [14] requires a temperature resistance of the exhaust air fan – and all other equipment inside the exhaust air duct – of 400°C during 120 minutes in transverse ventilated tunnels. For jet fans 250°C are sufficient, as long as the hazard level of the tunnel is below class IV or the jet fans are at least 200 m apart. As soon as class IV is reached, or the distance between fans is below 200 m, also for jet fans the temperature requirement is 400°C during 120 minutes. Depending on the design fire and the distances between the jet fans, the current version of RABT (2006) [13] prescribes a temperature resistance of either 250°C or 400°C for jet fans.

5. CASE STUDIES

A general trend is that due to safety considerations, longitudinal ventilation can only be accepted for tunnels up to a certain length. In case of bi-directional tunnels, smoke extraction is in any case envisaged, if they are longer than 1200 m in Germany [13] and longer than 800 m to 1500 m in Switzerland [16]. On the other hand in Norway, all tunnels are ventilated longitudinally [46]; however most tunnels in Norway have low traffic volumes.

The more stringent requirements on tunnel ventilation have a particular influence on short longitudinally ventilated tunnels with high slopes [18], [36] but less for longer tunnels with low gradients. For transverse ventilated tunnels, the consequences can be huge. An increase in the extraction volume of air/smoke results in an increase in construction and operation costs. Smoke extraction at high slopes is particularly difficult [41]. However, in the design of a new tunnel, the new requirements can normally be respected in a proper manner.

5.1. Existing tunnels

A tunnel is always designed according to the requirements valid during the design period. After one or two decades in most cases a refurbishment and/or upgrading of the tunnel has to be made. However, as the buildings, ducts etc. exist, they have to be reused, although the requirements have been changed and would call for a different design. The same situation emerges, when existing one bore tunnels are upgraded with a second tube. Such constraints can have large impacts on the design of the tunnel-ventilation system.

The following example considers a tunnel with transverse ventilation. The ventilation section 'TT-South' of the Tauern tunnel is chosen as example. Originally, this tunnel had only one bore but now several years after the opening the second bore is under construction. Unfortunately the ventilation building, the connection ducts to the new bore as well as a 70 m long connection to the exhaust-air shaft already exist and have to be reused, as they were constructed together with the necessary ducts and buildings for the first bore. The plan view of the ducts is depicted in

Figure 5. The ducts in red and orange are exhaust air ducts while the other two are for fresh air. According to the requirements at that time, the ducts for the first bore had suitable dimensions. The ducts for the second bore, however, are much smaller. They were constructed under the assumption that future vehicles would require much smaller air volumes. This would be correct if only the fresh-air demand required for normal operation was to be considered. But other requirements have been changed since that time. Nowadays the fire case is the determining one and not normal operation. When looking on one of the four ventilation sections, the following differences occur. Instead of an originally considered maximum exhaust air flow of 60 m³/s, the extraction capacity today has to be 165 m³/s. This results in an increase in pressure and ventilation power.

Table 1 shows the effects of the constantly increasing demands on the ventilation design. The requirements were set according to the different releases of the Austrian design guideline RVS 09.02.31 [14].

Table 1: Ventilation parameters and increase in ventilation demand according to the changing RVS design criteria

Design criteria	Volume flow [m³/s]	Pressure drop [Pa]	Power [kW]*
Normal operation	60	730	62
Fire case (1997)	80 + 22.5 (leakage)	1,570	236
Fire case (2001)	120 + 22.5 (leakage)	2,775	565
Fire case (2007)	120 + 45 (leakage)	3,095	730

*assumed ventilator efficiency 70%

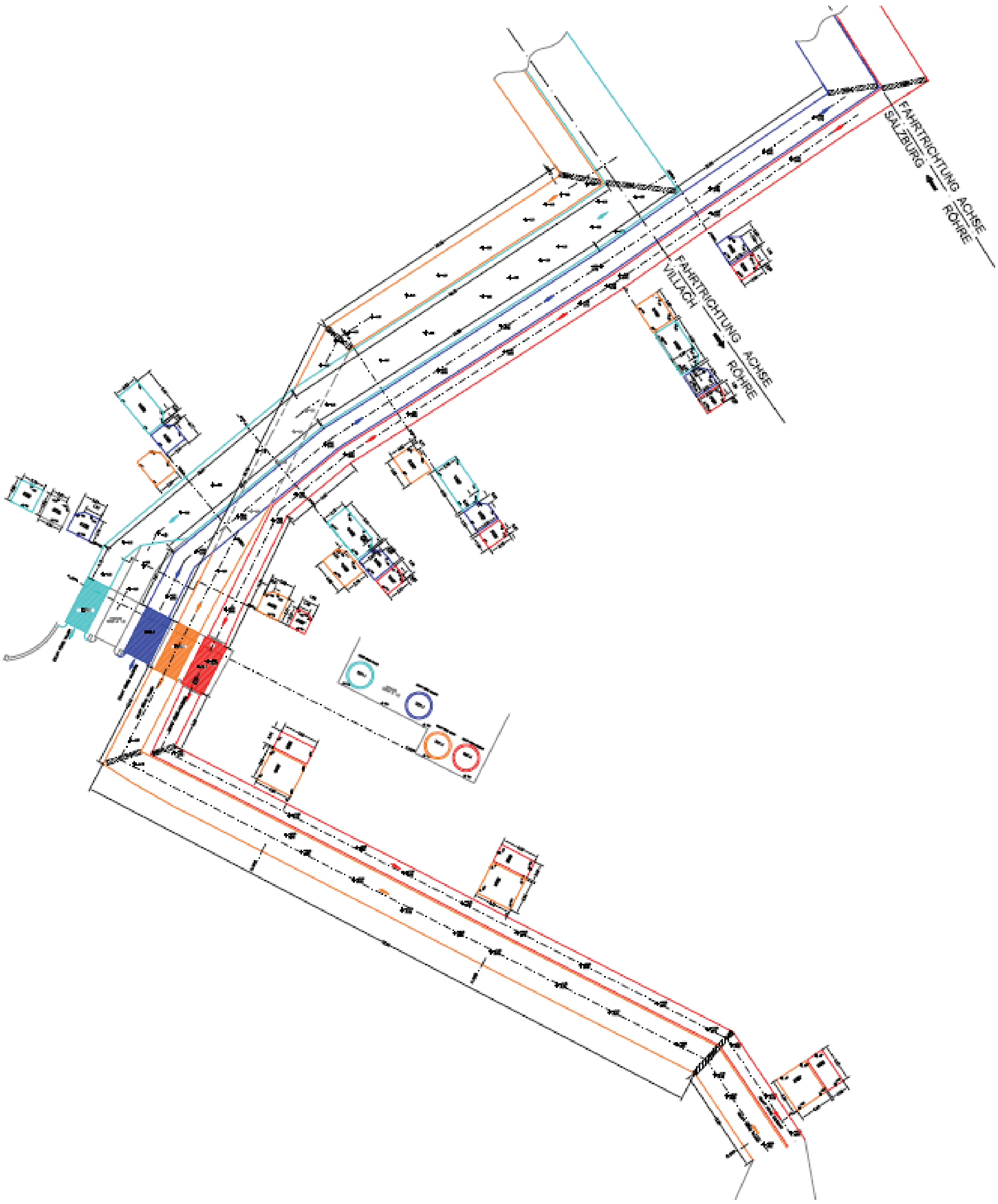

Figure 5: Plan view of the fresh-air and exhaust-air ducts of the Tauern tunnel ventilation section south, ventilation building south

5.2. Ventilation control in case of a fire

Another demanding issue is the control of the air velocity inside the tunnel. In case of fire, the demands are quite strict. If bidirectional traffic has to be considered or congestion in a unidirectional situation cannot be excluded, a low air velocity has to be achieved and subsequently to be maintained.

In longitudinally ventilated tunnels, this is normally done by activating and deactivating jet fans. In such cases, the whole system has a stepwise characteristic, as already achieved e.g. in 1999 for the Tunnel de la Vue-des-Alpes in Switzerland [38], [39]. Another method is to use point-injections/extractions [35]. The massive point extraction of smoke in transverse ventilated tunnels also requires a steering and control of the air velocity inside the tunnel. In semi-transverse systems with smoke extraction, the smoke movement has to be controlled by jet fans or Saccardo type air injections. In systems with a separate fresh-air duct (fully transverse systems), the smoke movement can be controlled by utilising the possibilities of increasing and reducing the air pressure in the tunnel using the existing fans. Such a system functions as long as there are more than two ventilation sections over the length of the tunnel and if there is no major meteorological or thermodynamic pressure difference between the tunnel portals. The Plabutsch tunnel was the first one in Austria using active control of the fans in the five ventilation sections in order to confine the smoke in the desired region between fire and extraction point (open damper) [24], [25].

In tunnels with strong meteorological pressure differences, such as the long tunnels in the Alps, an approach as chosen for the Plabutsch or the Gotthard tunnel might be insufficient, as the meteorological forces could be too high. For such cases, e.g. in the Mt. Blanc tunnel additional jet fans are employed in order to overcome these pressure differences [40]. The implementation of jet fans in transverse ventilated tunnels is often the chosen solution. Especially in semi-transverse tunnels with smoke extraction, frequently no other possibility for influencing the smoke movement exists.

The necessity of jet fans inside a transverse ventilated tunnel may not be satisfactory. Two different ventilation systems have to be used, and during maintenance of the jet fans, the tunnel – or at least the lane under the fans – has to be closed. In order to overcome this problem, an injection system of fresh air (like a Saccardo nozzle) can be used. The combination of fresh-air injection and ventilation control has been developed and patented [26], [27]. Such a system has already been implemented and successively tested, e.g. in the Katschberg tunnel. It consists of a damper used for fresh-air injection and a blocking element in the fresh-air duct sealing off the remaining of the fresh-air duct. In case of an incident, fresh air is injected at high velocities (up to 25 m/s) and hence with high momentum. By increasing/reducing the air volume and in certain cases also the angle of the injection nozzle, it is possible to control the air velocity inside the tunnel.

Figure 6: Fresh-air injection device: damper (left), blocking element closed (centre), blocking element open (right); construction IWN GmbH

The performance of this injection system was tested during the (hot smoke) fire tests in the Katschberg tunnel. **Figure 7** shows the development of the air velocity inside the tunnel. After the ignition of the fire event (~17:59:00), it took roughly one minute until the fire alarm was triggered (18:00:00, note: as a protective measure, the fire-detection cable was shielded against high temperatures). The axial fans reached its required capacity 30 s later. This short response time was possible because the fans were already running at the time of the alarm. At the beginning of the test, smoke was transported downwards beyond the open damper used for the smoke extraction. But within three minutes after the ventilation system was fully operational (extraction and fresh-air injection), the flow was adequately controlled such that the smoke was sucked back to the extraction zone. Subsequently, the smoke was confined within the zone between the fire location and the single open smoke-extraction damper. Optimal smoke-extraction and egress conditions were established. The velocity measurements (LG_5, LG_6) show that from both sides of the open damper (ABJ14) air/smoke was extracted at a velocity in the tunnel of 1.5 m/s and -2 m/s respectively. The volume flow of the exhaust-gas fan was 240 m³/s.

A matter of discussion is always the relation between the two air volumes (on the fire side / on the 'other' side). This relation has logically to be set at a 50 % / 50 % ratio in case of bidirectional traffic as well as for congested traffic [14]. Although after the initial stage of the fire event, theoretically 50% of the extraction volume might be fresh air, it is important to keep this side free of smoke, as it most probably contains blocked vehicles. In a test for unidirectional traffic, the relation was set to 75 % from the fire side and 25 % from the other side. In this case, it took very long to suck the smoke, which initially flew beyond the extraction damper, back to the extraction zone. The air/smoke velocity on this (originally downstream) side was very low (0 to 0.5 m/s) and the control mechanism is hence slow. It turned out that with this small air volume rate, the smoke density became rather high and a dense smoke plug blocked the downstream side for more than 15 minutes. Consequently, the relation between the two volume flows should be set to a 2/3 to 1/3 ratio, in order to improve the downstream situation.

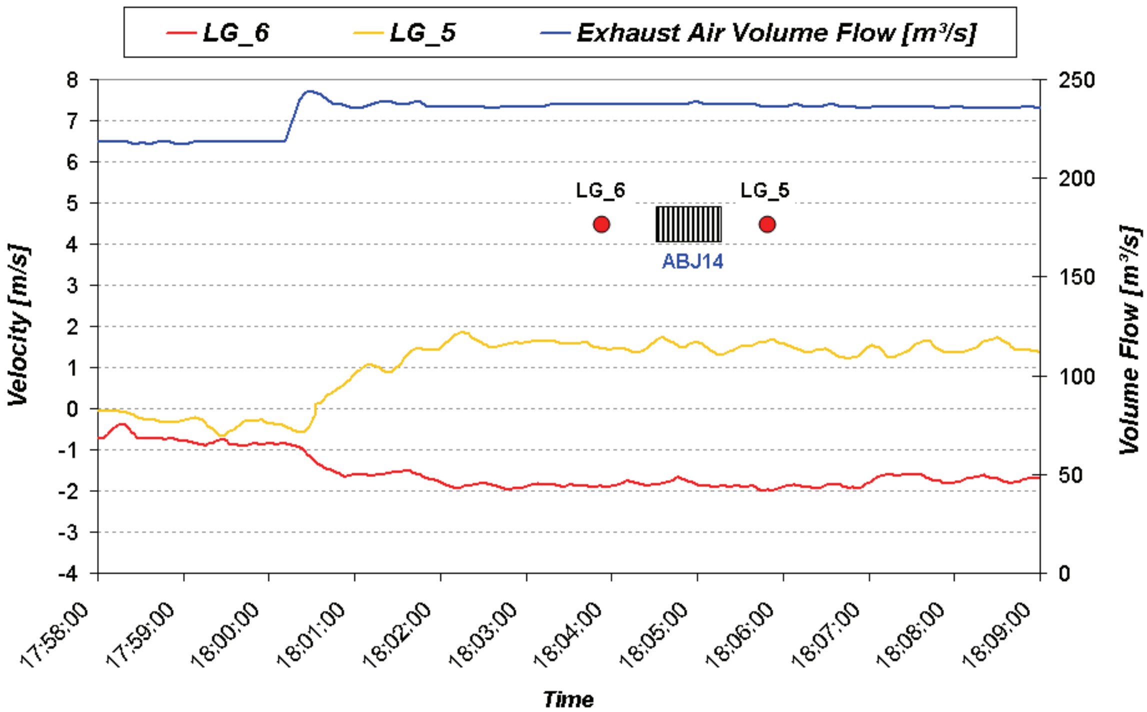

Figure 7: Air velocity vs. time during a fire test, bidirectional traffic mode

5.3. Portal emissions

An example for a complex control scheme for avoiding portal emissions is the Cross City Tunnel in Sydney [32]. This 2'200 m long tunnel consists of two tubes, each with unidirectional traffic. Both tunnels include entry and exit ramps. The tunnel is situated in an urban environment. During normal operation, portal air discharge is not permitted to the greatest extent practical.

In order to benefit the maximum from the piston effect of the vehicles and hence minimise energy consumption, the polluted tunnel air is extracted near the exit portal of one tube and injected shortly downstream of the entrance portal into the second tube. Near the exit portal of the second tube, the vitiated air is extracted and expelled through a vertical stack into the atmosphere. Jet fans are used to balance the flow and to prevent flow discharge at the portals. Air-flow measurements are constantly monitored and used in order to optimise the settings of the fans. Several jet fans are on variable-speed drives in order to prevent exceeding the maximum number of starts and stops and to enable an adequately fine adjustment of the flow (see **Figure 8**).

In congested traffic, the air-quality is too poor when it arrives at the cross-ventilation station to be used in the second tube. Therefore, the polluted air of the first tube is transported by the by-pass tunnel to the exhaust-ventilation station that is common for both tubes. Smoke-management is conducted with longitudinal ventilation. Dynamic simulations played an important role element in ensuring that the tunnel-ventilation control functions satisfactory [32]. This was extended to a tunnel simulator that was used to conduct exhaustive tests of the control system prior to installation on site. Consequently, the commissioning and testing time on site was very short.

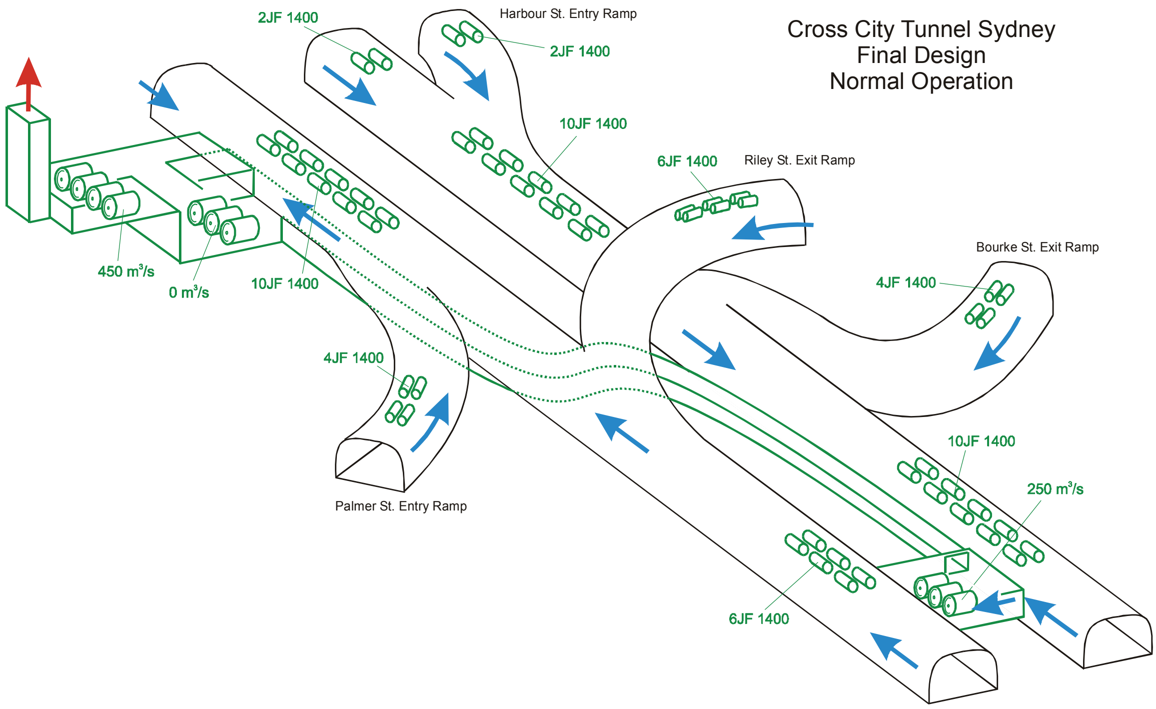

Figure 8: Cross-City Tunnel (Sydney, Australia). The capacity of the ventilation system is: cross-ventilation station 250 m^3/s; bypass-ventilation station 340 m^3/s, exhaust-ventilation station 690 m^3/s and 54 jet fans each with a static thrust of 1650 N.

Tunnels like this one might also have problems with the ventilation control in case of fire. On and off ramps cause air flows over these ramps which might influence the smoke control inside the main tube considerably [17]. In such situations special provisions have to be taken in order to elaborate ventilation designs meeting the requirements [19].

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SAFETY DESIGN FOR LONG ROAD TUNNEL

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ABSTRACT

According to the enhancement of economic conditions and prosperity in each Nations, long road tunnel projects are increasing year by year due to the extension of highway network for transportation business.

Many fatalities were inhaled the hot smoke and toxic gases which generated at vehicle itself and lording goods.

Selection of ventilation system, smoke control strategies with pressure balance control, and operation system with quick response are key issues for tunnel safety.

This paper describe the basic phenomenon of smoke propagation and key points of pressure control by point extraction system for the appropriate smoke control, for the arrangement of universal design concept.

Keywords: Ventilation system, smoke control, point extraction

1. INTRODUCTION: BASIC CONCEPT OF SAFETY DESIGN

In recent years, there are so many tunnel fire occurred in the world.

Fire and life safety design must be made sure for all of tunnel users in combine with all of relevant technology fields with appropriate understandings of tunnel users for fundamentals of tunnel structure.

On the other hand, International road network will be arranged more and more tightly transportation in the world, according to the world wide economic growth and trading net work.

For example, “Silk Road” was built in Asian Continent in more than thousand years ago for the purpose of connection of European continent for the International trade and cultural exchange.

Figure 1-1 presents the typical road network system of “Asian Highway network” in Eurasia continent. This Asian Highway Network should be linking with European Highway Network.

At present, new motorway net work is arranging under the each nation and UN, then these highway network will be integrated as “International Road Network System”

In the future, many of motor way users will take long distance drive to foreign countries for surface transport and tourism through the long road tunnels in some countries.

Especially, long road tunnel is specified structure in comparing with the other ordinary open roads with following characteristics,

Figure 1-1: Typical Net work of Asian Highway (by UN)[1)]

- Closed space with artificial lighting condition
- Different weather condition with open section
- Safety system and emergency service must be arranged in the case of incident
- High maintenance cost to be necessary with maintenance and operation.

If in the case of serious accident was happened in the long road tunnel within foreign vehicle involved, take communication within concerned personnel, also be difficult with different languages.

Based on these concepts, we must discuss more and more for the “How to arrange the “Appropriate Safety Design for long road tunnel, on the point of view of universal concept with common technologies for mutual understandings with passengers”

Reference

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2. VENTILATION AND SMOKE CONTROL SYSTEM

2.1. Introduction

In recent years, there are so many tunnel fire occurred in the world.

Due to the fire and life safety, structural design must be assured for life safety in combine with ventilation system.

Tunnel ventilation system with smoke control strategies is one of the key issues for tunnel safety in combine with traffic control system.

Basic planning of Tunnel ventilation system must be planned at initial stage in preliminary design.

In the recent years, required mechanical ventilation volume in normal traffic condition is decreasing year by year, due to the improvement of combustion technologies for vehicle engine.

On the other hand, magnitude of tunnel fire is becoming larger scale, due to the enlargement of fuel tank capacity for the long distance drive and loading materials.

2.2. Basic concepts for ventilation and smoke control systems

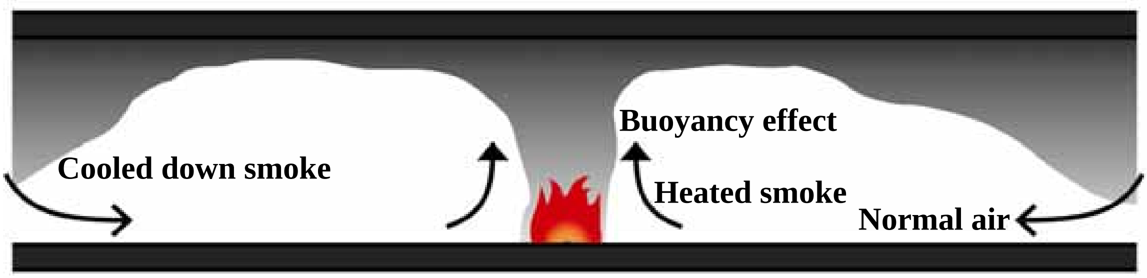
The following three points are key issues for tunnel ventilation design

- Traffic direction (uni-direction or bi- direction) must be considered.
- Air pressure must be over pressurized than incident tunnel space for the prevention of smoke inversion to evacuation space for passengers.
- Response time for smoke control must be quicker as possible in combine with appropriate fire detection system.

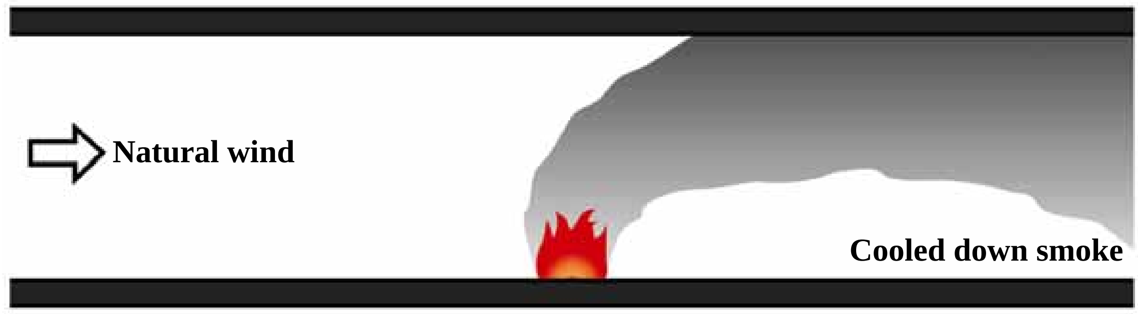
2.3. Basic behaviour of smoke propagation

If in the case of fire ignited and smoke spread into the tunnel space with natural condition. The heated smoke will be rising up to the ceiling by buoyancy effect, then, flowing to the down stream side with same as wind direction. According to the several experience of full scale fire experiment, the velocity of extreme head of smoke layer on that time will be 2.0 - 2.5m/s generally. Then, smoke will be dropping down to the carriage way by the cooling effects at the tunnel structure itself in the down stream section.

Figure 2-1 presents the basic behaviour of smoke propagation. The hanging length of smoke layer will be 200-250m, which was proved by the full scale test in several countries.[1)2)]



CaseA No wind effects



CaseB Natural wind effects

Figure 2-1: Basic description of smoke behaviour

2.4. Basic character of longitudinal gradient

Figure2-2 presents the typical phenomenon of smoke propagation and fuel spillage expansion in the grade section.

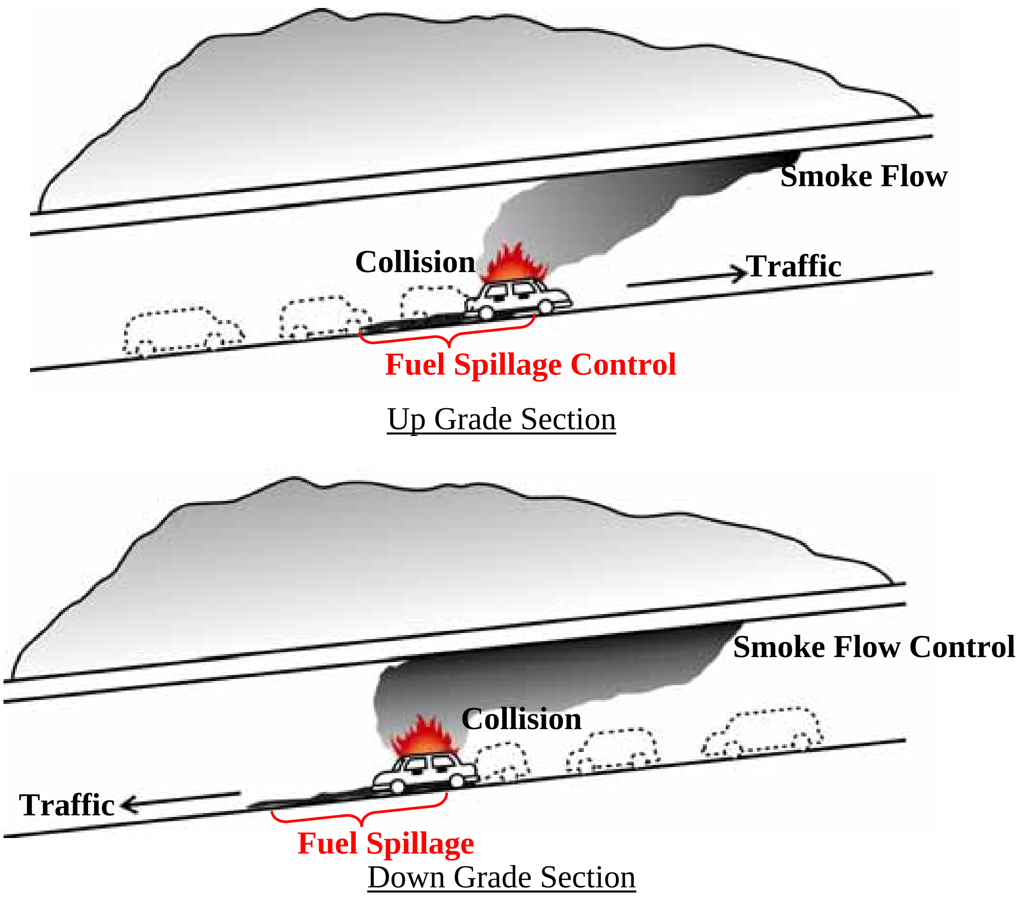


Figure 2-2: Basic concept for the safety design in grade section

- Hot smoke and fume from (HGV diesel) vehicle are very effective to the determination of the required mechanical ventilation volume.
- Smoke propagation phenomenon and expansion of spillage should be appeared in the opposite situation in the case of the up and down gradient section.
- In the case of fire occurred in the upgrade section. The smoke will be flowing to the same direction with traffic direction. On the other hand, flammable liquid spillage will be expanding to the backward. This is one of the causes of fire expansion to the following cars. This is big obstacles for evacuation and initial safety management. The design of drainage system with oil separator is very important for this case.
- In the case of fire occurred in down grade section, generated smoke will be propagated to the backward direction by the buoyancy (chimney) effect of heated smoke.
- This buoyancy effect must be taken into account of the computation of capacity of ventilators for the prevention of heated smoke inhalation.

2.5. Jet fan system

Generally, jet-fan system can be applied to the relatively short length tunnel. Appropriate Length of Jet fan system should be determined by the following conditions,

- Tunnel length
- Traffic volume and HGV(diesel contents) percentage
- Topographical conditions (Urban or Inter city tunnel).
- Traffic direction (Bi-directional or uni-directional).

Figure 2-3 presents the relationship between location of jet fans and static pressure distribution

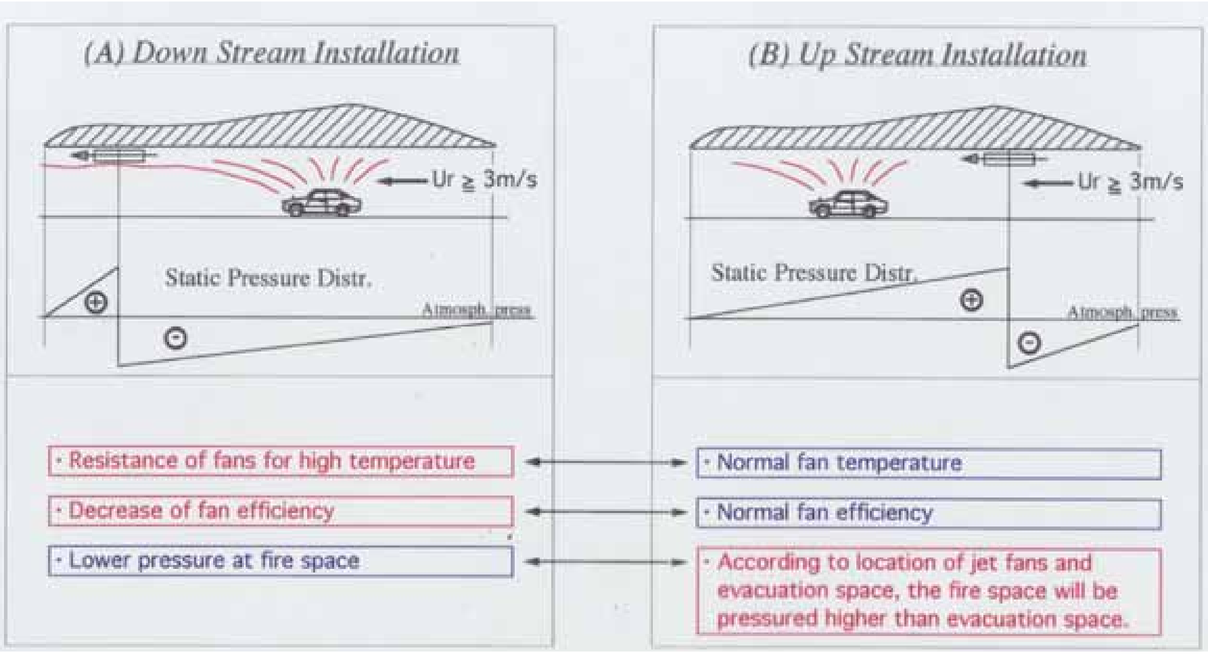


Figure 2-3: Relation ship between Static pressure distribution and location of Jet fans

If in the case of jet fan system employed for relatively short tunnel. Down stream installation (left side) seems to be better than up stream installation (right side) due to the possibility of creation the wider low pressure zone in longitudinal section.

There are two options,

(Case1) Push the smoke at tunnel entrance zone

(Case2) Pull the smoke at tunnel exit zone

2.6. Basic performance of point extraction system

If in the case of full transverse ventilation system or point extraction system employed for relatively long road tunnel, smoke propagation condition can be significantly improved for safety by the pressure balance control and utilize of Coanda effect (boundary layer attachment). Figure 2-4 presents the basic concept of improvement of smoke propagation.

Expansion of smoke free zone at down stream region can be realized by the application of Coanda effect in combine with ceiling extraction system.

This fact is also contributed to the extension of the spacing of the safety exit.

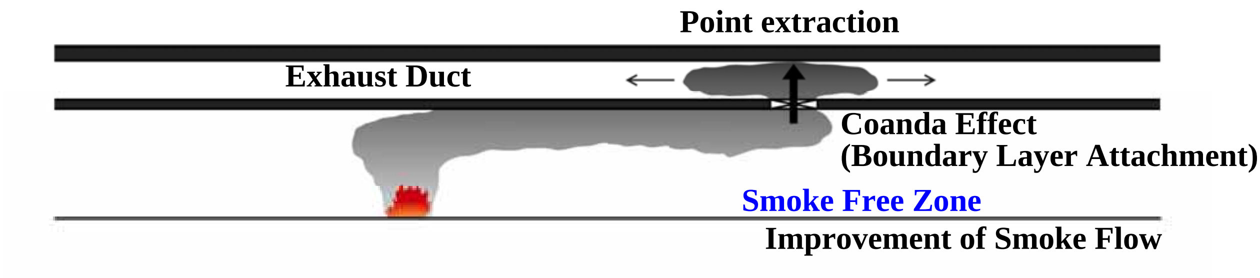


Figure 2-4: Smoke layer hanging by Coanda effect

2.6.1. Single point and multi point extraction system

Figure 2-5 presents the difference of smoke concentration of single port and double-point extraction system. The wind velocity changing point (high smoke density zone: neutral zone) will be extended according to the number of openings and extraction air volume at each exhaust port. In the case of single port opening with maximum extraction air volume, this neutral zone will be fixed at just below of exhaust port.

This high density zone should be varied by the natural wind or atmospheric conditions at both tunnel entrances.

This is one of the serious problems for smoke control strategies and decision making for the evacuation direction for tunnel users.

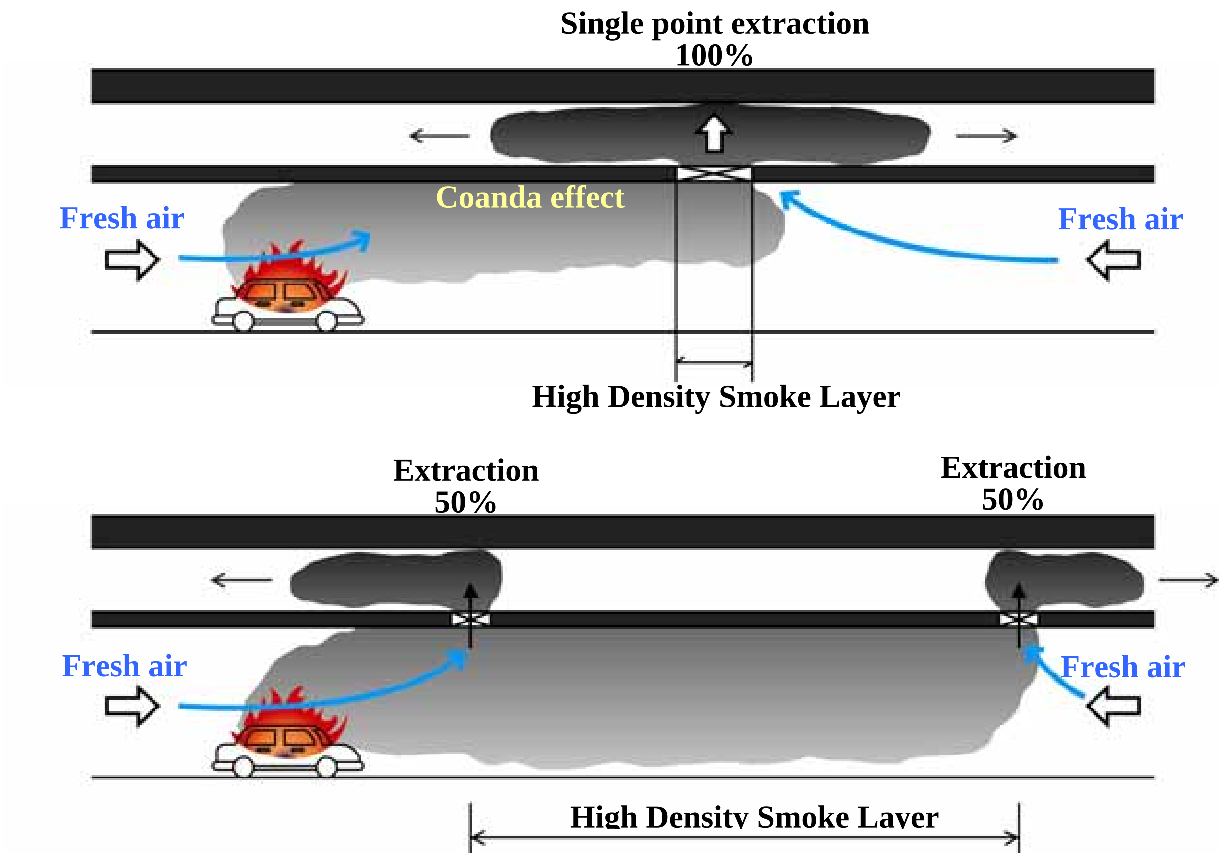


Figure 2-5: Difference of smoke layer between single and multi extraction port

The single extraction port is preferred rather than multiple extraction port (more than two extraction port) due to the creation of thin smoke layer concentration at extraction port.

2.6.2. Semi and Full Transversal ventilation system

Only fresh air is supplying to the traffic space in ordinary operation of semi-transverse system. Then, if in the case of fire, ventilator and smoke extraction damper should be operated to reverse flow and activate to the smoke control mode after the fire reported. Therefore, response time for smoke control mode takes certain minutes. This is big disadvantage of reverse operation in semi- Transverse ventilation system.

In the case of full transverse ventilation system in combine point extraction system (similar with Plabutsch tunnel in Graz, Austria), it is not necessary the ventilator control to reverse flow at initial stage in comparing with semi-transversal ventilation system. This means so that the response time for smoke control mode could be achieved with short response time for exhaust damper control.

2.6.3. Point extraction system in longitudinal ventilation

Figure 2-6 presents the point extraction system in the type of longitudinal ventilation.

Selection of extraction port will be able to the automatic control by several sensors and detectors, such as, traffic sensor, wind velocity sensor, visibility meter and fire detector.

The fresh air will be coming into the traffic space from both portals, then, polluted air is always extracted into the exhaust air duct through the single extraction port. Therefore, static pressure distribution in carriageway is always lower pressure than atmospheric pressure and other safety space.

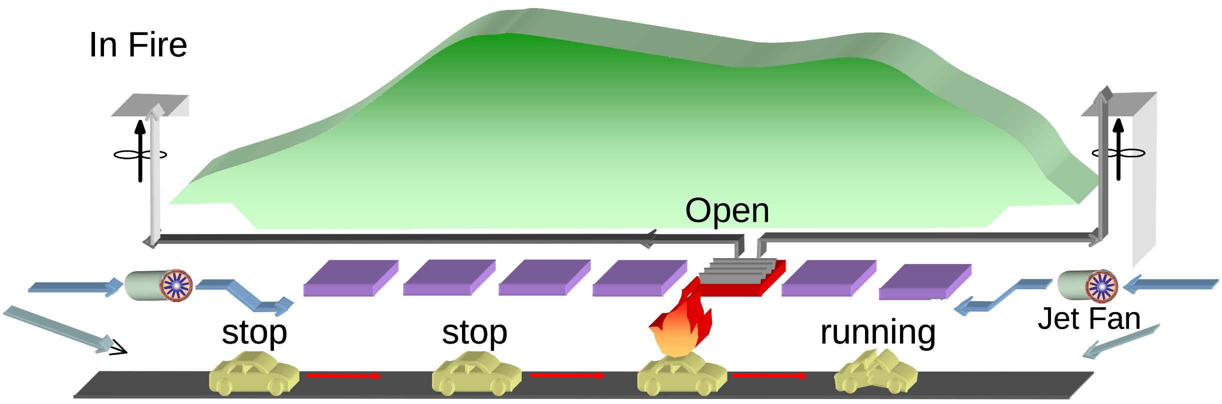


Figure 2-6: Point extraction system in the case of fire

(East Coast Freeway tunnel project)[3)]

This is one of the significant advantages of this system.

In addition, following advantages can be found,

- Not necessary to reverse operation of ventilator
- Fresh air duct is not necessary
- This system can be adapted to both of bi-directional and uni-directional traffic with movable extraction port due to the traffic conditions and atmospheric pressure balance at both sides.
- This system could be adapted to 6-7KM long tunnel according to the traffic condition.

Based on above basic concepts, fully transverse ventilation system with point extraction system and longitudinal ventilation system equipped with point extraction system seems to be preferable for relatively long road tunnel in comparing with the other ventilation systems.

The point extraction system is very effective for smoke control (smoke can be extracted at certain points) with depress the air pressure.

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3. CONCLUSION

Safety philosophy of long road tunnel is quite complicated system in all kind of highway structures. In addition, safety level can be achieved in collaboration with tunnel users and organization of related public agencies in each country, not only installation of advanced equipments.

On the other hand global motorization in expanding to all countries to Eurasia continent with appropriate automobile universal deign concept.

As a fact, due to the universal design concept, many of people who can easy drive the many brand of vehicles with their own taste, which is very important key suggestion for safety design.

Universal design concept must be arranged for all of tunnel systems for the purpose of system assurance to the fire and safety to tunnel passengers.

"The completion of installation of Tunnel structure and hard ware is just addressed on the starting point to the achievement of Real Quality of Road Tunnel."

VISUALIZATION AND LIGHT IN TUNNEL CONFINES

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1. INTRODUCTION

Within the scope of a study carried out by the Austrian Board of Trustees for Traffic Safety on the comparison of safety in Austrian tunnels [1.2.3] the cause of accidents between 1999 and 2003 came under scrutiny. As a result it was determined that the cause of six out of ten accidents in the transit domain of tunnels was due to a lack of vigilance (inattentiveness and distraction), human error (especially due to a lack of safe distance from the vehicle ahead) and misjudgment (in regard to vehicles driving ahead or stationary vehicles) on the part of the motorists. Interestingly, the cause of these accidents was marginally connected with inadequate tunnel lighting which substantially reduces motorist's visual perception and concentration.

The lightest areas of a tunnel (ceiling lights, the illuminated boundary, the luminous information and traffic signs, head-lights, tail-lights) all direct the eye and attention, which distracts the motorist from what should be the centre of attention, namely the flow of traffic.

The brightly illuminated areas of the tunnel are embedded in a relatively dark environment which cultivates physiological and psychological glare phenomenon and due to the high contrast, light areas seem lighter and dark areas seem darker. This rouses the motorist's desire for visual orientation when driving through a tunnel and diverts attention again to the lightest area. A vicious circle is established.

As a result of this study, it was also ascertained by the authors that in the tunnels entrance domain of 51 to 250 meters, 76% of all accidents occurred due to rear-end collisions. This also accounts for more than half (55%) of accidents which occurred in the rest of the transit domain. The main reason for these accidents is a lack of distance held to the vehicle ahead. Tunnel lighting which would generate an even vertical light could, in this case, also make a decisive contribution in reducing the number of accidents. However, only horizontal parameters are to be found in tunnel lighting standards.

In conclusion, we would like to mention that social-demographic population growth is a deciding argument for improvement of tunnel lighting. Forecasts for the European Union signalize that in about 40 years one third of the population will be over 65 years old. Although older motorists only drive about 40% of the distance of working motorists [5], many do possess a driver's license. In 2003 for example, 85.7% of men and 47.7% of women in Germany over 65 years old, possessed a driver's license with the potential possibility of driving a motor vehicle [**Fig.1**]. Together with increasing age, there is also an increase in the danger of human error on the part of the motorist due to a deficiency in perception (e.g. degeneration of eyesight, increased dazzle or a reduction in color perception). Current studies [4] suggest the double risk factor by older motorists [**Fig.2**].

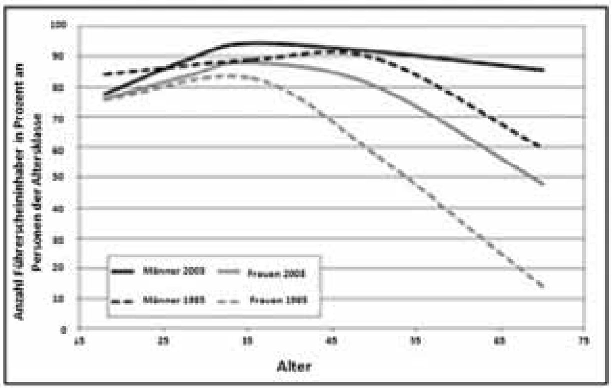

Fig.1: Age-related license availability, German motorist’s

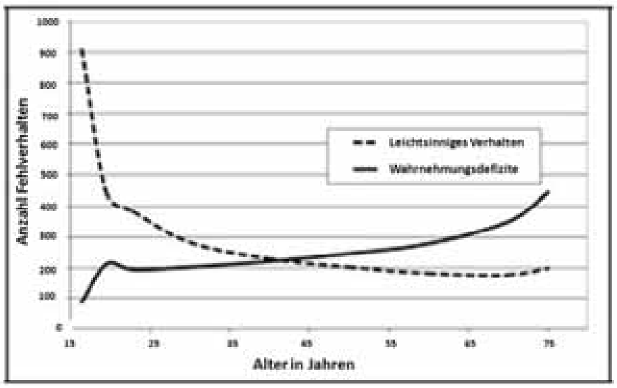

Fig.2: Age-related misconduct in road traffic [5]

A laboratory study, carried out in the “Kompetenzzentrum Licht”, indicated distinctly that a deficit in the perception of detail among older people could be partially reduced by means of higher roadway luminance.

2. LABORATORY STUDY ON TUNNEL LIGHTING

During a four-year laboratory study carried out in the Kompetenzzentrum Licht, 204 people were tested (31 of which were over 50 years of age) on the influence of different light environments in tunnels on the perception of detail, motion and space. It is precisely the changes in these perception parameters which should provide information as to which light intensity (road surface luminance of between 2 and 28 cd/m² was investigated) and light distribution (both continuous and punctuated ceiling lighting systems were investigated) provided the utmost attentiveness and the best speed variation- assessment of the vehicle ahead. The laboratory set-up ensured that each person was tested under equally good research conditions. The research was carried out using a projector [**Fig.3**] to simulate a tunnel with glare-free ceiling lighting (the maximum luminance of the projection amounted to 130 cd/m²) allowing for colors to be well identified and for a balanced distribution of light between the road surface and tunnel walls (it was about twice as bright in the central visual field as in the peripheral area) [**Fig.4**]. Such a research set-up makes it possible to exclusively record the influence of different light environments, characterized by light intensity and light distribution.

Fig.3: Research set-up

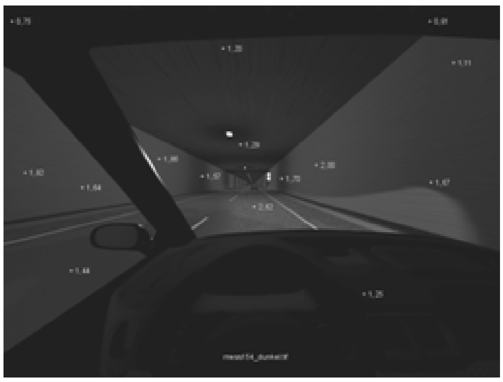

Fig.4: Balanced light distribution

Subject to the assigned visual task during the laboratory study, the following conclusions were reached: for a significantly improved perception of detail for younger motorists, a road surface luminance of 7 – 8 cd/m² is necessary. For motorists over 50 years of age, twice as much is necessary for a good perception of detail (approx.15 cd/m²). Furthermore, brighter conditions amplify the field of vision and the area of higher attentiveness.
Light distribution plays an extraordinary role in optimizing perception of motion and space. A continuous ceiling lighting system (with a luminance of 7 cd/m²) enables a significant improvement in space and motion perception performance.
Overall, it was concluded from the study that demands should be made for road surface brightness to be increased to at least 7 cd/m², together with installation of linear lighting systems in order to achieve a higher longitudinal evenness in horizontal and vertical directions.

3. VISIONS FOR TUNNEL LIGHTING

Last year, the ASFINAG commissioned the Lichtakadamie Bartenbach to carry out a concept study, the objective being, installation of innovative lighting concepts in tunnels. During the course of this study a conventional tunnel lighting system [**Fig.5, Fig.7**] was compared to various other lighting systems [**Fig.6, Fig.8**].

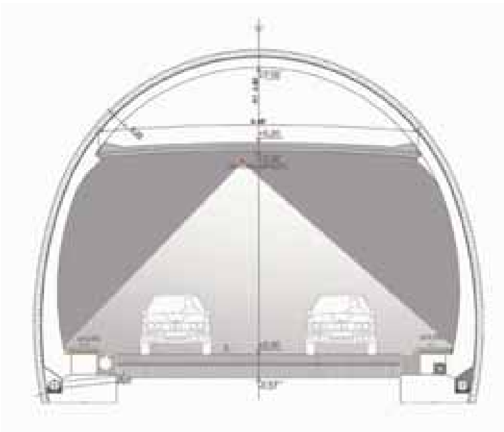

Fig.5: Conventional lighting

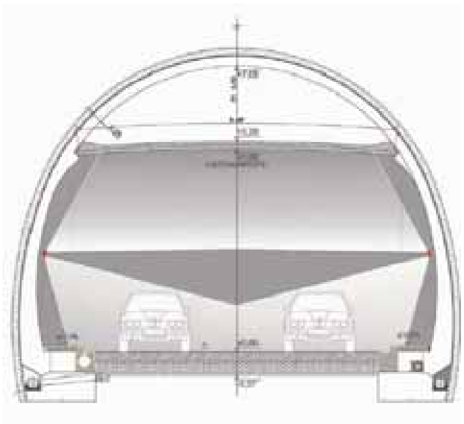

Fig.6: Lighting vision

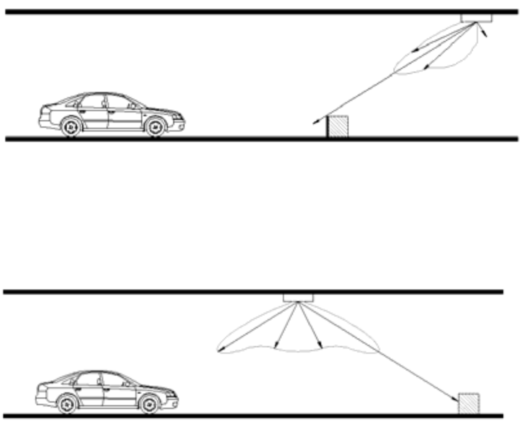

Fig.7: Conventional radiation principle

Fig.8: Radiation principle vision

This new concept was based on findings of the Kompetenzzentrum Licht laboratory study, together with a compilation of theoretical foundations and basic principles of motorist's visual perception when travelling through a tunnel, (e.g. recognition of contrasts, depth of accommodation and constancy of adaptation), and results in a high, even vertical lightness in the tunnel.
Apart from an innovative light distribution, this concept study implemented the application of LEDs for a tunnel lighting system [**Fig.9**].

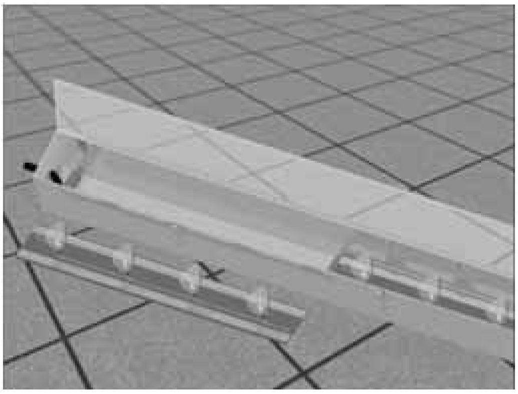

Fig.9: Sketch of a modular LED lighting system

With the application of LEDs, motorist's color perception during the journey through the tunnel will be optimally assisted. In addition, the small size of the lamps together with a special asymmetrical distribution of light (achieved through a lens system) makes it possible for directing light to be achieved by the luminance distribution, and not through the lights or road markings.
A subsequent result of this concept was the development of a prototype for LED tunnel lighting. The prototype fulfills all demands of the Austrian Tunnel Lighting Standards.

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REFURBISHMENT OF THE SAFETY AND VENTILATION EQUIPMENT OF THE TUNNEL CHAIN PACK

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1. INTRODUCTION

The A2 motorway runs from Vienna down to the Austrian/Italian border. The highest section of this motorway is the 'Mooskirchen-Pack'. The elevation ranges from 338 metres in the east and reaches 1,050 metres at the west portal of the Kalcherkogel tunnel. There are four tunnels along this section and a central control station at Unterwald. As a result of both the increasing traffic volume and the approaching end of useful life for the electrical and safety equipment, it became necessary to construct a second carriageway, and while doing so, replace all electrical systems.

Figure 1: A2 Motorway

Renovation and construction work on the new carriageway began on 6th May, 2003, and was completed on 28th June, 2007. Work on the new electrical and safety systems began on 1st December, 2004.

This presentation will focus on the new ideas used in the individual phases of the refurbishment process, and on the difficulties faced in overcoming conflicts between the new and old tunnel systems. Technical developments and test series will also be dealt with.

2. SUBJECT THEME

The ‘Pack’ chain of tunnels is part of one of the highest motorway routes in Austria. It was opened on 27th September, 1982, and included a section of approx. 20km in length with bi-directional traffic. By the time renovation work began, the initial traffic volume of 3,760 vehicles per day (1982) had risen to 18,300 vehicles per day. This fell somewhat during the construction phase, and reached a minimum of 17,100 vehicles per day by mid-2007.

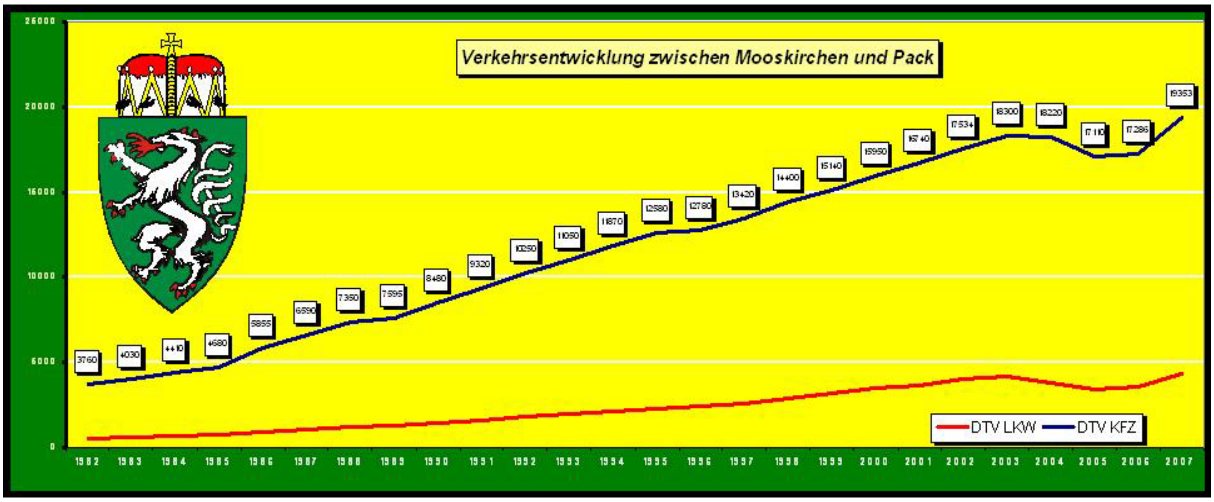

Figure 2: Development of traffic volume on A2 between Mooskirchen and Pack

The costs of refurbishment and renovation were as follows:

Table 1: Costs of the refurbishment and upgrading

	Tunnel Length	**Costs**
Assingberg tunnel	254 m	€ 2.4 million.
Herzogberg tunnel	2007 m	€ 9.3 million.
Mitterberg tunnel	1000 m	€ 6.0 million.
Kalcherkogel tunnel	2000 m	€ 8.2 million.
Central Control Station / Unterwald		€ 3.9 million.
Adaptation of open carriageway along the 32km ‘Mooskirchen Pack’ section		€ 2.3 million.

These figures cover the costs for all safety systems as well as the costs of adapting the energy supply systems.

The Pack tunnels are among the oldest in Austria and in part, they retained original structures in operation up to 2006. A further possible ‘highlight’ is the fact that the new tube of the Herzogberg tunnel was used as background scenery for the film ‘The Tunnel of Death’ (‘der Todestunnel’), which was shown in Germany, Switzerland and Austria.

Figure 3: Film scene

The logistical planning of Pack tunnel refurbishment had to be such that it allowed for maximum safety for the on-coming traffic diverted to the opposite tunnel tube, and to ensure sufficient progress such that unidirectional traffic flow was possible during holiday periods.

This resulted in the following phasing:

- Refurbishment of Herzogberg tunnel, southern tube,
- Renovation of Herzogberg tunnel, northern tube,
- Renovation of Mitterberg tunnel and Kalcherkogel tunnel, southern tube, followed by,
- Renovation of Mitterberg tunnel and Kalcherkogel tunnel, northern tube,
- Re-equipping of Assingberg tunnel, southern tube, and
- Renovation of control station in Unterwald, after which,
- Renovation of Assingberg tunnel, northern tube, and finally,
- Completion of the whole tunnel system.

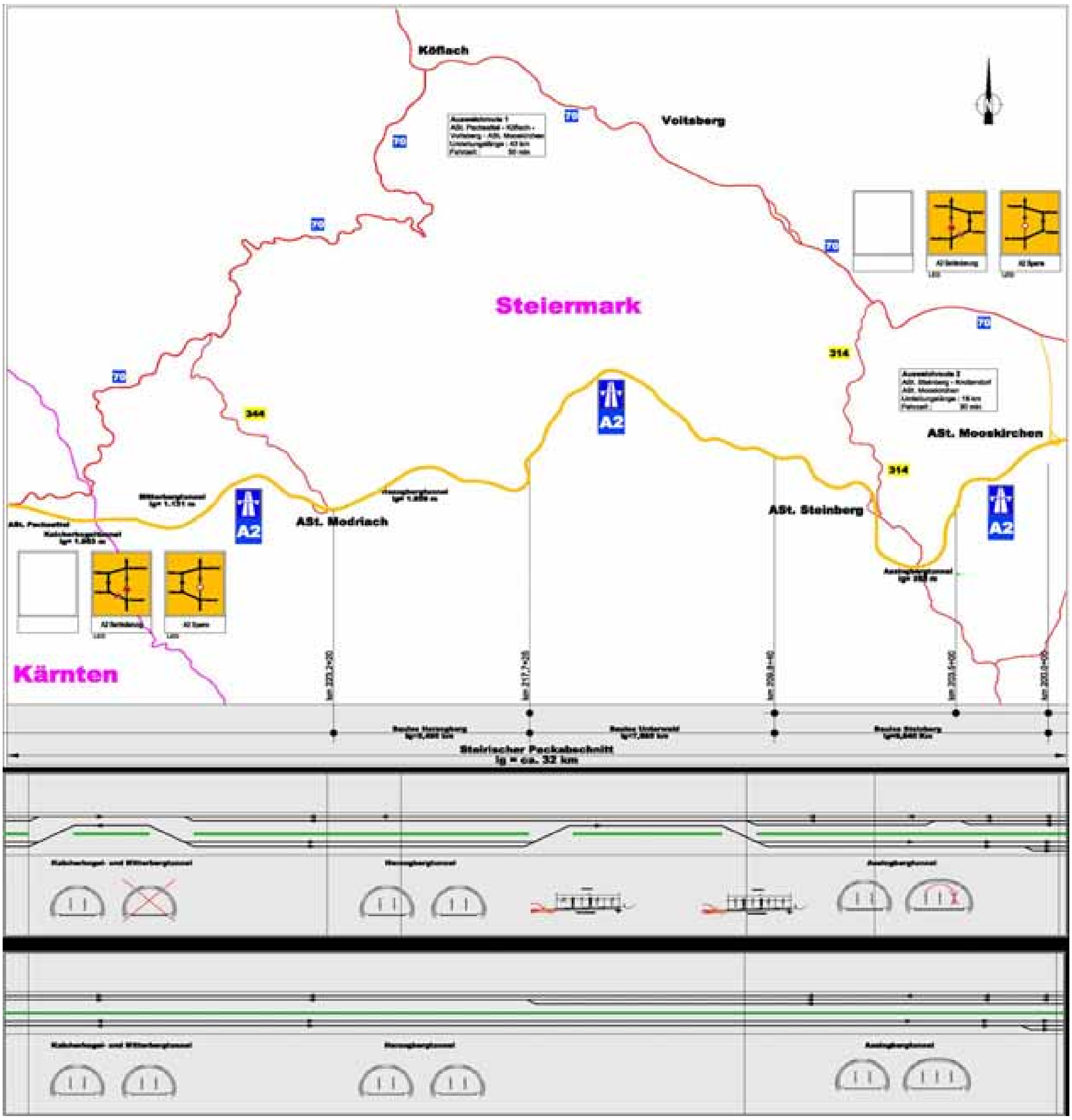

Figure 4: Example of traffic management

Emergency power, illumination, ventilation, traffic management, and emergency call systems, as well as all other systems necessary for safety control were completely renewed. However, during the traffic re-assignment and transition period, one tube was operated using old safety systems, and one with new systems.

The new safety plan was designed to accommodate full back up systems, including all those needed for communication and monitoring networks in Unterwald. Full back up was also arranged for the control station and two workplaces were set up. At the same time, preparations were also made to ensure that all necessary data could be relayed to a further central control station in the Plabutsch tunnel.

Figure 5: Unterwald Control Station

The need to ensure that a 24 year old system remains available for parallel operation and that no serious disturbances are caused by necessary reconstruction work meant that a number of unusual measures had to be taken. One example here was the need to physically suspend the old, fully operational distributor units(see Figure 6). In the Mitterberg and Kalcherkogel tunnels, parallel cables in the second tube were used to supply the sub-stations, until following the diversion of traffic, the old supply network was removed.

Figure 6:
Temporary suspension of distributor panels

In connection with the safety system refurbishment in the Pack tunnels, one of the subcontractors, SWAREFLEX, developed a new intelligent signalling system which operates via the LED kerb indicators. Here, inductance coupling is used to supply the LEDs and the new system also means that single lighting units on both sides are independent and can be programmed individually. This makes it possible to achieve a variety of sequencing and flashing programmes even for on-coming traffic.

With regard to component quality, in particular cable quality, a special cable was developed which is easily capable of withstanding the relatively high temperatures found in asphalt road surfaces. Initial tests were also undertaken involving the installation of inductance coils and cables under the final road surface. These are particularly useful in periods requiring rapid re-assignment of lanes since centre line indicators can be activated for on-coming traffic. As damage of single inductance units has no impact on other units, activation of emergency exit indicators can still be carried out reliably in the event of fire. Based on research carried out at RWTH Aachen on the impact of light sequencing on traffic speed, initial trials were attempted in the Assingberg tunnel. Tests showed that a four unit light sequence might be beneficial. Apart from its impact on traffic speed, such an intelligent LED lighting system has the further advantage that it provides for active sequencing of exit indicators as well as the possibility to activate centre line indicators.

Figure 7: LED sequencing speed

Figure 8: Emergency exit indicators

Figure 9: Centre line indicators

The ventilation system in the Pack tunnels is the first of its kind to use jet fans capable of withstanding temperatures up to 400°C. The fans were tested on a full scale model by the Munich University of Technology and easily survived such temperatures over 120mins.

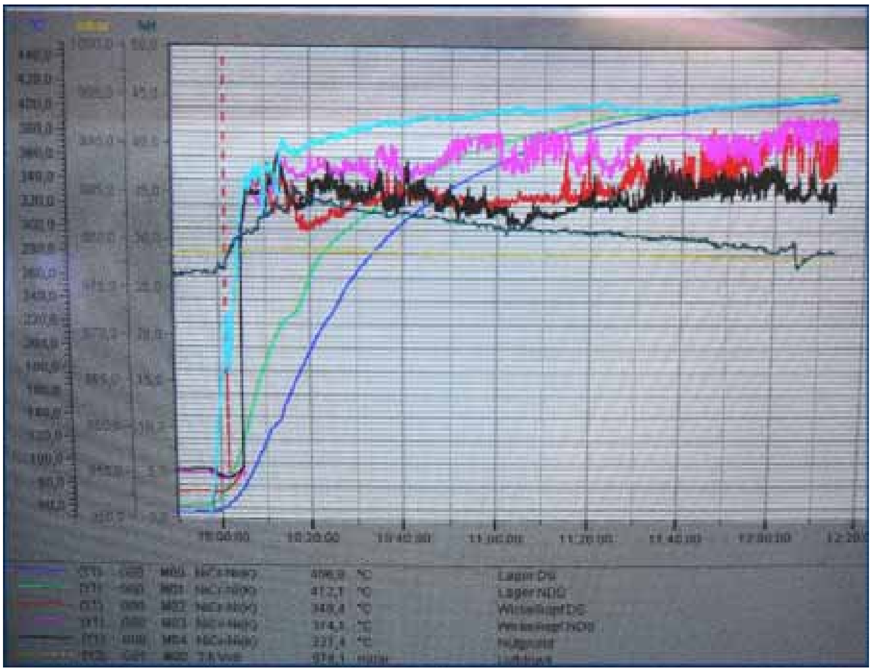

Figure 10: Testing at 400° C

The acceptance trials for the tunnel safety equipment involved numerous fire tests under a variety of circumstances. A great deal of valuable knowledge was thus gained with respect to the interplay of various factors, e.g. backlayering, tunnel gradient, the influence of connecting doors on ventilation control, smoke reversal etc. The new regulations for tunnel equipment (RVS 09.02.31,'Tunnelausrüstung, Belüftungsanlagen Grundlagen') reflect the insights acquired.

In one test, an attempt was made to reverse the direction of smoke flow using the existing ventilation equipment. The attempt was not at all successful since by the time the automatic fire detection system reacted smoke had already travelled a few hundred metres upstream in the traffic direction. Reversing smoke flow then meant that the cooled smoke had to be fully extracted back along the tube resulting in a smoke-filled tunnel for a considerable length of time.

A second test was carried out in the (descending) tube of the Kalcherberg tunnel. Strong backlayering resulted in the pair of jet fans (situated ahead of the fire) filling the empty half of the tube with smoke and reducing visibility to zero. It is thus important to take tube gradient into account when considering the distance between fans and the location of the fire.

A further test revealed that an open door to a cross-connection had such a strong impact that the flow of smoke during longitudinal ventilation was no longer in the desired direction. Here, the inflow of fresh air results in a movement of smoke away from the fire and in the opposite direction of the traffic flow. Thus, as far as ventilation control in the case of fire is concerned, all openings to cross-connections ought to be considered as a potential source of risk and the control mechanisms need to be set accordingly.

All Pack tunnels have now been operating with the latest safety equipment and systems since 28th June, 2007. One-way traffic now operates throughout and the return of traffic flow to its pre-renovation days is well underway.

MADRID CALLE 30:
AN URBAN TRANSFORMATION PROJECT

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ABSTRACT

The M-30, major ring road of the city of Madrid, was designed during the sixties in the past century as a main part of the road network of the city.

However, during the last few years a transformation project has been planned to redesign different areas of the city considering, as starting point, the conditioning of the M-30 ring road. The challenge to be tackled included the construction of more than 40 kilometres of urban road tunnels in addition to different actuations on other peripheral roads.

As a result of this project, with the opening of the whole tunnels network in June 2007, the improvement in mobility all along the ring road has been complemented with a significant environmental improvement related, not only to the reduction of traffic congestion levels, but the consequent recovery of surface space.

Keywords: city tunnels, project, safety facilities

1. BACKGROUND (INFORMATION)

The M-30, major ring road of the city of Madrid, was designed during the sixties in the past century as a main part of the road network of the city.

Different design criteria were applied during its construction phases during the sixties and seventies, when Madrid was immersed in a remarkable economical growth, with a strong increase in population, an important development of the metropolitan area and a constant increment of the motor pool.

These differences in its planning and construction turned the M-30 a collector highway with very heterogeneous average speed depending on the considered section, and affected by different malfunctions caused by:

- The different capacity of each section, with important variation in the number of lanes.
- The highly heterogeneous characteristics of the road, due to diversity in the number of lanes as well as the different traffic conditions among sections: free flow, traffic-light regulated,etc.
- The notable complexity of its junctions.
- The high number of lanes dedicated to lateral movements of vehicles, mostly of short length.
- The excessive number of entrance and exit ramps.

As a consequence, a strong reduction of mobility levels was being suffered in the M-30 ring road, causing an elevated number of accidents due to rear-end collisions (related with the aforementioned heterogeneous speed) and lateral collisions between vehicles (associated with the existence of entrance and exit ramps without acceleration and receiving lanes and the resulting change movements of vehicles).

In addition, the environmental impact was significant due to the important barrier effect, which was due to its surface layout.

2. URBAN RECONDITIONING VS M-30 ENHANCEMENT

In order to promote the M-30 retrofitting project, a mixed company (joint government-private company] has been established. This company, named 'Madrid Calle 30' and mainly owned by Madrid City Hall (80 % of its capital), is devoted to develop the M-30 restructuring project.

Under the responsibility of Madrid Calle 30 is, not only the performance of the most important works of renewal, updating and improvement but also the operation and maintenance of the ring road.

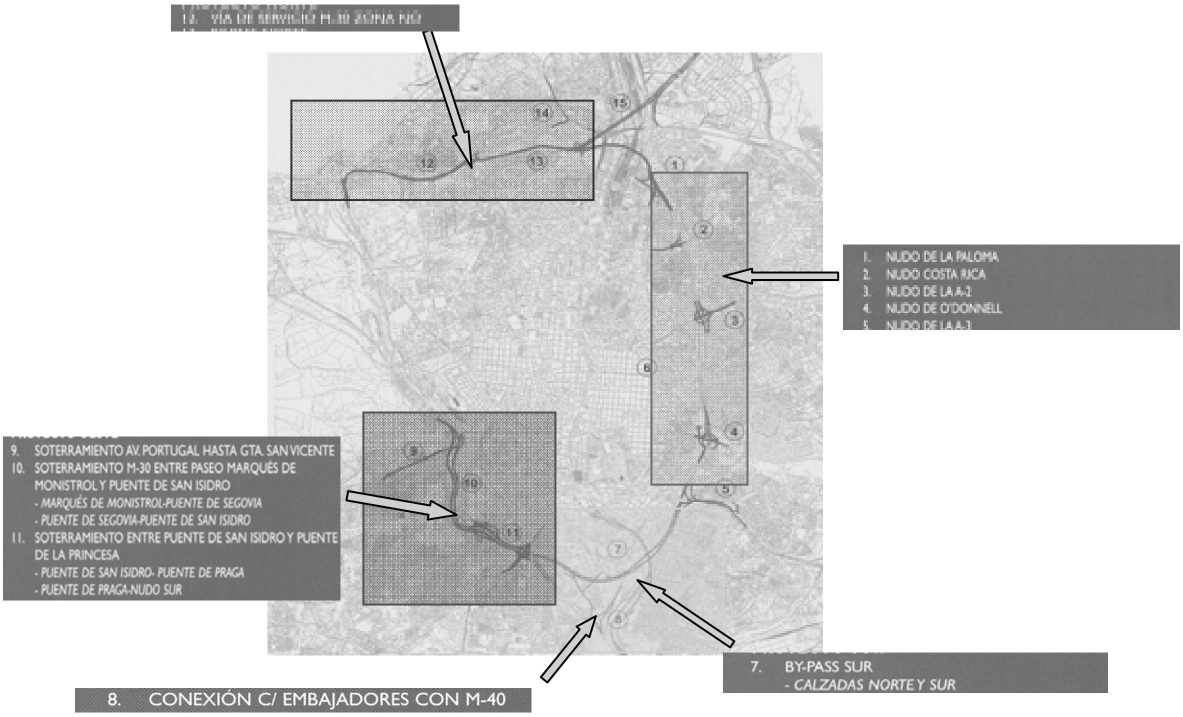


Figure 1: Scheme of the M-30 restructuring project

The whole project, which represents a milestone with no precedents in the field of urban restructuring projects, has been accomplished in less than 30 months, with the consecution of the following three main lines:

2.1. Improvement of junctions and general layout

Under this subsection, three different types of lines can be considered:

a.1) Improvement of junctions: simplification of vehicle movements in junctions which connect radial highways with East-West general routes with the use of new direct branches, both underground or raised.

Furthermore, one of the detected problems was the inexistence of connection roads necessary to allow certain movements with remarkable traffic demand, which were redesigned.

a.2) Capacity increase of certain sections: construction of an additional (fourth) lane in 'Avenida de la Ilustración' section and redesigning of its surrounding and approaching roads.

a.3) Restructuring of the layout of the East sector of the M-30: extensive works have been done in order to allow vehicles to move between the inner core of the M-30 and its adjacent secondary roads by means of specially designed lanes. The objective was to eliminate direct links, without transition lanes, between the inner core and the approaching roads, which were closely related to collisions and traffic jams.

2.2. Coverage of the West sector and its access from the A-5

This project covers the construction of tunnels for the complete transformation of the West area of the city. The objective was not only the improvement of the traffic flow, but minimizing of environmental impacts (acoustic, visual and pollutant emission) derived from the high traffic levels on surface.

In addition to the benefits of the coverage works that where accomplished in the 6 kilometres of the former M-30 close to the river and 1.5 kilometres of Avenida de Portugal, the increase in the number of lanes or the enhancement of the safety levels have been complemented by the suppression of the physical barrier that the M-30 constituted between the centre of the city and the surrounding green parks as that one denominated Casa de Campo and the future conditioning works of the river surroundings.

To achieve all these goals safe tunnels have been constructed, equipped with the latest technology which has allow an incremented in the number of available lanes to four, five or even six and buried direct branches at different depth have also been designed.

It is also remarkable that restoring works on historical bridges of Madrid have been accomplished.

Furthermore, taking advantage of the fact that the traffic will flow underground, filtration systems for particulates have been installed which allow to eliminate (with a performance above 90 % –even for particle sizes up to 0.5 microns) almost all the pollutant particles exhaled by the more than 200000 vehicles that will daily use these infrastructures. This means a notable improvement in the environmental pollution parameters, not only in the river area but also in the whole city.

2.3. Design of underground alternative routes

And last but not least, new tunnel connection have been constructed: the link between Embajadores street and the M-40 (the outer ring road of the city of Madrid) and the By Pass South tunnel. Both tunnels have allowed to reduce the traffic intensity in more than 30% in the road junction with the largest traffic intensity of Spain –more than 250000 vehicles per day.

3. CONSTRUCTIVE TECHNIQUES APPLIED

For the construction of the more than 50 km of tunnels that forms the new M-30 –both main and branch tunnels-, a wide variety of techniques have been used, ranging from classical methods for shallow tunnels (sections between sheet pile walls), traditional techniques for deep tunnels (Madrid method) or sophisticated high performance methods for deep tunnels (earth pressure balance tunnel boring machines).

Some figures that give an idea of the magnitude of the project are the following: more than 1.2 millions of square metres of sheet pile walls, 0.5 millions of linear metres of piles, 1.2 millions of square metres of carriageways, 3 millions of cubic metres of structural concrete, 0.5 millions of tonnes of steel for structures and 12 millions of cubic metres of soil dug during the works.

In those sections in which an improvement of its functionality and capacity was required the cut-and-cover technique has been used. The East sector junctions, the whole West sector and the access through 'Avenida de Portugal' are examples of the use of the cut-and-cover method.

Since it was a requirement to maintain, upgrade and, in most cases, increment the number of available connections with the surface roads, the depth of this infrastructure could not be excessive. This all conditions make the cut-and-cover method particularly suitable in this context.

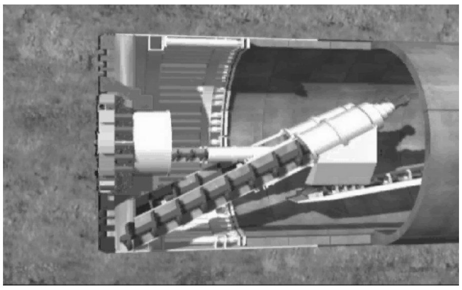
For the construction of the medium-size new underground alternative routes, as the tunnel connection between 'Embajadores' street and the M-40, classical mine digging methods have been used. The 'Madrid method' is a clear example of these classical digging techniques.

In the case of the long size new underground alternative routes, as the south by-pass of the M-30, minimum construction time and maximum safety conditions –both for workers and for surface equipment- were requirements to be fulfilled.

For that reason the two world largest earth pressure balance tunnel boring machines were specifically designed, with a digging diameter of 15.16 metres. Tunnel boring machines (TBM's) are particularly suitable for long and depth tunnels which have to be dug in a short term period.

The average month performance reached by the TBM's in the south by-pass were 15 and 18 metres advances per day, reaching maxima of 750 and 930 metres per month. This allowed to dig both tunnels –3.6 km length each- in a record time of 6.5 and 7.5 months respectively.

South by-pass
North tunnel TBM



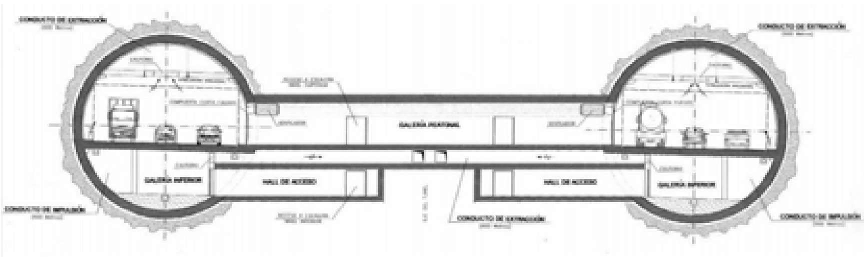
<u>Technical characteristics:</u>

Drilling diameter:	15.20 metres
Maximum thrust:	315880 kN (usually 10-20 %)
Maximum relief torque:	125 MN·m (usually 30-40 %)
Maximum penetration speed:	65 mm/min
Power on cutting wheels:	14000 kW
Number of hydraulic engines:	50 in outer wheel, 10 in inner wheel
Number of hydraulic pulling jacks:	57 (in 19 groups)
Foam equipment capacity:	417 m^3/h

South by-pass
South tunnel TBM

Technical characteristics:

Digging diameter:	15,20 metres
Maximum thrust:	317.000 kN (usually 10-20 %)
Maximum relief torque:	86 MN·m (usually 30-40 %)
Maximum penetration speed:	65 mm/min
Power on cutting wheels:	10024 kW
Number of electrical geared motors:	28 units of 350 kW
Central shaker:	5 metres diameter, 5 engines of 45 kW each
Number of hydraulic pulling jacks:	57 (7 groups of 7 units and 1 group of 8 units)

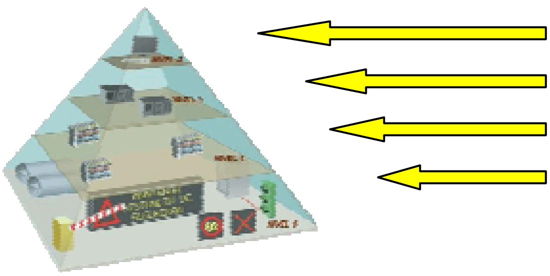


COMPLETE CROSS-SECTION **TYPICAL CROSS-SECTION**

4. CONVENTIONAL AND SPECIAL SAFETY EQUIPMENT

With the aim of ensuring the safest conditions in the operation of the new tunnels of the M-30, a pyramidal control system has been implemented. This control system comprises four levels, ranging from field level to main Control Centres level.

1. Main control level: Control Centres
2. Communications level
3. Distributed control level
4. Local equipment level



CONTROL CENTRES
COMMUNICATIONS
DISTRIBUTED CONTROL
LOCAL EQUIPMENT

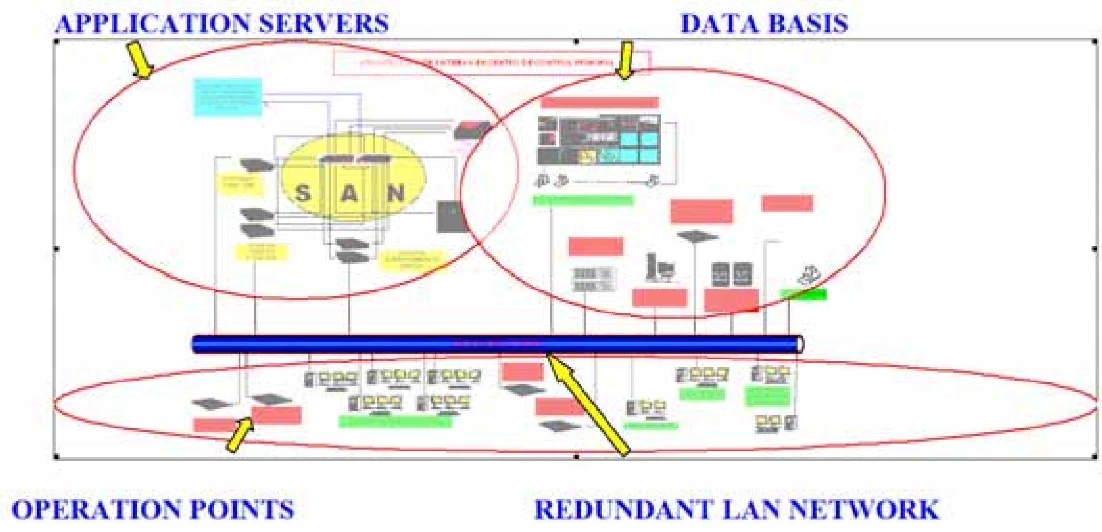
CONTROL SYSTEM HIERARCHY

4.1. Main control level: Control Centres

Equipment and human resources are coordinated from two major control rooms. The Main Control Room is the location where all the surveillance tasks for the M-30 tunnels are accomplished. Its functional design allows the latest technology in control systems with the needs of the daily operation.

To cover possible incidences that could damage or destroy the Main Control Room, there exists a Backup Control Centre from which traffic control, as well as the others functions of the Main Control Centre, would be assumed.

System architecture in both control centres is formed by the application servers, the data basis and the operation points, all connected by a redundant high capacity LAN network. The application servers comprises systems such communications network management, simulation, monitor, maintenance, Internet, vehicle number detection, radar system, PA system, video management system, SOS points and AID system.



4.2. Communications level

A powerful Gigabit Ethernet communications network has been set. Provided with redundant topology, it allows to connect the control centres with all equipment installed, as well as other emergency centres of Madrid (Fire Brigades, Police, medical assistance, DGT, Department of Urban Mobility, etc.).

Some characteristics of the communications infrastructure are: wire ring of 128 single-mode optic fibres along the whole M-30, two main access nodes located in both control centres, 36 nodes provided with Gigabit access located in the technical rooms of the tunnels and 302 Field Ethernet nodes (ERU's and UCDT's).

4.3. Distribution control level

Its functions are data acquisition and order transmission to the local servers from which directly depends tunnel equipment.

4.4. Local equipment level

- *Energy supply system:* with a medium voltage ring topology. It is capable to provide up to 56 MW by means of three main substations and several backup substations.
- *Ventilation and filtering systems:* with 165 high power axial fans, 270 extraction support fans, 470 jet fans, 30 stations for particle filtering and 4 stations for gases purification. Control ventilation is made by means of opacity, CO and NO_x analyzers, placed every 300 metres, as well as by anemometers placed every 100 metres.
- *Fire protection system:* comprising a fire hydrant network (one fire hose every 30 metres in both sides of the tunnel) and wet and dry hydrants network in every emergency exits (every 200 metres at the most). Moreover, there is a water-mist system in every technical room and in the deepest sections of the tunnels. Fire detection is performed by linear detection wire; indirect measures such opacity analyzers and AID system are also considered.
- *Radio communications system:* formed by redundant and independent radiant wires for security and general services. For security services, TETRA system is provided for Fire Brigades, Local Police and medical assistances, and TETRAPOL for National Police and Guardia Civil. In terms of general services, mobile GSM telephony, eight FM channels and two channels for maintenance are supplied.
- *Emergency exits:* every 200 metres an emergency exit is accessible. All emergency exits are pressurized, automated, remote-controlled in its connection to the surface and permanently supervised.
- *Lightning system:* tunnels have been equipped with continuum lines of white light luminaries in both sides, in order to ensure homogeneity, comfort and safety conditions. It is possible to adjust light intensity from the Control Centre.
- *Traffic control system:* which includes variable-message panels, maximum height control (both mechanical and electronic systems), safe closing barriers, traffic lights, vehicle number detection system and radar system along the tunnels.
- *Closed TV circuit and Automatic Incident Detection system:* more than 600 cameras supervise tunnel conditions every 80 metres, as well as the emergency exits, technical rooms and emergency exits. A codifier-recording MPEG-4 system stores the images and then sends them to the Control Centre. Additionally, an Automatic Incident Detection system, with capacity for eight cameras, is available.
- *Emergency boxes:* SOS points are accessible every 75 metres. The communication protocol used is TCP/IP.
- *Loudspeaker system:* a loud speaker system with TCP/IP protocol covers the whole tunnel network.

To ensure a correct operation of all systems, a comprehensive document (Operation Manual) have been written, in which all activities required for the proper operation of the tunnels –security, traffic control, maintenance, etc.

For every single task, a detailed list of the human and material means that should be available is collected. So on, the classification of possible events or incidents has been accomplished taking into account the severity classification, the procedures to manage the situation with the main objective of achieving the goals of safety and comfort for the users.

VENTILATION SYSTEM DESIGN AND LARGE SCALE FIRE TESTS

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ABSTRACT

The design, construction and operation of the tunnels of M-30, the major ring road in the city of Madrid (Spain), represent a very interesting project in which a wide variety of situations – geometrical, topographical, etc. - had to be covered, in variable conditions of traffic. For that reasons, the M-30 project is a remarkable technical challenge, which, after its completion, turned into an international reference.

From the 'design for safety' perspective, a holistic approach has been used to deal with new technologies, integration of systems and development of procedures to reach the maximum level. However, one of the primary goals has been to achieve reasonable homogeneity characteristics which can permit operate a network of tunnels as one only infrastructure.

In the case of the ventilation system the mentioned goals have implied innovative solutions and coordination efforts of great interest. Consequently, this paper describes the principal ideas underlying the conceptual solution developed focusing on the principal peculiarities of the project.

Keywords: ventilation design, city tunnels, environmental management

1. INTRODUCTION

Traditionally, the construction of long size tunnels has been associated with major interurban roads or railway lines. However, in the urban scope, large road tunnels have seldom been constructed due to the inherent characteristics of the urban traffic.

In the last decades, an improvement of the environmental conditions, as well as the need of recovering urban spaces for social purposes, joined the growth of major cities. In the city of Madrid this trend has taken the form of the works of coverage of an important part of the M-30, major ring road of the city of Madrid, which had been surrounded by the urban buildings due to the growth of the city.

The project for the redesigning of the M30 (Madrid M30, 2007), with more than 71 different construction works all along the ring road and peripheral routes, has been completed during the cycle 2003-2007 and among these actuations, several tunnels of moderated length have been constructed (O´Donnel, 1440 m; Ventisquero de la Condesa, 1500 m; Costa Rica, 630 m; Sor Angela de la Cruz, 1600 m; Embajadores-M40, 1800 m).

However, the most challenging project included an underground network of different tunnels, with a total length of more than 40 km of twin tubes tunnels. One of the most interesting aspects is that due to administrative and organizational reasons the whole project was divided into smaller sub-projects. Consequently, each one of them was awarded to different construction companies or joint ventures of them (figure 1).

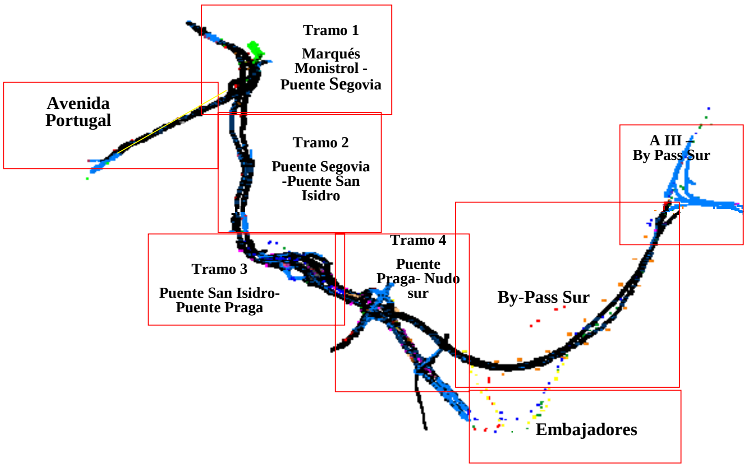


Figure 1: General layout of the project and administrative division.

By one side, this disaggregation permitted a quick execution with enormous human and technical resources; from the other, coordination to get the necessary homogeneity between all the works was of the utmost importance.

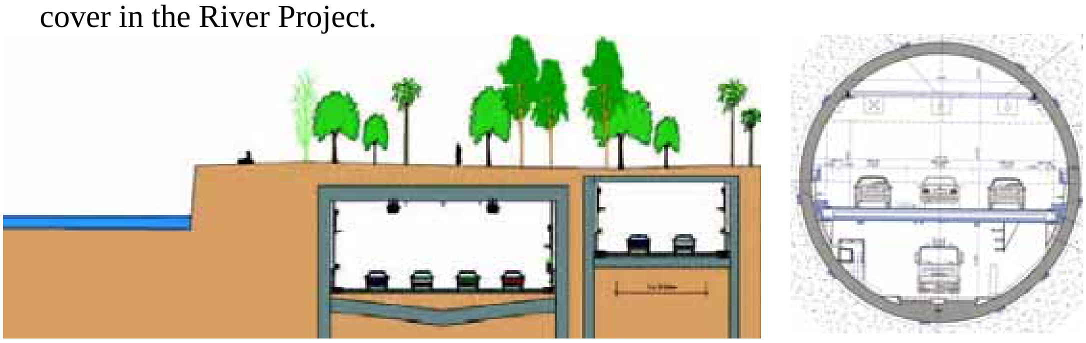
Looking to the past, it must be said that the organization of interdisciplinary working groups during the design and construction phases and the creation, in an early stage, of the actual operation company, Madrid Calle 30, has been one of the key aspects in the success of the objectives fixed.

In the case of safety and ventilation systems, the homogeneity and uniformity goals, could be reached through the preparation of technical specifications which gained the "ideal" criteria to be followed by the engineering companies and technical departments of the construction companies, which were responsible for the elaboration of the detailed projects and the search of imaginative solutions that could appear during the construction phase.

2. VENTILATION CONCEPTUAL DESIGN AND DIMMENSIONING CRITERIA

Strongly related to the construction methods, but focused to the goal of homogeneity in the ventilation conceptual design, the election of the type of ventilation system was conditioned by the main characteristics of the tunnels:

- Geometry: urban topology with high density of surrounding buildings and population highly concerned with environmental impact
- Two different construction methods: TBM section in the By Pass tunnel and Cut and cover in the River Project.



- Traffic composition: prohibition for dangerous goods, low heavy good vehicles (with limitation to the maximum weight up to 8 tonnes and busses)
- Traffic scenarios: fluid flow and possible congestion (even with traffic control measures adopted). AADT up to 100.000 veh /day

- Other operational aspects: High surveillance level, fast response time of (internal and external) fire emergency services, etc.

Based on the characteristics of the project different alternatives were evaluated during the basic design stage. However two main topics were highlighted: environmental impact during normal operation and fire management.

Concerning the environmental management, in shorter tunnels inside the city of Madrid is based on the dispersion of the pollutants through the portals. However, due to the great length of these tunnels the strategy has been double: the definition of shorter ventilation sections and also dilution of the contaminants with large air flow rates.

In this way, a lot of ventilation stations have been installed to split off (in sections of around 600 meters) the contaminant charge to avoid the emissions concentration on a very few points. In addition, reinforcement on the contaminant dilution levels, both inside and outside the tunnels, has been used.

Since there are no specific Spanish guidelines for dimensioning ventilation systems for tunnels (either in normal operation or in case of fire), PIARC reports (PIARC 1995, 1999, 2000, 2004) and French guidelines (CETU, 2005) have been the main references.

According to PIARC criteria, but also considering larger dilution air flows for environmental reasons and since it was expected to have large times of permanence in the tunnels due to congested traffic, a maximum CO level of 30 ppm was considered. Accordingly, parametric studies to calculate the ventilation needs for a standard 3 lanes section, 1 km length tunnel for slopes between -5 and 5%, conduced to air flow rates of 285 m^3/s/km for a 3 lane tunnel.

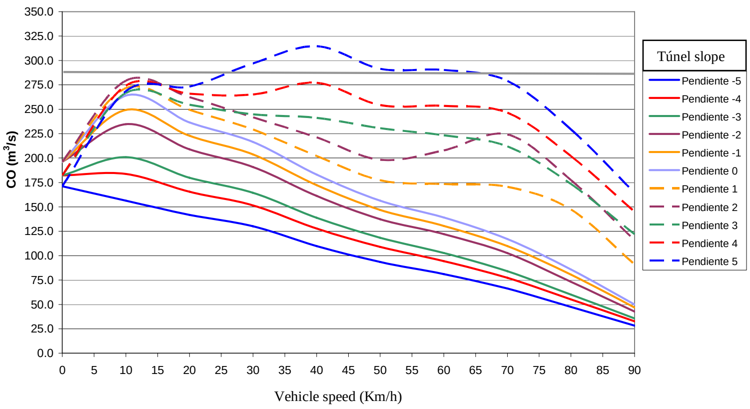


Figure 2: Parametric study for the determination of air flow rates.

In addition to those measures, to improve the quality of the environmental air conditions in the city, particles and NO_2 filtration stations have been installed on the ventilation shafts (4 units of 680 m^3/s each) of the By-Pass Sur (where there was enough space for them), and only particles filtration stations (15 units) on the river section of the project with expected efficiency not below 80% for both PM10 and PM2.5.

These filtration stations have been complemented with electric, control and storage installations and also By-Pass systems to minimize damages in case of fire. It is worthwhile to mention that, as far as four different companies have been contracted to supply the electrostatic precipitators and the filtration stations, it was decided to install, one in each of the ventilation stations, the same model of equipment for the monitoring process of the emission levels and efficiency estimation. It is expected that, in the close future, very useful qualitative and qualitative information about the behaviour of this filtration systems will be available.

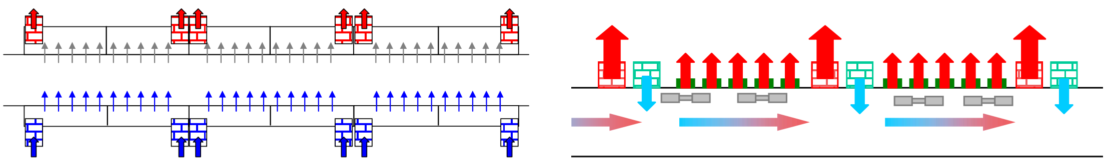
Concerning the fire incident management, taking into account a design fire size of 30 MW, two different approaches were possible, related with the construction method:

- In tunnels where ventilation ducts could be used, mainly the By Pass tunnel constructed with TBM technologies and the links to the adjacent tunnels (A-III link and Section 4), a purely transverse ventilation system was proposed, with a maximum length of 600 meters with separated fresh air and exhaust circuits (Figure 3 a).

  The fresh air was transported through the duct formed under the carriageway (which should be used also as a evacuation and emergency access way) and supplied to the traffic space through nozzles (70 x 35 cm^2) situated each 10 meters in both sides.

  The exhaust duct, situated above the roof, was designed for the extraction of the vitiated air during normal operation and the smoke in case of fire, which was connected with the traffic space trough, regulated but not remote controlled, openings of 2 m^2 each 25 meters.

  The total air flow capacity is 170 m^3/s per section, i.e. 600 meters, what was accomplished with the construction of ventilation shafts each of one covered not more than 4 ventilation sections and expelled up to 680 m^3/s of treated air.



a) By Pass tunnels

b) River section

Figure 3: General layout of the ventilation system

- In cut and cover tunnels very close to the building and where the existence of other infrastructures (pipelines, underground lines, river channel) made impossible the construction of ventilation ducts a longitudinal system with exhaust reinforcement was proposed.

  The general layout consists on ventilation sections of separated around 600 meters. The air flow enters the tunnel through an injection station and is extracted at the end of the ventilation section. The shafts are complemented by jet fans to direct the air flow movement in the traffic direction (Figure 3 b).

  However, to improve the behaviour of the ventilation system in case of fire it was proposed the installation of additional single exhaust points of 30 m^3/s and separation of 100 – 200 meters, what permitted the desired homogeneity with the transversal solution in case of fire.

  The dimensioning criteria for the exhaust ventilation stations consist is based in the use as massive exhaust points which should allow an air velocity in the way of the traffic higher than the critical velocity. This criteria has been fulfilled with exhaust air flows ranging 200-300 m^3/s what has implied an extraordinary effort to the engineering and construction companies in charge of the detailed engineering design, to achieve innovative solutions and, in case of impossibility, the adoption of complex designs where interconnection dampers or intermediate ducts have been necessary.

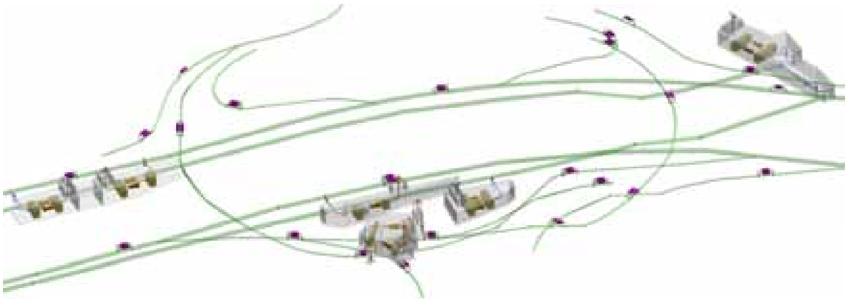


Figure 4: Detailed design for the ventilation system of the River Project

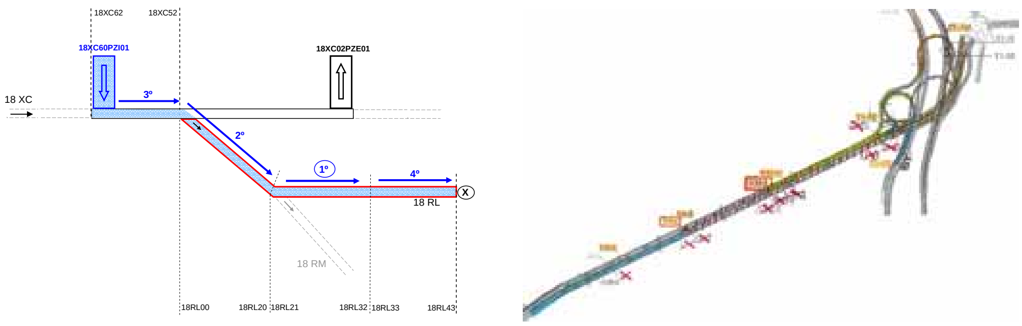
3. VENTILATION CONTROL SYSTEM

Ventilation control system consists of carrying out automatic ventilation operations as well as proposing others actions to the operator in order to facilitate his decision making in any situation. The principal purpose is to minimize the reaction time in either normal or emergency operation.

For **ventilation during normal operation,** a distributed control system has been developed, dividing the tunnels network into sectors which are controlled by independent remote control units. For simplification of the maintenance process, only one algorithm has been developed but specific configuration can be set for each independent ventilation zone.

Control logic is based on regulation by intervals consisting of rules that compare pollutant and velocity (treated) measurements with pre-set reference values. The set values determine the ventilation strategies, and therefore they must be adjusted during normal operation.

Because of the complex road tunnels network, ventilation control during normal operation has been set up in zones called "preferential paths for mechanical ventilation". In order to harmonize ventilation operations, the entire tunnels network has been divided into zones of similar characteristics, in particular, according to the kind of road. The three basic types are: (1) zones which belong to a main road, (2) entries in main roads, and (3) exits from any road.



a) Preferential paths definition for normal operation   a) Predefined automatic actuations in case of fire

Figure 5: Strategies schemes for ventilation control

In case of fire, the ventilation scheme is completely different from normal operation. On one hand, the actions which must be carried out for controlling ventilation in the fire zone depend on the information of other zones. And, on the other hand, synchronized operations must be realized simultaneously over a lot of equipment. Therefore, the ventilation strategies to apply must be based on decisions which are made by the Main Control Centre, including the following stages:

- Detection of fire alarm either automatically by means of linear heat detection system or manually activated by an operator upon visual detection through (CCTV).
- Identification and validation which allows the operator to confirm or not the existing alarm in order to start or avoid the automatic ventilation operations. If there is not any operator response, the control system will confirm automatically the fire after a certain time.
- Ventilation operations: Once the fire location is confirmed, automatic ventilation operations are launched.

From the point of view of the actuations on the ventilation system three stages are defined:

- 'Safety-state': in order to minimize the response time in case of fire, safety ventilation operation starts on as soon as a fire alarm is detected including actuations which are not harmful in case of a false alarm or wrong identification. In general, operations include the stop of ventilation algorithm for normal situation (only in specific zones), the stop of fans which generate high levels of turbulence (supply stations and jet fans) and the starting on of the exhaust system.
- 'Automatic response': after the identification and validation process the following steps will be carried out automatically:
    - operations called 'Initial ventilation' with the main objective of maximize the smoke extraction through both fire-zone and surrounding-zones and, secondly to reduce air velocity in the fire-zone in order to achieve smoke stratification.
    - activation of the algorithm for the longitudinal airflow control to improve the response of the 'Initial Ventilation' if necessary, and, on the other hand, to keep the velocity between reference values, which directly depend on the traffic conditions. For this purpose, the system must to change automatically the reference velocity values as a function of the traffic conditions of previously selected zones.

In addition to those automatic systems other procedures are available to make the necessary changes in ventilation conditions at any time, for example, for supporting Emergency Services.

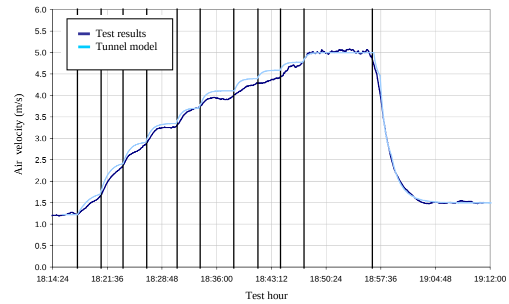
4. IN-SITU VENTILATION TESTS

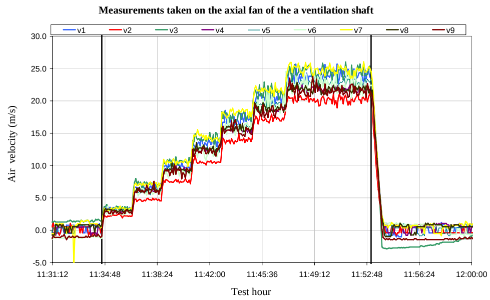
A whole test campaign has been carried out in the Calle 30 tunnels installations by the quality departments in charge of each branch of the project.

Related to the ventilation system, several tests have been carried out in the tunnels: from individual tests of sensors and ventilators to in-situ test to determine parameters of the installation and the verification of the global behaviour of the ventilation system to check how the system behaves when working as a whole (that is to say that every part of the ventilation system and the software programmed for the normal working of the tunnel and in case of fire does indeed work as projected).

Some of these in-situ tests are listed below:

- Verification of the hydraulic behaviour of the ventilation system, jet fans and big axial fans to check their air flow rates, efficiency, rotating speed, electric expense…
- Verification of the hydraulic parameters of the tunnel (friction factor that usually includes wall roughness as well as the lights, information panels,…)





- Verification of the correct working of the fresh and exhaust air ducts and the correct regulation of the dampers regulation (specially in case of fire), on transverse ventilation system.

5. LARGE SCALE FIRE TESTS

In the search of high security levels for the Calle 30 tunnels, the chance of complemented the expected ventilation system with automatic extinction ones was planned.

However, accumulated experience about mixed effects of these two systems is scarce, so it was needed to tackle it from an experimental planning. During 2006, together with Madrid fire department and different manufacturers specialized in water mist systems, a large scale fire tests campaign was carried out.

Among the objectives of these tests it is necessary to emphasize the study of escape conditions in the presence of different ventilation and extinction systems conditions, the verification of control or extinction capability under different ventilation conditions and the firemen participation in extinction tasks and as observers in fire tests for evaluating the systems behavior.

Fire tests were carried out with different predefined loads (normalized wood euro-pallets, diesel pools and real vehicles) with estimated heat released rates between 5 MW and 30 MW (according to the expected fire loads). During the tests, different ventilation conditions (similar to the available ones at the tunnels), temperature evolution, visibility and air velocity were evaluated.

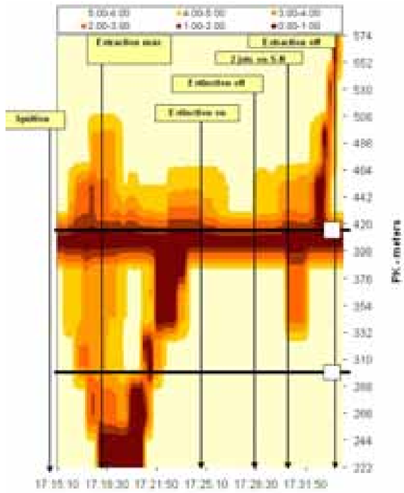
On the other hand, one of the main difficulties for large scale test planning was the need to fix a test matrix that allowed the obtaining of significant results. In this way, among all factors that were involved in an actuation process in case of fire, the decisions taken were based on ventilation and extinction activation times, due to the reaction time depends of non-contemplated factors.

About ventilation system, the test matrix definition was made on two dimensions: passed time up to extraction activation and longitudinal velocity value during the test.

With respect to the extinction system, the considered significant parameters were activation time and fire location capacity of the operator.

Temperature, air velocity and visibility measurements were carried out to evaluate the interaction between ventilation and extinction systems. These tests campaign have provided a lot of valuable data and information to support the decision judgment and to try to avoid interferences between water mist systems and ventilation ones.

In addition, it is necessary to remark, the constant and active Madrid city council fire department participation, not only in the test definition but also in their realization; which has helped them to develop intervention and organization procedures.



6. CONCLUSIONS

The construction of the Calle 30 tunnels represents a very interesting project in which a wide variety of situations had to be covered, in variable traffic conditions. For these reasons, both the project and its development have been a remarkable technical challenge and it has turned into a national and international reference after its completion.

The authors have had the chance to participate on the technical advisement for the definition of the general operation and design criteria of the ventilation system, so that the projects elaborated by the different engineer companies would maintain the necessary homogeneity and coherence. Additionally the authors have participated in the different multidisciplinary workgroups formed during the project development for the management of the environmental issues, fire safety and operation.

The authors warmly appreciate the challenging opportunity provided by Ayuntamiento de Madrid and Madrid Calle 30 to participate in this singular project.

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SCENARIO-BASED RISK ANALYSIS FOR ROAD TUNNELS

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ABSTRACT

In the French process for tunnel safety management, application of scenario-based risk analysis is used as a complementary tool to prescriptive requirements. For tunnels at design stage, at commissioning stage, or for tunnels in operation, the first major link in safety chain consists in defining reference condition. In this frame, place of scenario-based risk analysis in the safety chain is only complementary. In this paper, the specific aspects of scenario-based risk analyses are described and discussed.

Keywords: *risk analysis, scenario, specific hazard investigation, safety documentation, road tunnel*

1. INTRODUCTION

When notion of Specific Hazard Investigation has been introduced in French regulation for the first time [4], the question of its contents and objectives was raised. Very rapidly, CETU published a technical note, the objective of which was to define the content of such risk analyses. This definition derived from methodologies for Hazard Investigations conducted in the field of hazardous industries for more than 30 years.

Since that time, European Directive 2004/54/EC on minimum safety requirements for tunnels in the trans-European road network has made mandatory the Specific Hazard Investigation, as part of Safety Documentation.

In the meanwhile, a number of booklet have been published in France, that aim at providing guidelines for elaboration of Safety Documentation [1], of Specific Hazard Investigation [3], and to provide guidance for definition of a reference condition of an existing tunnel [2].

2. PROCESS FOR ROAD TUNNELS SAFETY

In France, for a tunnel at design stage or at commissioning stage, there are generally few discussions about acceptance of its level of safety. It is well defined by prescriptive requirements for new tunnels, as it is in Technical Instruction [4] – TI – for instance. At most, some discussions can arise about organisation for operation and rescue.

On the contrary, prescriptive requirements for new tunnels are not systematically applicable to tunnels in operation. That is why a specific process is required, so as to define a reference condition that can be considered as acceptable regarding safety conditions. In France, this process is defined as illustrated in the following **Figure 1**. This illustration is derived and extrapolated from [2].

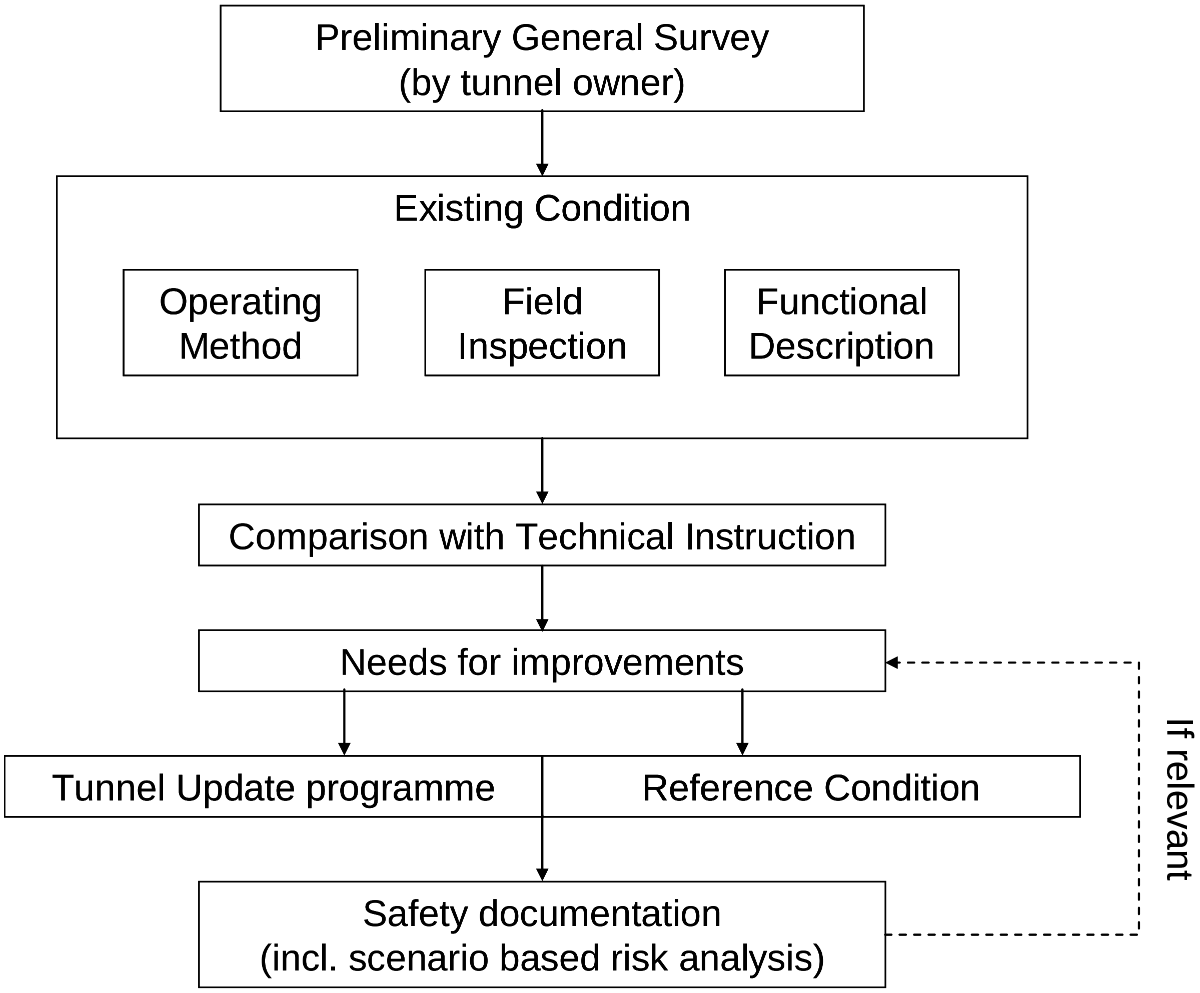

Figure 1: Specific process for tunnels in operation, so as to define an acceptable level of safety. Derived from [2]

Process is then made of the following steps:

- **Step 1**: A preliminary overview of tunnel existing condition is conducted by the tunnel owner. This first step aims at sorting between provisions / parts of organisation that do not need any further investigations (for instance: emergency stations have been renewed recently and do not need any further improvements) and provisions / parts of organisation that need detailed investigations (for instance: principle of longitudinal ventilation in a urban 2.1km long tunnel, and potentially congested traffic in peak hours);
- **Step 2**: Detailed investigations are conducted for provisions / parts of organisation that need it, as identified in step 1. Those detailed investigations may necessitate specific analyses of organisation for operation, or specific inspections, for instance to check the conditions for creation of new emergency exits, etc.;
- **Step 3**: Once existing conditions of tunnel are known with an appropriate level of accuracy, a comparison with requirements of Technical Instruction [4] is performed. This comparison aims at giving an idea of existing gaps between the investigated tunnel and a new tunnel of the same type;
- **Step 4**: Based on feasibility studies that contain an estimate for costs and planning, and based on expert judgment, a set of improvements is defined;
- **Step 5**: An update programme is then defined. Reference condition is the result of implementation of update programme;

- **Step 6**: At this stage, tunnel reference condition is provisional. Its consistency has still to be checked, and a Specific Hazard Investigation is performed in this aim.

3. METHODICAL ASPECTS OF SPECIFIC HAZARDS INVESTIGATIONS

In French approach, Specific Hazards Investigations consist in scenario-based risk analysis, although other methods would have been possible [5]. They are made of the 5 following chapters:

- **Overview of tunnel and environment**. This chapter is dedicated to description of tunnel in its reference condition, with regard to safety.
- **Functional description of tunnel**. This chapter allows description of how civil engineering, equipments, organisation for operation and rescue, etc. work towards safety.
- **Identification of hazards and choice of scenarios**. Contents and objectives of this chapter are described in **§3.1** below.
- **Examination of scenarios**. Contents and objectives of this chapter are described in **§3.2** below.
- **Conclusions**. This last chapter aims at giving an opinion on reference condition, and to recommend further improvements, if needed.

3.1. Choice of scenarios to be studied

3.1.1. Trigger events

Based on experience, a list of potentially hazardous events is built, in relation with the tunnel studied and its environment. Those potentially hazardous events generally result in a limited number of trigger events:

- Breakdowns,
- Collisions, with or without injuries,
- Fires,
- Accidents with dangerous goods involved. Note that even in a tunnel where dangerous goods are prohibited, such events could be possible, due to trespassing vehicles.

3.1.2. Analysis of frequencies and consequences

Considering the above mentioned trigger events, and the different categories of vehicles admitted in a tunnel, an estimate of frequency and severity is performed, and situated on pre-formatted scales:

- *Quantitative frequency analysis:* Frequencies are calculated, as a function of several factors as tunnel length, traffic volume, accident rates, etc. In most cases, calculation is based on an analysis of accident data (collection of local incident data) or based on default values (case of tunnels at design or commissioning stages). The calculated figures are then placed in a A (one event per year or more) to F (one event per 10 000 year or less) scale;
- *Qualitative consequence analysis:* Each trigger event is estimated to be of a given class of severity, from I (only material damages) to V (50 fatalities or more).

3.1.3. Frequency x Severity matrix

Based on the preceding estimate, a Frequency x Severity Matrix is built, in order to support the choice of scenarios to be studied, as shown on **Figure 2** below.

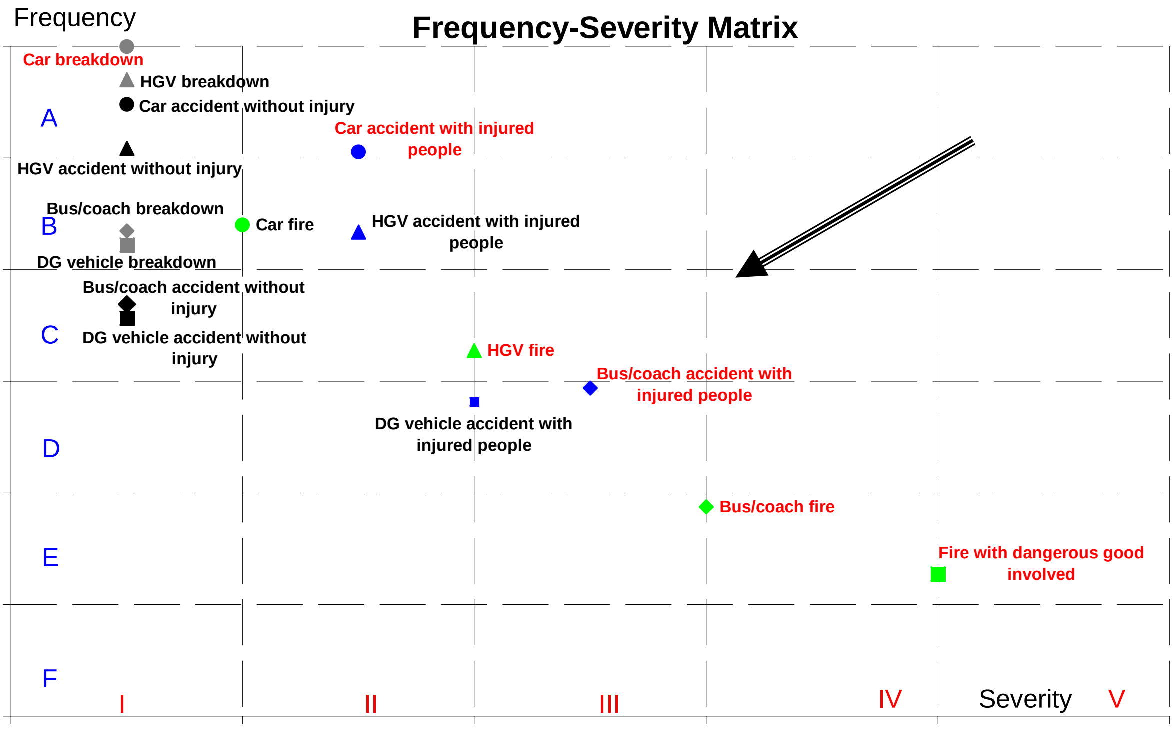

Figure 2: Frequency – Severity Matrix, according to [4]

Scenarios to be studied are derived from the most potentially severe and/or frequent trigger events. On **Figure 2** above, the corresponding trigger events appear in red colour. Note that, French guidelines [4] make imperative the selection of "standardised" trigger events, such as:

- 30MW Heavy Goods Vehicle (HGV) fire,
- 200MW HGV carrying Dangerous Goods (DG) fire,

for tunnels where HGV carrying DG are admitted.

At this stage, a choice of scenarios among the selected trigger events has to be done. Those scenarios are defined by a context, made of specific meteorological conditions, specific level of traffic, specific conditions for operation, specific human behaviour, etc.

So as to avoid the study of an excessive number of contexts, a few representative situations must be considered, together with a sensitivity study on main parameters.

3.2. Examination of scenarios

Once a few scenarios have been selected, possible consequences are estimated for people, with support of 1D or CFD modelling, depending on required level of accuracy. **Figure 3** below gives an overview of possible representation of scenarios, based on time-space graphs.

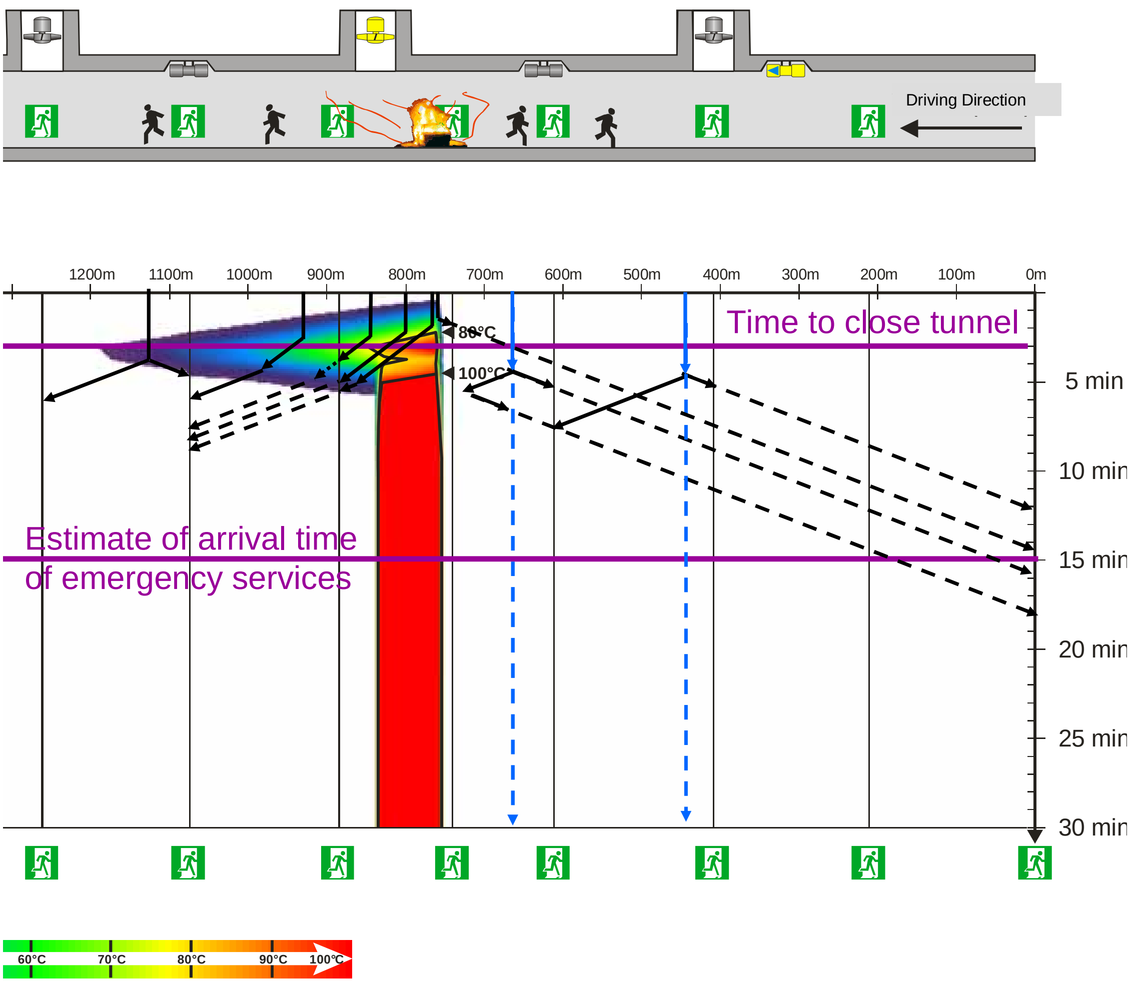

Figure 3: Representation of consequences for people of a fire in tunnel

On this graph:

- Distance, in meters, from upstream portal, is represented from right to left, in X-coordinates,
- Time, in minutes, is represented in Y-coordinates,
- Average temperatures in a given section of tunnel are represented from a blue colour (low temperatures) to a red colour (high temperatures),
- Possible or expected movements of people are represented by means of blue/black arrows. On this graph, several behaviours, expected or not, are investigated: people that move escaping, people that move toward the fire, people that stay in their car, etc.

So as to represent people behaviour (including: tunnel operator, road users and evacuating people), the following standardised assumptions are made, according to [4]:

- Drivers respect the speed limits;
- Drivers are not supposed to respect interdistance when they stop, if any;
- If there are red traffic lights inside the tunnel (typically every 800m), drivers are not supposed to respect them;
- If there are intermediate barriers inside the tunnel, drivers are supposed to respect them;
- It is generally considered that people begin to evacuate when they can themselves perceive danger. For instance if they are in smokes, or if they see other people evacuating;
- Once danger is perceived, starts a 1.5 minutes delay for people to effectively evacuate vehicles – 5min in case of a bus / coach;

- If any, the effect of systems of alert can be checked, by reducing time to perceive danger: messages in vehicles transmitted by radio, flash lights around emergency exits, messages enforcing evacuation on variable message road signs, etc.;
- People know that they are expected to go to an emergency exit when evacuating;
- People that have reached shelters are not supposed to come back into the tunnel, for instance in order to help other people, or to retrieve their belongings;
- Tunnel operator (if any) reacts in line with his guidelines and operates available systems correctly.

In addition, a sensitivity study is generally performed to test effect of main parameters regarding behaviour of people, fire size, meteorological conditions, etc. on scenarios. If relevant, more sophisticated methods to represent behaviour of people against conditions in tunnel can be used [6].

In the end, level of safety is checked, and further improvements can be recommended, for instance if the conclusions of study of scenarios show that conditions would be much worse than in case of a new tunnel.

4. CONCLUSIONS

As shown above, French approach to road tunnels safety is mostly based on prescriptive requirements [4] and expert judgment. In this frame, scenario-based risk analysis is performed mainly so as to validate organisation for operation and general functioning of defined system – tunnel reference condition -, rather than to make easier a choice between different possible provisions for safety. Indeed, for a tunnel in operation, the choice of a set of safety provisions is required before performing a Specific Hazard Investigation, the scenario-based risk analysis. Therefore, such risk analyses rather aim at verifying whether the reached level of safety can be considered as acceptable or not.

Moreover, and so as to allow for comparability, methodical aspects and assumptions of such scenario-based risk analyses have been specified in guidelines [3]. This includes specifications for road users' behaviour. That is why misunderstanding of human behaviour is of less importance as it would have been if a scenario-based risk analysis is used to decide on safety provisions, in the absolute.

In this frame, improvements in understanding human behaviour are more useful if they are used to update prescriptive requirements for safety provisions and operation, rather than if they are used to increase relative accuracy of risk analyses.

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SYSTEM-BASED RISK MODELS FOR ROAD TUNNELS

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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 has gained greater importance in the last years. System-based risk models for road tunnels allow a structured, harmonised and transparent assessment of risks for a specific tunnel including the consideration of the relevant influence factors and their interactions. Based on the basic principles of risk-based approaches, the specific aspects of system-based risk models are discussed.

Keywords: risk assessment, risk analysis, risk evaluation, scenario, cost-effectiveness

1. INTRODUCTION

Risk analysis is a tool which was initially developed to investigate safety of potentially dangerous industrial processes (e.g. in the chemical industry) or potentially dangerous industrial plants (such as nuclear power plants). The application of risk analysis should help to establish a proactive safety strategy by systematically investigating potential risks. This proactive safety strategy was intended to replace experience-based concepts mainly relying on findings from incidents or accidents that had already happened.

During the past 20 years, some system-based risk assessment methods have been adapted to the investigation of tunnel safety in general and road tunnel safety in particular. For road tunnels risk analysis is explicitly required by the European Directive 2004/54/EC, on minimum safety requirements for road tunnels on the Trans-European Road Network, which was passed in April 2004.

2. BASIC PRINCIPLES OF SYSTEM-BASED RISK MODELS

In general, risk assessment models deal with potential negative consequences of a system such as road tunnels. The meaning of a system-based risk assessment and its characteristics can be summarised as follows:

- System-based risk assessment is a systematic approach to analyse sequences and interrelations in potential incidents or accidents, hereby identifying weak points in the system and recognising possible improvement measures.
- The terms “Risk assessment” and “Risk analysis” covers a large family of different approaches, methods and complex models combining various methods for specific tasks.
- System-based risk assessments usually include a quantification of risks which can be used as the basis of a performance-based approach to safety.
- A general basic principle of all kinds of system-based risk assessment models for road tunnels is a holistic approach including infrastructure, vehicles, operation and - last but not least – tunnel users.

For system-based risk assessments for road tunnels a broad range of qualitative and quantitative methodical modules are available. The general principle of a system-based risk assessment is shown in the following **Figure 1**.

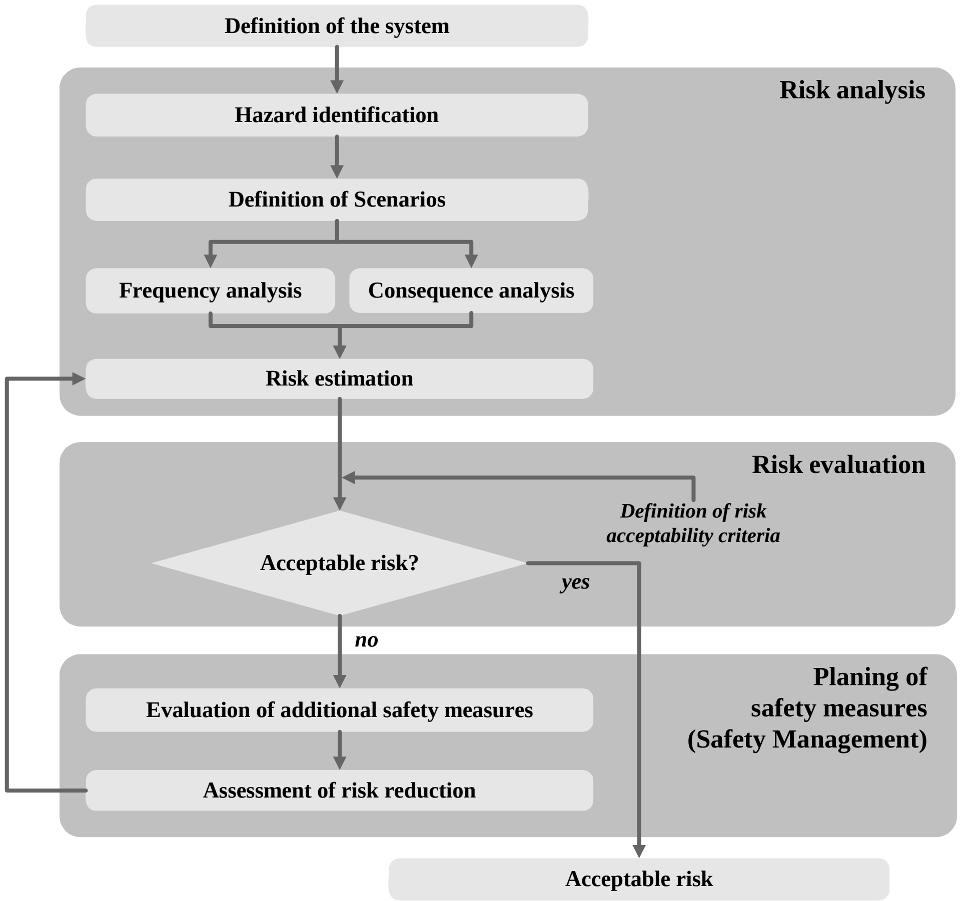

Figure 1: Procedure for a system-based risk assessment

Three steps characterise the system-based risk assessment procedure:

- Risk analysis
- Risk evaluation
- Planning of safety measures (Safety management)

2.1. 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 estimated quantitatively.

2.2. 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?"

As experience shows, the question of risk evaluation and the definition of what level of risk is acceptable, is a significant and debatable part of the risk management. In this context, a valuation of the different aspects of risk has to be included.

2.3. 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?"

3. METHODICAL ASPECTS

3.1. Spectrum of methodical components

A broad spectrum of applicable qualitative or quantitative methodology modules exists for each step of the procedure of risk management as described (see Figure 2). The available methodical modules can be arranged roughly into two groups:

- *Qualitative modules* normally have a lower complexity than quantitative and are based on the application of arbitrarily definable evaluation standards. Qualitative methods are often simple and easily and flexibly applicable and can be used for almost every problem (even in situations, where no quantitative data is available). On the other hand there is the risk that too much weight is put on subjective impressions and that correlations of different individual measures/modules of the analysed system are not (or not in a sufficient way) taken into account.
- *Quantitative modules* try to structure possible events of a system in a logical and integrative way: Different scenarios and possible subsequent events are analysed and the relevant influences are identified. For each path of subsequent events the scenario-specific frequency and consequences are estimated. The measured variables, which affect the development of a specific event, are identified and the appropriate risk is determined. A substantial advantage of using quantitative methods is the transparent representation of the risk estimated, whereby a better understanding of complex correlations can be achieved. On the other hand there are problems which cannot be modelled in an adequate way (with reasonable resources of time and money) and it also may happen that not sufficient quantitative data is available to enable a proper quantification of the most important parameters. Quantitative approaches are often characterised by a high degree of complexity, which reduces their comprehensibility as well as their controllability.

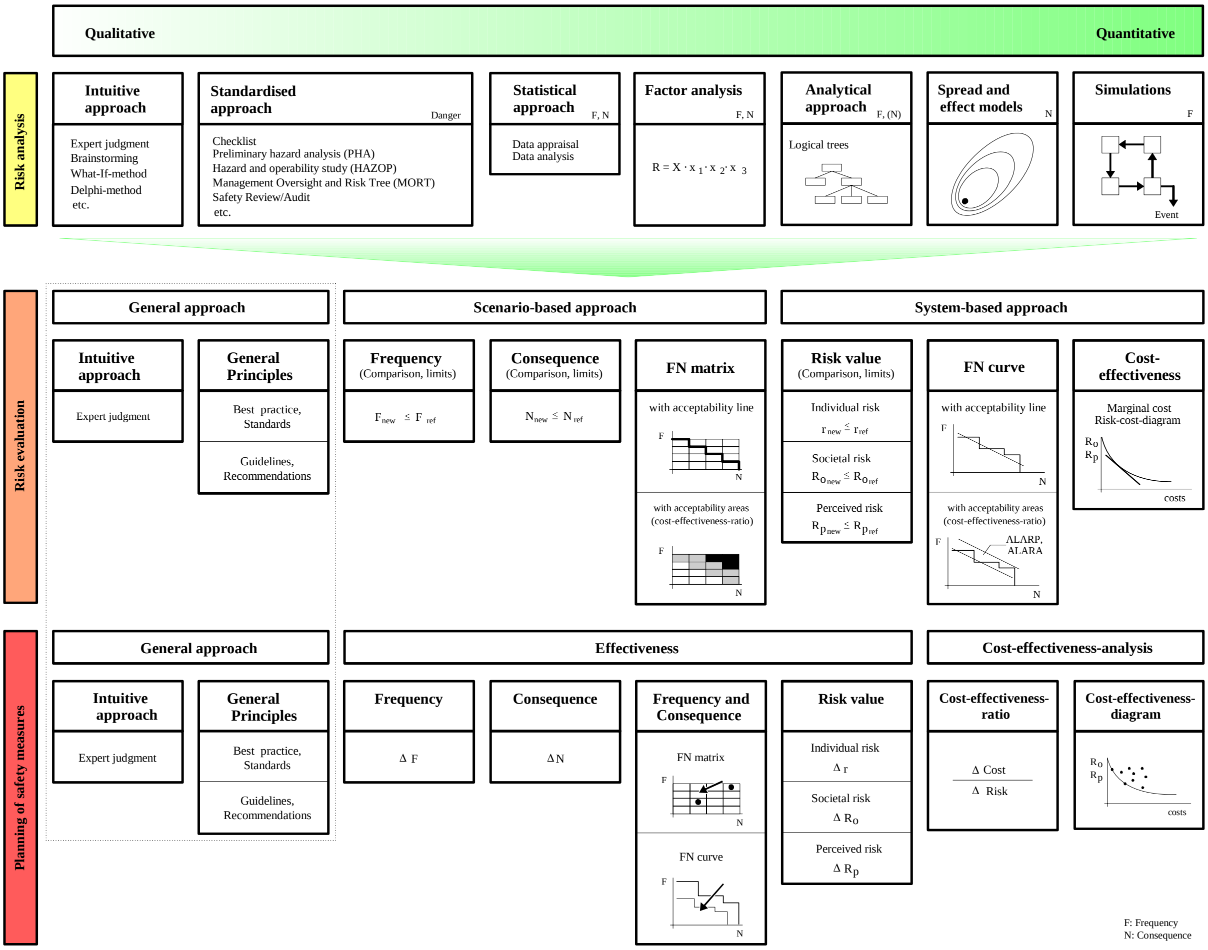

Figure 2: Methodical components for risk assessments

The experience in handling risk assessments shows, that for some applications (such as comparison of different design features, comparison of different safety measures, cost-effectiveness-analysis of safety measures) the use of quantitative methods is practically preferable for system-spreading safety evaluations. By using quantitative methods, comparable evaluations can be ensured. The integrated approach, quantitative comparability and in some cases also comprehensibility are the most important advantages of quantitative approaches. Simple qualitative methods, as for instance “expert judgements”, often do not keep the two steps risk analysis and risk evaluation sufficiently apart.

3.2. Methodical aspects of system-based risk models

3.2.1. Scenarios

In the past years several system-based risk assessment models have been carried out for road tunnels. All of them take several different scenarios into account. They can be grouped into four types of scenarios:

- Break-downs
- Collisions
- Fires
- Accidents involving dangerous goods

Normally the scenarios of fires, collisions and release of dangerous goods are in the focus of the assessments which are mostly based on a quantitative event-tree-analysis.

3.2.2. Analysis of frequencies and consequences

The two following aspects of risk are analysed separately:

- *Quantitative frequency analysis:* Analytical approach for analysing the sequence of events from an initial event (e.g. accident, release of dangerous goods) to a set of consequence scenarios. Therefore an assessment of the scenario frequencies depending on risk relevant factors such as type of tunnel (unidirectional/bidirectional traffic), length, volume of traffic etc. has to be done. In most cases the assessment is based on a statistical analysis of accidents or analytical methods such as fault-tree-analysis.
- *Quantitative consequence analysis:* The consequences of mechanical effects of collisions can be assed on the basis of a statistical analysis. The consequences of tunnel fires are mostly assessed by using specific models in order to simulate smoke spread and the effect of the tunnel ventilation. In addition specific models to assess evacuation are used (considering the location of the accident, the location of the emergency exits, the spread of smoke and the resulting visibility, the constellation of the vehicles on both sides of the accident etc.). For investigations of issues of transport of dangerous goods separate methods according the DG-QRA model from OECD/PIARC or comparable models are in use.

3.2.3. Risk estimation

The resulting calculated risk – based on the analysis of frequencies and consequences – for tunnels are mostly graphed as FN curves or expressed as expected value of the societal risk (see **Figure 3**).

Figure 3: System-based risk model

3.2.4. Risk evaluation and planning of safety measures

At the time being, risk evaluation is done mostly by relative comparison, mainly by comparing the tunnel as it is to the situation as it should be, taking the requirements of the relevant guidelines into account. Some countries (e.g. Switzerland, Netherlands) have introduced a maximum tolerable level of risk in terms of an acceptability line in an FN diagram in order to evaluate risk.

For the planning of safety measures the aspects of cost-effectiveness often are to take into account. This approach allows comparing the effect of additional safety measures in terms of risk reduction with the required costs for implementation and operation.

4. CONCLUSIONS

System-based risk models for road tunnels allow a structured, harmonised and transparent assessment of risks for a specific tunnel including the consideration of the relevant influence factors and their interactions. But 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 system-based risk 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. Hence, the system-based risk assessment approach in the context of tunnel safety management can be an appropriate supplement to the implementation of measures to respect the requirements of standards and guidelines.

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MODELLING HUMAN BEHAVIOUR IN TUNNELS – EXPECTATIONS AND REALITY

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ABSTRACT

In case of tunnel accidents, the tunnel user, the tunnel operator and the rescue teams play a crucial role. In this paper we will focus on the first category, that is the tunnel user. In order to predict driver behaviour in case of tunnel incidents or accidents, more and more models are being developed. However, behaviour has shown to be quite unpredictable, with variations from person to person and from incident to incident. This paper describes the variability in behaviour and discusses the possibilities and difficulties to capture this behaviour in models.

Keywords: human behaviour, driving, tunnel, accident, safety, models.

1. INTRODUCTION

History has shown that road accidents in tunnels can result more easily into catastrophes than accidents in open landscapes, especially in case of tunnel fires. Therefore, it is important to try to reduce the probability of incidents inside tunnels and to find measures to minimise the consequences of an accident when this occurs. The understanding of human behaviour could be a significant help. Tunnel user behaviour was studies in the European UPTUN project and is described in this paper.

In case of accidents or incidents in tunnels, the tunnel user has to understand what is going on and act accordingly. But the question is whether tunnel users can understand what is going on. Since an accident or a fire is not directly visible for the traffic downstream, the driver can only guess what is going on. However this first period is very important, since there is still time to win. In case of fires, significant time can be lost from the moment the fire starts until people understand that they are in mortal danger and the start of the actual evacuation process. When this period is long, the possibility for loss of lives increases. In order to predict human behaviour, many different models are being used.

2. TUNNEL USER BEHAVIOUR

A model is a (simplified) representation of what happens in the real world. Evacuation models allow designers and tunnel owners to get a better understanding of how people respond to different scenarios, including walking speeds, response to heat and fire, egress times, choice of emergency exit etc. A model allows the user of a model to vary specific input variables (e.g. distance between emergency doors) and see how that changes behaviour (what exit do people choose). Some examples of human evacuation models are CRISP, EVACS, Exodus, FIRESCAP, TRAFFIC, Wayout and many many more. Models about human behaviour all have specific assumption about how the user responds to situation A, B or C. Some models do have a large variability in the model output (behaviour), some models are very simple with less flexibility in output. The validity of a model (how well does the output of the model correspond with what would happen in real life) depends on the validity of the assumption that underly the model.

Some behavioural assumptions, used in evacuation models will be discussed here and will be compared to what is found in experimental studies in real life situations. Only by continuously updating models with new knowledge about human behaviour from experiments and real life accidents and fires, models will develop and become more and more useful.

2.1. Assumption 1: In case of an accident or incident, people have a proper understanding of what is going on

In a driving simulator study, TNO studied how well drivers understand what is going on in case of a tunnel fire much further upstream (Martens, 2005). In this study, some of the drivers were already warned about what could happen since they read a EU instruction leaflet about how to behave in case of tunnels and tunnel calamities, including tunnel fires. The European leaflet is shown in Figure 1.

Figure 1: The EU leaflet, shown to some subjects before driving in the driving simulator.

In total, 58 subjects participated in the TNO driving simulator experiment. Participants completed 4 drives, all on a simulated motorway. All rides included a section with a tunnel, that participants entered (emergency escape doors inside as well as first aid posts with fire extinguishers, clearly marked as such). The first 3 drives were only to get used to driving in general and to get somewhat familiar with the tunnel. Nothing peculiar occurred. Other traffic was surrounding the subjects (on both lanes). However, in drive 4, participants were confronted with an accident with fire much more upstream (the fire itself was not visible). Just before entering the tunnel the traffic intensity would increase, leading the cars around the participant to slowly brake. This slowing down of traffic was the result of a simulated accident with a car fire about 1 kilometer downstream. The traffic signals above the driving lanes were activated and eventually the traffic came to a complete stop inside the tunnel. Three and a half minutes after the virtual accident happened, smoke appeared in the tunnel.

coming from the front towards the participant in the car, getting thicker and thicker. Group 1 (control group, 20 participants) were not provided with any extra information. Group 2 (20 participants) had read the EU leaflet just before the start of the experiment. Group 3 (18 participants) had read the EU leaflet and received two specific instructural messages while inside the tunnel from a virtual tunnel operator (voice message). This group received information from a virtual tunnel operator 1 minute before the smoke would appear ("Please turn off the engine. I repeat, please turn off the engine" (this was indicated in the EU leaflet as best behaviour) and 30 seconds after the smoke had appeared the operator voice would say: “Please go to the escape exits, I repeat, go to the escape exits“ (this was also indicated in the EU leaflet as best behaviour). Participants were asked to give a verbal protocol during all the rides, meaning that they had to speak out loud and name everything that they noticed.

We studied how tunnel users behave under these circumstances, and what they mention in the verbal reports and in the questionnaires. In this, we concentrated specifically on behaviour that was related to the required behaviour suggested in the EU leaflet (switching off the engine, putting on the radio, and getting out of the car). In this paper we will mainly focus on getting out of the car.

What we found in this study is that in the scenario we presented, that is a simulated fire, it is hard for people to realise what is going on. When we specifically asked subjects to describe what they thought that happened, their answers were diverse, as is shown in Table 1. We did not test for any statistical differences between groups since none of the groups received any specific information about what was going on.

Table 1: Answers in percentages of participants per group and in total.

Group	fire in car	fire in tunnel	smoke	accident	motor problems	explosion	traffic jam
1	55%	10%	20%	5%	5%	0%	5%
2	20%	30%	15%	5%	5%	15%	11%
3	28%	33%	17%	0%	11%	11%	0%
Total	35%	24%	17%	3%	7%	9%	5%

The answers fall into seven categories. The first category: “fire in car”, includes only answers that include the remark that they thought there was a fire in a car. The second category includes answers in which the participants concluded there was a fire in the tunnel without referring to a car being on fire, but merely fire in general. The third category consists of answers that only include references to smoke, but not that the smoke was the result of a fire. The fourth category: “accident”, consists of answers that referred to the occurrence of an accident and no mention of a fire, smoke or an explosion. The category: ”motor problems” refers only to answers that include a reference to a boiling motor of a car as the source of the occurring smoke. Only two of the four answers included a reference to smoke. However these participants specifically mentioned that the smoke was white and thus had to originate from a boiling motor. The other two participants did not mention the smoke at all, only motor problems. The category: ‘explosion' consists of answers that refer to an explosion as the source of the occurring smoke. All answers in this category included a reference to smoke.

In summary, the majority of participants thought that there was a fire, a total of 65% for condition 1, 50% for condition 2 (with leaflet) and 61% in condition 3 (leaflet and operator). In fact most people registered something was wrong and most participants concluded some sort of accident must have occurred. Only 5% of all participants (1 person in condition 1 and 2 in condition 2) were not sure what had happened (answer in the category “traffic jam”).

2.2. Assumption 2: People in general know how they should behave in an emergency (incident or accident)

The question is whether it is true that people know how to respond in case of emergency situations in tunnels. In the same driving simulator study, some people read the leaflet how to respond just before starting the experiment, so this would be a so-called ideal situation.

However, the study showed that even though subjects already drove the tunnel three times before and had a chance to see the emergency exits inside the tunnel on drive 4 as well, some people still indicated wanting to use the tunnel entry to leave the tunnel. In the group that specifically got operator instructions to go to the emergency exits, no-one mentioned this. What was striking was that quite some people indicated they did not have an idea of how to handle in the given situation (even in the condition with the leaflet and the operator help). This means that there is a lot of uncertainty in the case of accidents or incidents in tunnels, and even though there is an operator voice that tells them to go to the emergency exits and even though people read the leaflet. This is something we have to be aware of in the near future: even though designers may think that all information needed is there, this may not be enough for the road users. Information provided needs to be over-complete, with a repetition of the messages if possible. Also, people with visible official status should be sent inside the tunnel in order to help people make the right decisions. Also, we need people with exemplary behavioural function, for instance by means of training professional drivers.

In group 1 (not having read the leaflet), three people indicated to not have taken any action since they were waiting for other people to take action. One person indicated to feel safer in the car. Two participants in group 2 did not take action because of the smoke, with one person indicating the smoke was too thick to get out and the other person saying the smoke was not very thick and he therefore saw no readon to leave the vehicle. Even if the operator informed road users to evacuate, one person mentioned he was afraid to get out of the car. Some others indicated it was unclear where to go and one person indicated to need more clarity of how to respond. That reading the leaflet is not enough is shown by the people who said that they did not take action (e.g. because they did not want to panic, did not see any panic, tried to stay calm, were looking for more information etc.) even though they read the leaflet. There were less people stating that it was not necessary to respond in group 3, but even with the operator voice, not all people indicated to evacuate. Even in the condition that an operator announced switching off the engine and getting to the emergency exits, people thought information was lacking. In general, remarks were made about the necessity to light emergency exits, warning signs, information about what is going on, how serious it is and what to do, the need for information to be more extensive or information on the radio.

2.3. Assumption 3: People do not start evacuation until they realise that they might be endangered = when the smoke approaches their position (that is the way how it is modelled)

As the driving simulator study showed, people do not always indicate they will evacuate, even when smoke approaches their position. In the first group, that received no operator help and did not read the leaflet, only 65% of the participants indicated that they would evacuate after the smoke appeared. This was 75% for the group that read the leaflet and 94% for the group with the leaflet and operator help. So even if they just read a leaflet about how to perform and there is an operator that tells them to evacuate, and there is smoke approaching and surrounding them, not everyone says they will evacuate. Since it was a driving simulator study, we could not study actual evacuation behaviour.

That not everyone evacuates as soon as smoke approached their position is confirmed by a large scale field test by Boer (2003). In this study, naïve participants (they were not aware of what would happen) were confronted with a truck that blocked the tunnel lanes inside a tunnel, with smoke coming from the truck. Behaviour of the drivers was recorded on tape, with some drivers being close to the smoke and others being further away from the truck and the smoke, being confronted only with stillstanding traffic. Several runs were made, with a new group of participants in each run. In one of the runs, not one driver responded, even after the smoke started to approach the cars and even surrounded the cars.

In the driving simulator study, some people even mentioned that smoke was the reason not to act. Two participants did not take action because of the smoke, that might be toxic. Some people closed the ventilation system of the car, closed the window and thought they would be safer in the car. One person said the smoke was too thick to approach the accident. The other person said the smoke was not very thick and that he therefore did not see any reason to go out of the car.

So even though smoke is a proper cue in many occasions, smoke is definitely not always a cue for people to evacuate (see also assumption 6).

2.4. Assumption 4: As soon as they start evacuating, all people leave their cars immediately and go directly to the next emergency exit

This is also related to the group process as discussed in assumption 6. There is indeed a large group effect, as was shown in the evacuation studies of Boer (2003). As soon as some people start to evacuate, other people start to evacuate as well. That is, they start to leave their car based on other people starting to leave their car. However, in many cases this only happens after the operator warns for explosion danger. Also, people that spontaneously leave their car (before an operator voice warning for explosion danger), there is a large hesitation time. This means that people do not directly go to the emergency exits. Even in clear visibility, there is quite a large hesitation phase, with time passing between opening the car door and the moment the motorists begin walking.

Boer (2003) showed that many car drivers lost time between leaving their car and actually going to the emergency exits. Those reacting before the announcement of the operator hesitated much longer than those who reacted after the accouncement. The hesitation time in the group that spontaneously evacuated (without operator announcement) was over 100 seconds in many occassions. From the 35 participants, only 3 left their car and walked to the emergency exits without hesitation. Of the group that only evacuated after the announcement (155 people), only 1 person showed a hesitation time of longer than 100 seconds.

These results show that assumption 4 is not right, since people may hesitate. If this occurs also depends on whether there is spontaneous evacuation or if evacuation takes place based on an operator voice. This also may very with what other people in the direct surroundings do.

2.5. Assumption 5: Although the traffic lights at the tunnel portals show red, the traffic does not stop immediately (car drivers neglect the red traffic light for some time)

This is a type of behaviour that was shown in many real life situations. Tunnel operators were aware of an emergency inside the tunnel and switched on the red traffic lights. However, a problem is that this is an occasion that is hardly ever experienced by any driver in his or her driving career. With normal traffic lights at intersections, drivers encounter red traffic lights all the time. Therefore, a red traffic light is to be expected. In case of tunnels, this is not to be expected. So even though there may be a red traffic light, this is not always interpreted as such, even if drivers were to fixate these red lights. In that case, red crosses above the driving lanes would need to be shown as well. However, even this is not strong enough, as was proven in the Westerschelde tunnel project (Martens, Koster & Lourens, 1998). In that case, drivers were confronted with two red crosses above the driving lanes inside a tunnel, but as long as other drivers continued to drive, participants in the study kept driving under the statement ‘everyone else kept on driving so I kept up with the traffic stream’. It is known from real life situations that the only countermeasure that gets people to stop in front of a tunnel entrance is the presence of physical barriers after the red light is being switched on. At the St Gotthard tunnel, emergency procedures worked properly as barriers automatically stopped more traffic entering the tunnel. At the Tauern tunnel on the other hand, many drivers simply passed the red lights and continued into the tunnel. A similar test was made some months later at another tunnel for a TV report and it also showed lots and lots of cars ignoring the traffic lights. Traffic lights present no physical obstacle, and also do not say why entry to the tunnel is not allowed. Without additional information, a prolonged red light may simply be taken for a malfunction, and once the first drivers ignore it, others will follow.

Only this physical barrier stops drivers from entering the tunnel. Therefore assumption 5 is true, but could be more firm: Drivers do not stop, instead of drivers do not stop immediately.

2.6. Assumption 6: In the evacuation process, there is no consideration of group dynamics

As was already discussed before, there is a large group effect, in two possible directions. This means a positive direction in the sense that if some people start to evacuate, other people will evacuate as well. Boer (2003) showed that as soon as action was taken by one person within a group, more people followed and started to react. Evidently people sat tight in their cars and prepared to react, but were unwilling to act until anybody else acted. On the other hand, he also showed a negative group effect. That is if some people wait in the door, or even go back into the tunnel to stay with their cars, other people start to do that as well. And, if other people stay in the car, people will not respond since others do not respond. This was also confirmed in the Martens (2003) driving simulator study, in which participants literaly mentioned that they did not respond since no-one responded, and they therefore concluded that it would not be so bad.

As is often assumed, it is also not the case that social groups always stay together. In the Baku Metro fire one of the victims said: “I grabbed my two daughters and buried their faces into my chest, holding them close so they wouldn't breath the fumes… My daughters helped me off the train-I don't quite know how. They fell down from the train, when they tried to run they kept falling, tripping over bodies. The air was so bad, we were all coughing. It was so hard to breath. Then I collapsed and felt like I couldn't go on any more. I begged my daughters to go on without me, to make it to safety-to save themselves. As I lay there, people stumbled and fell over me. It was hell. People at the Depot finally rescued me.” This last statement is interesting because it shows the family group breaking up under extreme stress.

3. CONCLUSIONS

The human response is a very important factor in case of tunnel accidents. As we have seen there are a lot of factors that can prevent the human being from doing the right thing, and behaviour is very unpredictable and differs from condition to condition. Road users do not always know what is going on, and even if they know what is going on, they do not always know how to behave properly. Even though operator messages do help, they do certainly not overcome all problems. Since there is a large group effect as well, proper action of some people will help guide the behaviour of others, but wrong actions will also stimulate wrong actions in other people.

Models offer the opportunity to study how people respond in various situations. However these models are a simplified form of reality. However one should keep in mind that this is also the case for experimental studies. The only valid data we can get are data from real life accidents, but in most cases these data are only the verbal reports from the survivers. Human behaviour is the most complex and difficult aspect of evacuation to simulate, yet is crucial to get good results. A simple but useful approach is to consider what types of behaviour are considered rather than the details of the calculation. The simplest level (“egress only”) considers no other form of behaviour, apart from an abstract representation of “pre-movement” activities by a delay time for each occupant before they may start to move. The people may however be allowed some flexibility in exit choice. The intermediate level (“fixed”) covers models where the occupants may have a number of tasks to perform before they are allowed to commence evacuation. However these tasks are usually carried out in a deterministic sequence. The highest level (“adaptive”) also has occupants with a variety of tasks to perform, however the choice of task, and whether these are completed or replaced by alternative actions, is determined by the state of the environment, actions of other people encountered, etc. Adaptive behaviour models are potentially the most realistic, since the complexities of human behaviour are made explicit and amenable to users’ control (rather than reflecting the original program developer’s perceptions in a hard-wired algorithm). Although each person’s decision process is modelled separately, this does not preclude the option for co-operative or group behaviour. For example a person may have a task to rescue a dependent person; the dependant person may wait to be rescued. However when the rescuer meets the dependent, the task of both may change to “escape”, and the movement process modified to keep the pair together.

These adaptive behaviour models can offer designers an idea of the large variety of behaviour they can expect, the effect of interference or countermeasures and the effect of smoke, presence of emergency exits and the effect of group aspects. Even though one must keep in mind that the output of these models do not represent the exact outcome from real life scenarios, they can still be very valuable. Only by continuously updating these models with real life data and data from different kind of tunnel studies, these models will continue to improve their quality.

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EFFECTIVE THRUST TRANSFORMATION INSIDE TUNNELS WITH JET FANS (BANANA JET)

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ABSTRACT

Every few years an idea comes along, which in its simplicity and clarity is so obvious that one is left to wonder: „Why only now?". Such an idea is the Banana Jet. By bending the air jet of a jet fan in a tunnel away from the restrictive surface (walls / ceiling) the performance of the fan in the system can be dramatically improved. This can be done with silencers or ducts which are bent with an angle of 5 – 25 %. The source of the improvement is that not only are the losses directly behind the fan virtually eliminated, but the airflow profile down-stream in the tunnel can be improved, further significantly reducing aerodynamic losses. The net result is a reduction of the required installed thrust by 30 – 50 %. Not only does this mean that far fewer (or smaller) fans need to be installed, but the installation cost for cabling, mounting etc. is also reduced in the same proportion. A 30 – 50 % reduction in required thrust directly translates into a reduction in energy consumption in the same order of magnitude so there is a larger savings in operating costs in addition to the benefit of lower capital cost and environmental pollution.

Keywords: jet fan, tunnel, effective thrust, niche, CFD

1. THE BANANA JET PRINCIPLE

Jet fans are installed in road tunnels to move the air by giving it an impulse (measured as thrust in Newton) in the desired direction. In order to achieve a required air speed, a number of loss factors must be overcome. (see Table.1). The use of Banana Jet can reduce these losses by 25 – 50 %, depending on the design of the tunnel. All those losses described in chapter 2 are a result of an analysis performed by the author and the company Witt&Sohn AG. The physics behind this improvement is relatively straightforward:

Table 1: Losses for traditional and Banana Jet fans in % of total losses

	Traditional Jet Fans	Banana Jet
Wall friction losses	30 – 50 %	25 – 40 %
Background velocity losses	8 – 20 %	5 – 17 %
Impulse loss	10 – 20 %	0 – 4 %
Losses in bends, installations, road signs, niches, corners, lamps, etc.	2 – 20 %	5 - 17 %
Inlet / outlet portal losses	15 – 30 %	15 – 30 %
Total*	100 %	50 – 75 %

* assuming an empty tunnel; traffic jam or piston effect not taken into account.

Figure 1: Average flow rate in a tunnel (Uznaberg West)

1.1. Friction loss

An air stream that blows along a surface becomes "glued" to the surface due to the induced swirl and one-sided low pressure. This effect, called "Coanda-Effect" creates a less uniform flow in the tunnel, with larger velocities along the wall, compared to the flow that is achieved with Banana Jet. With Banana Jet the highest velocity is in the centre and upper half of the tunnel. This effects can be seen Figure 1, 6 and 7.

Overall this results in lower friction losses along the walls of the tunnel. A 5 – 10 % improvement is realistic. In tunnels with a very rough surface the improvement can be even higher.

1.2. Background velocity correction

The energy that a fan gives to the air flow in the tunnel is a function of the difference in airspeed at the outlet compared to the speed of the air at the inlet of the fan. The higher the background velocity is around the fan, the less impulse can be transferred to the air streaming by the fan. Due to the Coanda-Effect the actual air velocity around the down-stream jet fans is higher than it would be in a free field. The different airflow profile with Banana Jet means a slightly smaller correction factor is required. Measurements in various tunnels have shown a difference in airspeed around the fans of 10 – 20 %. A 3 – 5 % reduction in losses can be expected, more if the fans have to be spaced closely together. (< 100 m between the fans)

1.3. Impulse losses

10 – 20 % of total the thrust generated by traditional jet fans is lost right behind the fans as part of the air jet hits the surface the fans are mounted on with a high velocity (Fig. 2) due to friction and impulse losses.

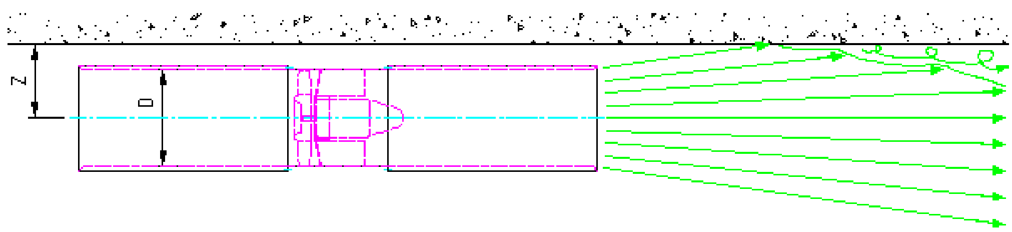


Figure 2: Impulse and friction losses behind a traditional jet fan

By bending the flow away from the surface this loss can be virtually eliminated. Since the losses are a fixed factor of the overall losses in the tunnel, so at least the above mentioned 10 – 20 % can always be avoided by using Banana Jet.

1.4. Losses in corners, niches and other installations

Fans are generally hung outside the traffic area, typically in corners or niches of the tunnel. The same space is also used for lamps, road signs and other installations. Because the jet from a Banana Jet can be flexibly directed, the losses can be reduced, especially in corners and niches. (Fig. 3) Also, the jet can help to overcome losses from bends, changes in diameter etc. The actual design of the tunnel must be analysed to estimate the improvement that can be achieved.

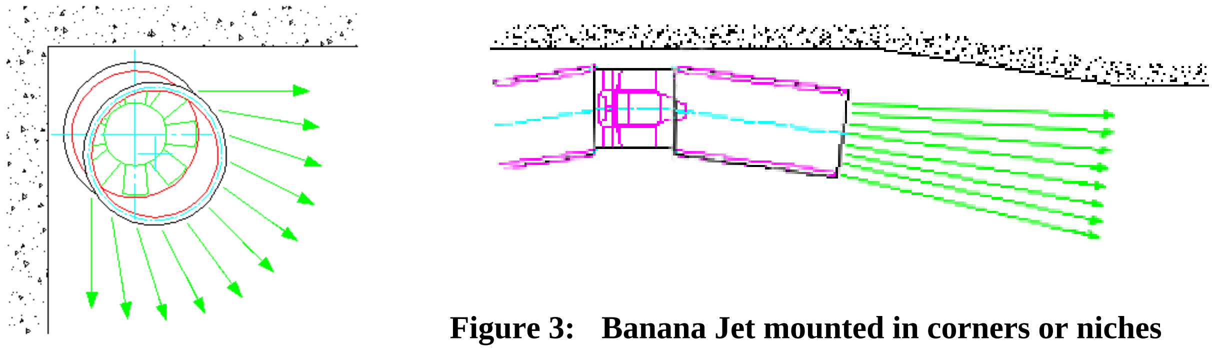


Figure 3: Banana Jet mounted in corners or niches

2. MEASUREMENTS

2.1. Introduction phase of Banana Jet Technology

Banana Jet has been tested in 3 tunnels, 2 of which were measured by an independent Swiss engineering company. For comparison purposes, the Banana Jet was converted into traditional jet fans by means of transition pieces removing the bend of the silencers. The air speeds have been taken on a defined grid in each tunnel for the traditional jet fan version and the Banana Jet. As can be seen from Fig. 4, the measurements confirm the expected results.

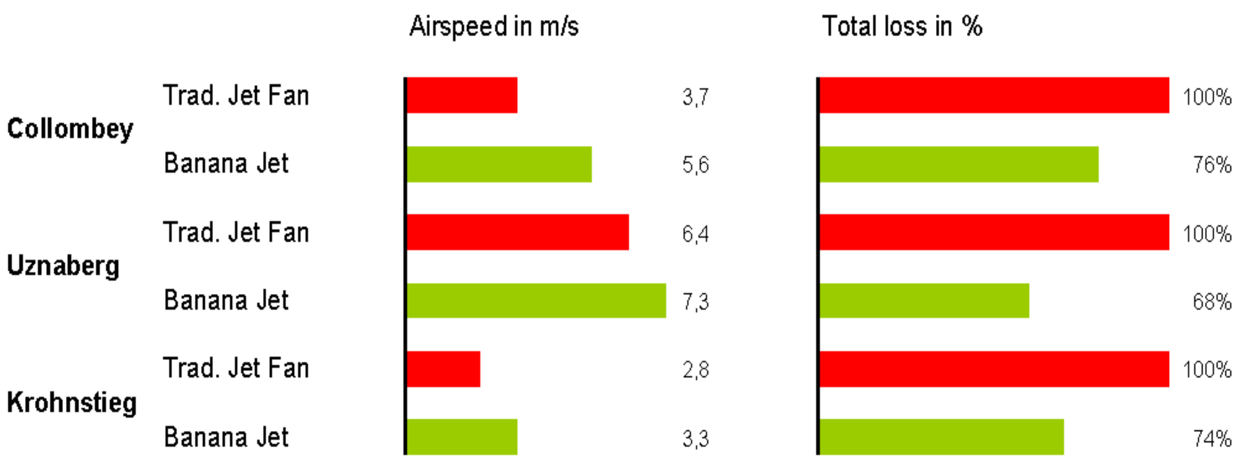


Figure 4: Comparison of measured airspeed in the tunnel

The Banana Jet produced a significantly higher airspeed in the tunnel. This is equal to a reduction in total losses of 24 – 32 % (i.e. an increase in thrust of 32 – 47 %)

In all 3 tunnels further reduction in losses seemed possible if the orientation of the jet had been further exploited e.g. by better countering the effect from bends, walls, lamps, etc.

2.2. Bypass Schmerikon (Tunnel Uznaberg/ Balmenrain)

Location: Switzerland, Kanton St. Gallen
Length: 1 x 1318 m + 2 x 940 m
Traffic: bi-directional + unidirectional
Realised: 2003
Tests: Banana effect proven by independent measurements

Figure 5: Bypass Schmerikon

Table 2: Values and measurements Bypass Schmerikon			
		Originally scheduled	Realized with Banana Jet
Quantity of fans		21	21
Thrust per fan	N	966	770
Installed thrust	N	20 286	16 170
P electric per fan	kW	30,5	26,1
P electric total	kW	640,5	548,1

By adding of the bent silencers the measurements gave the prove that the required air speeds could be achieved with lower installed thrust.

In a comparative 6x6 grid measurement in the Uznaberg west bore acc.to Log-Tschebyscheff-procedure[1], the air speed for the traditional jet fan was 6.14 m s^{-1}. The bent silencer version created an air speed of 7.45 m s^{-1}. This results in an increase of 21,3% air speed and 47% effective thrust in the tunnel. Measured data for all cross sections are available.

[1] P. Pospisil, (2002), Hauptstrasse T8/A8, Tunnels Balmenrain und Uznaberg; Vorgaben an die Steuerung der Tunnellüftung; 87-95-08. HBI. Zurich

To give a more detailed view on the flow results a chart with the results of the grid measurement is given in figures 6 and 7. The grid diagram show the measured air speeds that had been taken 20m, 40m, 60m and 120m behind the fan group.

The measurements have been performed with a anemometer of type Schiltknecht.

The resulting error of measurement is a combination of measurement and reading failures. An analysis of the components of failures resulted in a total margin of +/- 19%.

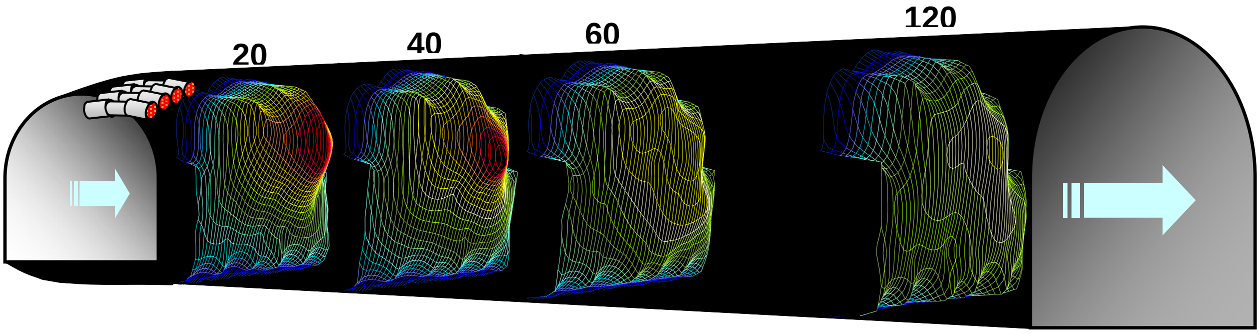


Figure 6: Air speed profile across the tunnel cross section of Uznaberg West tunnel Banana Jet

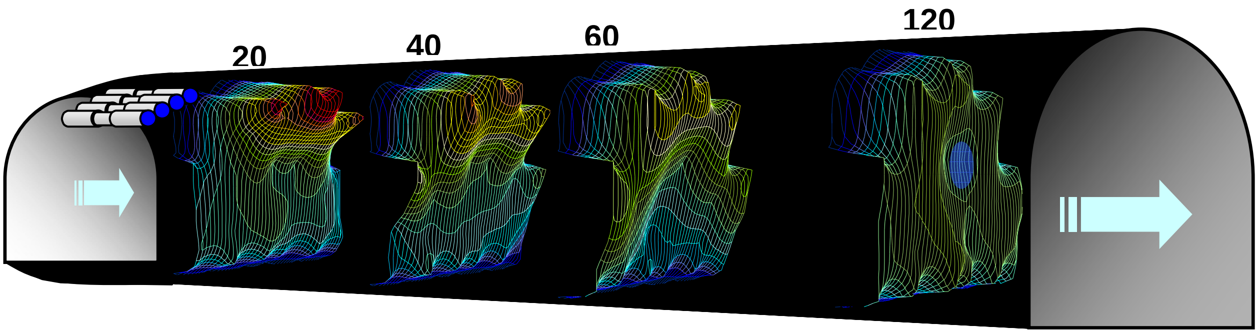


Figure 7: Air speed profile across the tunnel cross section of Uznaberg West tunnel Traditional Jet Fan

The measured air speeds in the tunnel show the effects of the above described principles. With the traditional jet fans the air speed along the walls and the ceiling with their frictions is a lot higher than with the Banana Jet. Even at 120m an air speed minimum is in the middle of the tunnel. In case of the Banana Jet the air speed peaks are directed to the upper half of the tunnel cross section. This results in lower friction losses.

3. CFD SIMULATION

A CFD simulation project was started to create an accurate simulation model in order to calculate realistic air flow values for tunnels in planning phase. In the first stage of the simulation project the air speed and the effective thrust in the tunnel have been compared for traditional and Banana jet fans installed in the tunnel centre or in the corner of the tunnel.

A 630mm jet fan with 21 m s^{-1} outlet velocity was used as the reference fan in a 100 m long, rectangular, empty tunnel segment.

3.1. Installation in the centre of the tunnel ceiling

Figure 8: Case 1:

Traditional jet fan, located centre of tunnel, 100m tunnel length, v_T outlet = 21 m s^{-1}

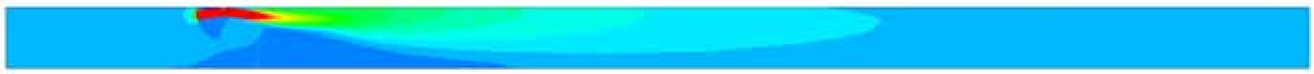


Figure 9: Case 2:

Banana Jet fan, located centre of tunnel, 100m tunnel length, v_B outlet = 21 m s^{-1}

Result: Average air speed v_B = 2.81 m s^{-1} v_T = 2.49 m s^{-1} ⇨ $v_B = 1.13\ v_T$. The simulated thrust increase is approx. 27%

3.2. Installation in the corner of the tunnel ceiling

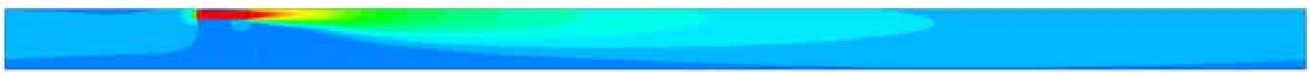
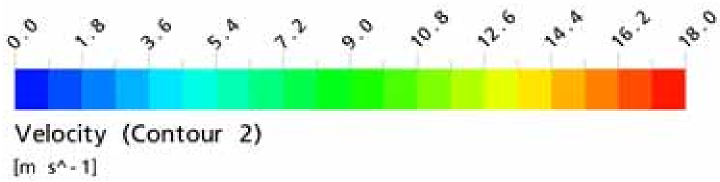


Figure 10: Case 3:
Traditional fan, located centre of tunnel, 55m tunnel length, v_B outlet = 21 m s^{-1}

Figure 11: Case 4:
Banana Jet fan, located centre of tunnel, 55m tunnel length, v_B outlet = 21 m s^{-1}

Result: Average speed v_B = 2.61 m s^{-1} v_T = 2.09 m s^{-1} ⇨ $v_B = 1.24\ v_T$. The simulated thrust increase is approx. 53%

3.3. Forecast



The project is still running for different tunnel cross sections (round and rectangular), for jet fans with different static thrust and for different installation positions (centre, corner and niches). The results will be presented in later publications.

4. REFERENCES

4.1. Krohnstieg Tunnel

Location: Germany, Hamburg
Length: 420 m
Cross section: rectangular
Traffic: bi-directional + unidirectional
Realised: 1998
Tests: Comparative measurements with standard and Banana Jets

By adding of the bent silencers the air speed could be increased from 2.8 m s^{-1} to 3.3 m s^{-1} . These air speeds result in an effective thrust increase of 35%.

Figure 12: Krohnstieg Tunnel

4.2. Tunnel Aubing

Location Germany, Munich
Length 2 x 1950 m
Cross section: rectangular
Traffic unidirectional
Realised 2005 – 2006
Tests Onsite performance test of the Banana Jet performed by independent body

By replacing 2x30 standard fans by 2x24 Banana Jets the specified air speed of 2.92 m s^{-1} was exceeded to 3.28 and 3.59 m s^{-1}

Figure 13: Tunnel Aubing

4.3. Realised Banana Jet projects

The Banana Jet has been installed in tunnels all over the world, e.g. in the following countries:

- Australia
- Austria
- Chile
- France
- Germany
- Norway
- Portugal
- Russia
- Switzerland
- Spain
- UAE
- UK
- Venezuela
- …

5. ENVIRONMENTAL AND ECONOMIC IMPLICATIONS

A reduction in the thrust required to move the air in a tunnel has dramatic consequences for the general contractor and also the end user / tunnel operator.

- Fewer (or smaller) fans are required, proportional to the reduction in thrust required.
- Less cabling (or smaller cable cross sections) necessary. Often the total cabling cost incl. installation is more than the price of the fans.
- Less energy consumption, CO_2 production, operating cost, proportional to the reduction in thrust achieved.
- Fewer (or smaller) niches can be built.
- More flexibility in the choice of the fan locations.
- Ability to increase the volume flow rate in old tunnels by 10 – 20 %, without changing the cabling and power supply.

The effect that was achieved for the 3 tunnels measured by installing Banana Jet resulted in an overall life cycle costs reduction of 25 – 35 %. The capital costs were so much reduced that the savings were almost as large as the total price of the fans.

6. CONCLUSION

The use of the Banana Jet can reduce the installation and operating cost for longitudinal road tunnel ventilation significantly. An improvement of 25 – 50 % compared to traditional jet fans is realistic.

The improvement is in principle due to an aerodynamic adaptation of the fans to their real purpose. Instead of aligning fans geometrically to the contours of the tunnel, the air flow is directed away from the tunnel walls, thus greatly reducing the losses.

There seem to be no disadvantages from using the Banana Jet. Excessive airspeeds at lower levels can be avoided, just as increased turbulence in potential smoke layers or other secondary effects can be minimized. In addition, a better flow profile, also when there are traffic jams or other obstructions in the tunnel, can more readily be taken into account compared to traditional jet fans. The Banana Jet effectively come “free of charge”, the saving in the electrical installations pay for the remaining fans that need to be installed.

STARTING-UP-TIME AND -METHOD OF FANS FOR EMERGENCY TUNNEL VENTILATION SYSTEMS

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Zitron Nederland B.V.

ABSTRACT

In case of an emergency situation in a tunnel, for instance fire, it is vital to have a ventilation system that responds to control commands as quickly and as reliable as possible. Furthermore it is essential to avoid that the fans operate in stall. Depending on the length and the size of the smoke extract ducting in a tunnel the mass of the air that has to be accelerated during start-up of the ventilating system can be substantial. The paper highlights the effect of system dimensions, fan types and starting methods on the starting time and the time the fans operate in stall during the start-up.

1. INTRODUCTION

To be able to predict, especially during a fire or another emergency situation, if and how fast a desired volume flow can be reached is very important. As a supplier of tunnel ventilation systems we decided to develop a calculation method and tools to be able to determine the start-up behaviour of fans in tunnel ventilation systems.

It is generally known that operating a fan in stall conditions should be avoided. During stall operation high dynamic loads on the blades and increased vibration levels can occur. A fan operates in stall if the actual volume is below the “stall volume” (See figure 1). During start-up an axial fan will always operate in stall for a short period, however this stall period increases significant if a large mass of air has to be accelerated.

Besides that there is a possibility that during parallel start-up/operation or sequential starting one (or more) of the fans remains operating in stall. This occurs if the system resistance line the fan “feels” or “experiences” is higher is that the saddle-pressure of the fan (See figure 5).

With the developed method and tools it is possible to predict and compare the start-up behaviour of fixed blade angle fans to fans equipped with a variable pitch system.

2. CALCULATION METHOD

The calculation method is based on the following assumptions:

- The difference between fan pressure and system pressure accelerates the air mass.
- The actual motor torque reduced by the aerodynamic torque of the fan is the torque that accelerates the rotating speed of the impeller.
- The start-up is finished and the volume flow is stationary when the volume flow has a value at which the corresponding fan pressure equals the pressure loss of the system.
- The air density is constant (incompressible flow).

The calculation is performed in small time steps and based on the following formulas:

Pressure loss of the system

P_{sys} = P_0 + $Zeta_{sys}$ x 0.5 x Rho x Q^2
P_0 : System Pressure at zero Flow
P_{sys} : Pressure loss of the ventilation system
$Zeta_{sys}$: Pressure loss factor of the system
Rho : Air density
Q : Actual volume through the system.

Aerodynamic power of the fan

POW_{aero} = Q x P_{fan} / Eff
POW_{aero} : The aerodynamic shaft power of the fan
Eff : The efficiency of the fan

Aerodynamic torque

T_{aero} = POW_{aero} / Ω
T_{aero} : Aerodynamic torque
Ω : rotating speed of the fan

Acceleration of the impeller

T_{motor} - T_{aero} = J x dW/dt
T_{motor} : actual motor torque
J : Inertia of the motor-rotor and the impeller
dW/dt : acceleration of the impeller

Acceleration of the airspeed

(P_{fan} – P_{sys}) x A = dV/dt x M_{air}
A : Area of the ventilation duct
dV/dt : acceleration of the airspeed
M_{air} : Mass of the air that has to be accelerated

Fan pressure

The fan pressure depends on the actual volume, the fan speed and the fan type (Fixed Pitch versus Variable Pitch).

Fans with fixed pitch

If the fan speed is (during start-up) below the nominal speed the fan curve of the fan for the actual speed can be calculated with the following fan laws:

P_{fan} = $P_{fannominal}$ x $(RPM/RPM_{nominal})^2$
P_{fan} : Pressure at actual speed
$P_{fannominal}$: Fan pressure at nominal speed
RPM : Fan actual speed
$RPM_{nominal}$: Nominal fan speed
Q = $Q_{nominal}$ x $(RPM/RPM_{nominal})$

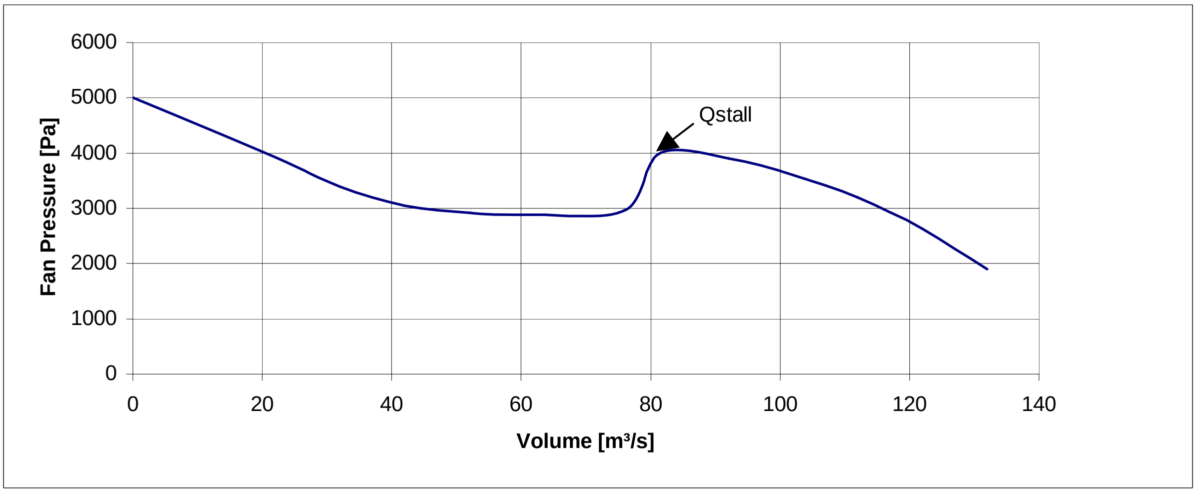

Figure 1: Fan curve fixed pitch fan

If the actual volume is above Q_{stall} (See figure 1) the fan operates in the stable area.
If the actual volume is below Q_{stall} the fan operates in the stall area.

Fans with variable pitch

If the fan speed is (during start-up) below the nominal speed the fan curve of the fan for the actual speed can be calculated as described above.
During start-up the fan starts with a small blade angle. With this reduced blade angle the relation between fan pressure and volume is according to stall line in figure 2.

If the actual volume is between Q_u and Q_{stall} (see figure 2) the blade angle should be regulated in a way that Q_{stall} is/stays slightly smaller than the actual volume.

Regulating the blade angle this way has the following advantages:

- The fan does not operate in stall if the volume is between Q_u and Q_{stall}.
- The fan pressure is higher than the pressure of a fixed pitch impeller.

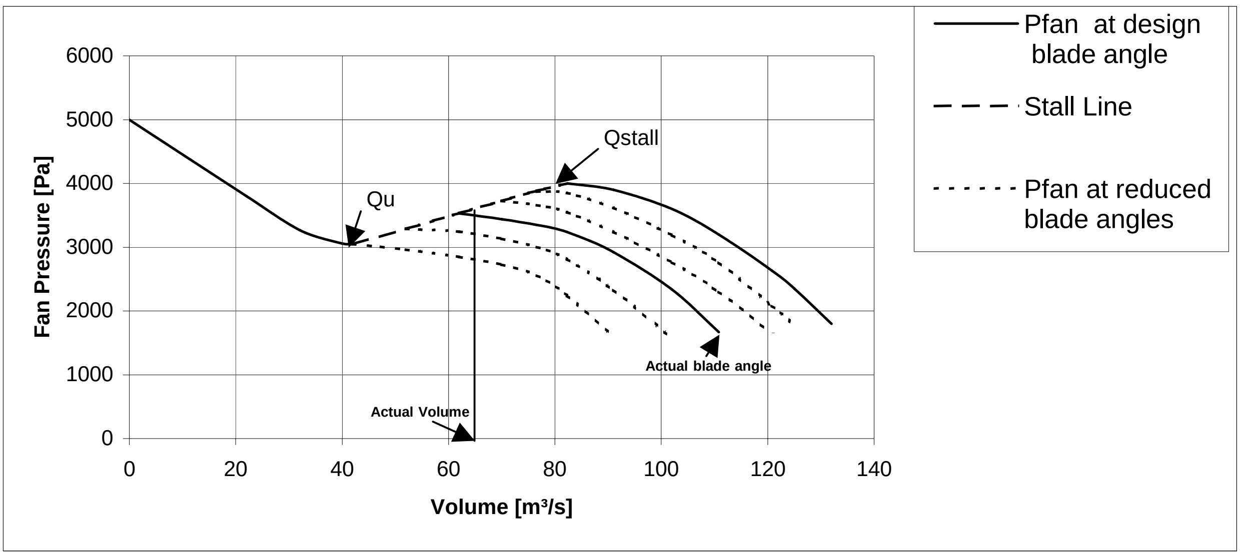

Figure 2: Fan curve variable pitch fan

3. RESULTS AND DISCUSSION

The above-mentioned method was used to determine the start-up time of the ventilation system of a tunnel in Switzerland, were smoke extraction is performed over a duct, which is equipped with extract dampers.
Two parallel axial flow fans for extraction are located in a fan room.
During a fire in the tunnel 3 dampers next to the fire are opened for smoke extraction.
For this tunnel the required start-up time of the ventilation system is less than 90 second.
For an overview of the main dimensions of the extract duct and the fans see table 1.

Table 1: Dimensions of the extract duct and fan data

Description		**Remark**
Total length of the tunnel	3200 m	
Maximum length between the fans and the fire	2000 m	
Number of fans in parallel	2	
Extract volume fans in parallel	100 m³/s per fan	
Extract volume with one fan	140 m³/s	In case one of the fans is not available.
Total fan pressure with fans in parallel	3600 Pa	
Static counter pressure due to atmospheric conditions (wind pressure)	260	
Area of the extract duct	10 m²	
Air density	1.14 kg/m³	
Fan-motor drives	Variable speed drive	
Power of the Emotors	260 kW	
Required start-up time of the system	60 seconds	
Impeller diameter of the fans	2.1 m	
Fan curves	See figure 1 and 2	

Start-up calculations
Based on the tunnel-data as a first step the start-up time is calculated for the fans equipped with fixed blades and with a variable pitch system.
The calculations are based on the following assumptions:

- Because of the variable speed drive the torque of the motor is equal to the nominal torque of the motor over the whole frequency range.
- The fans start-up at the same time and during the whole start-up the both fans have the same speed.

Results

See figures 3 and 4 for the variation in time results of the fan total pressure, system pressure, volume, and speed.

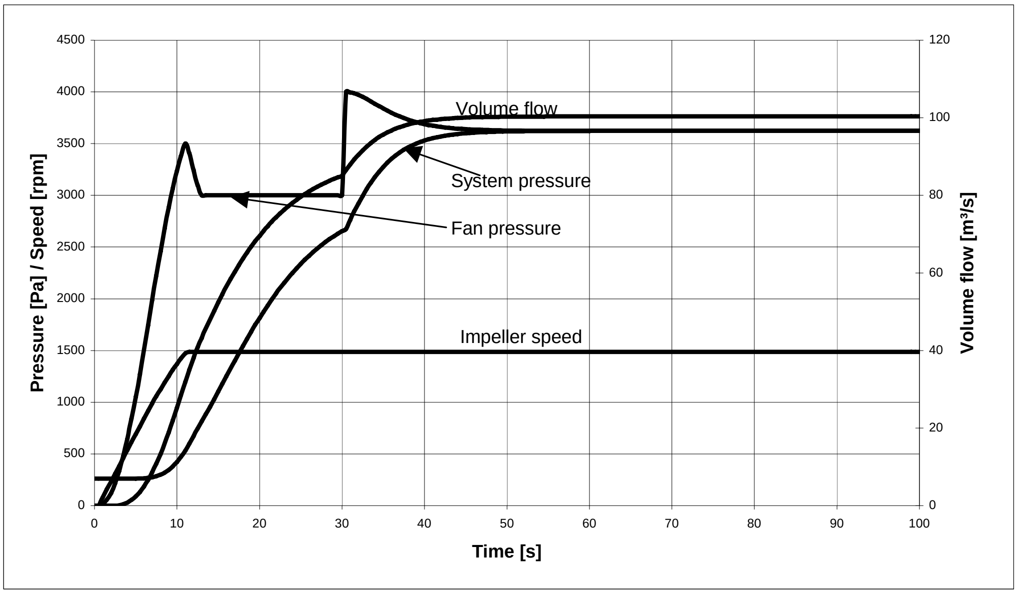

Figure 3: Start-up fixed pitch fans

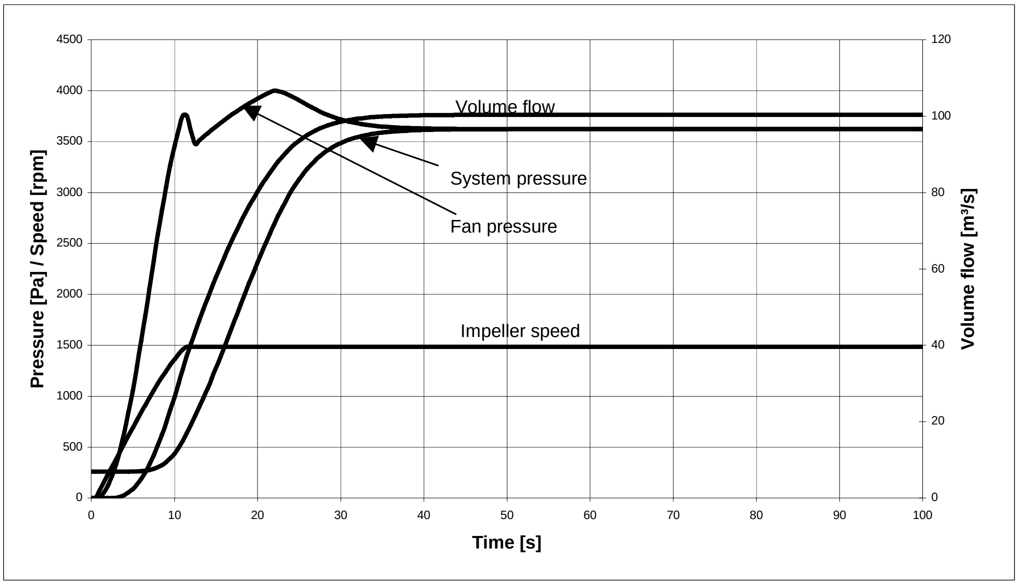

Figure 4: Start-up variable pitch fans

From the previous figures the following summary (Table 2) can be noted:

Table 2: Compare Fixed Pitch versus Variable Pitch

Variable	**Fixed Pitch**	**Variable Pitch**
Total start-up time of the system	50 seconds	40 seconds
Acceleration time of the impeller	10 seconds	10 seconds
Time the fan operates in stall	30 seconds, from t=0 to 30 seconds	3 seconds, from t=0 to 3 seconds
Critical margin between fan stall pressure and system pressure.	$P_{fan} – P_{system}$ = 335 Pa, at t=30 seconds	No critical margin

Influence of the start-up method.

The start-up calculations described above are based on the assumption that both fans have the same speed during the start-up. But what happens if one fan is running at full speed and the second fan has to start-up due to a fire? The quickest and most simple way would be to start-up the second fan while the first fan keeps running at full speed. To be able to perform this calculation the system-resistance line the second fan experiences has to be determined. If one fan is running the volume flow of this fan is 140 m³/s. At this volume the pressure loss of the ducting is 2000 Pa, so at zero flow the system-resistance for the second fan is 2260 Pa (2000+260). At full speed and a volume of 100 m³/s the system-pressure is 3600 Pa (pressure of the two fans in parallel). The fan curve and the system resistance line can be seen in the figure 5.

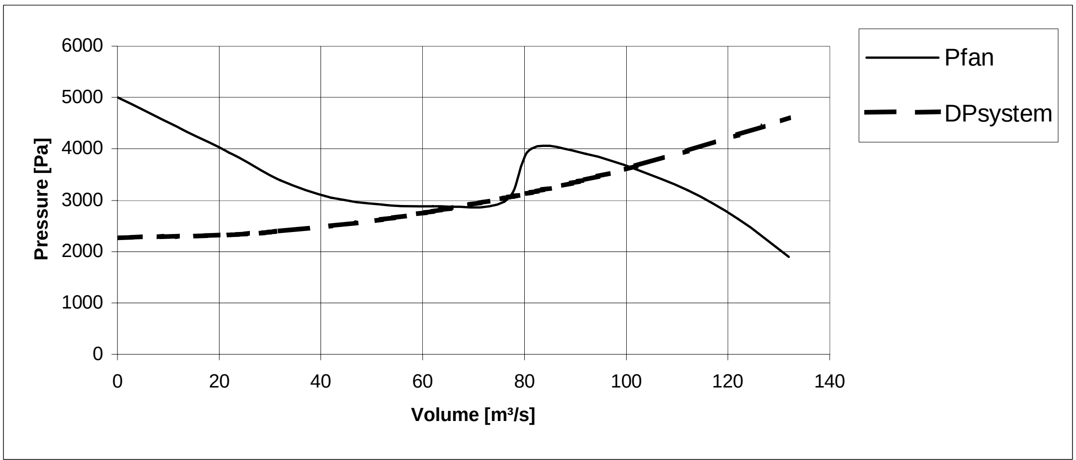

Figure 5: System resistance line and fixed pitch fan curve

Start-up the second fan with a fixed pitch system.

The above figure shows that between 70 and 75 m³/s the fan curve lies below the system resistance line, so in this area the critical margin between the fan pressure and the system resistance line becomes negative. This means that the fan will remain operating in stall at a volume of 70-75 m³/s (also see figure 6).

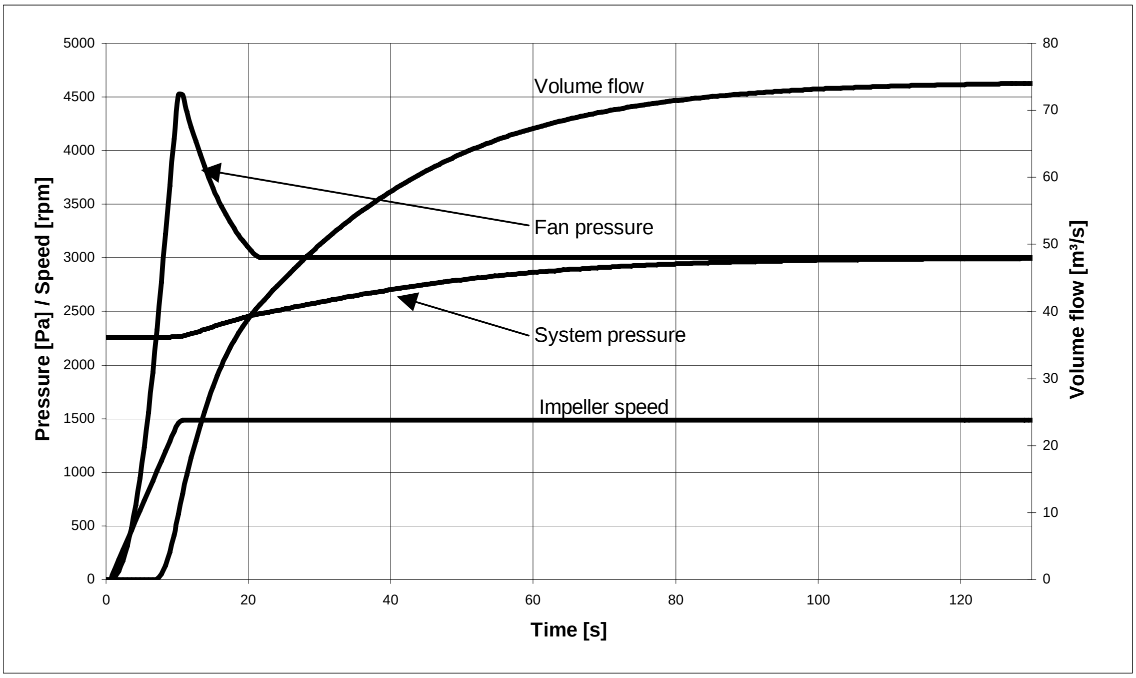

Figure 6: Start-up second fan with fixed pitch system

Start-up the second fan with a variable pitch system.

Also with a variable pitch fan the fan goes into stall if the volume is below Q_{stall}. However during start-up the volume-pressure curve can be “moved” to the left if the volume is lower than Q_{stall}. So by starting the fan with a small blade angle the blade adjusting system has to “follow” the volume by increasing the angle in a way that Q_{stall} stays smaller than the actual volume. Doing so prevents stall and the maximum fan pressure is still available for accelerating the air.

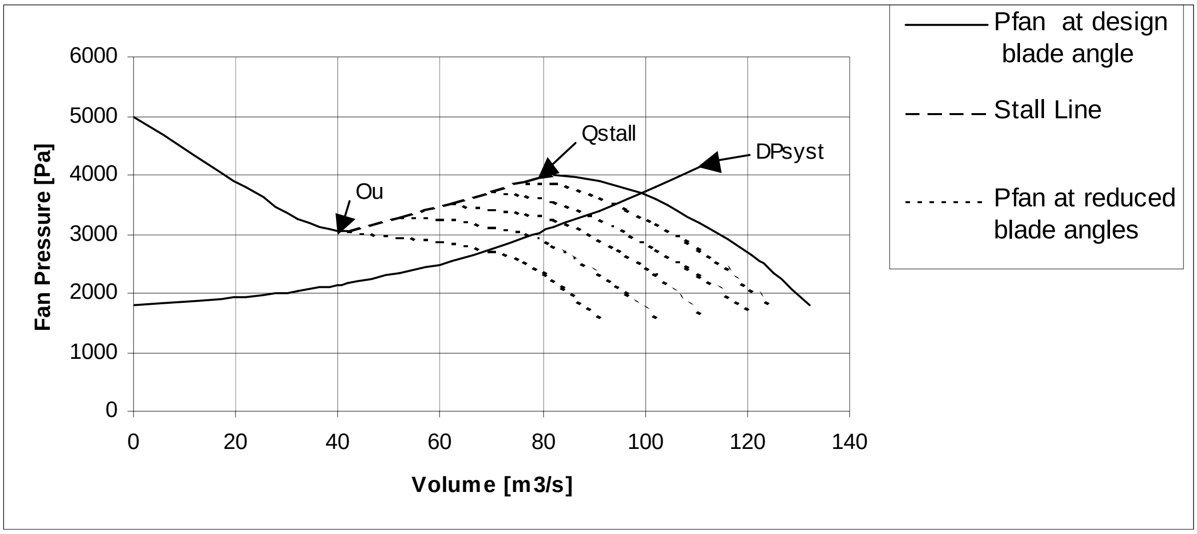

Figure 7: System resistance line and variable pitch fan curve

For the change of the fan pressure, system pressure, impeller speed and volume flow in time see figure 8. The figure shows that the start-up time of the second fan is about 55 seconds.

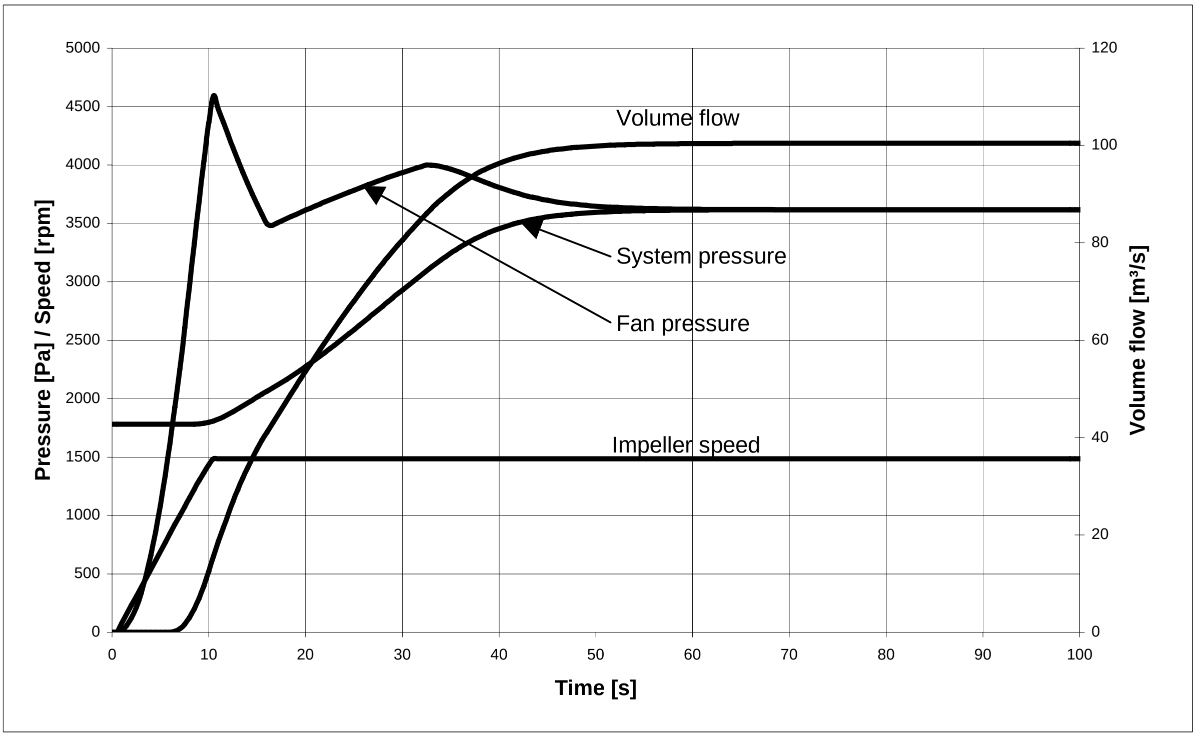

Figure 8: Start-up second fan with variable pitch fan

Influence of the length of the extract duct on the start-up time

To determine the influence of the length of the extract duct the start-up time is calculated for different duct lengths. The results can be seen in the following graph:

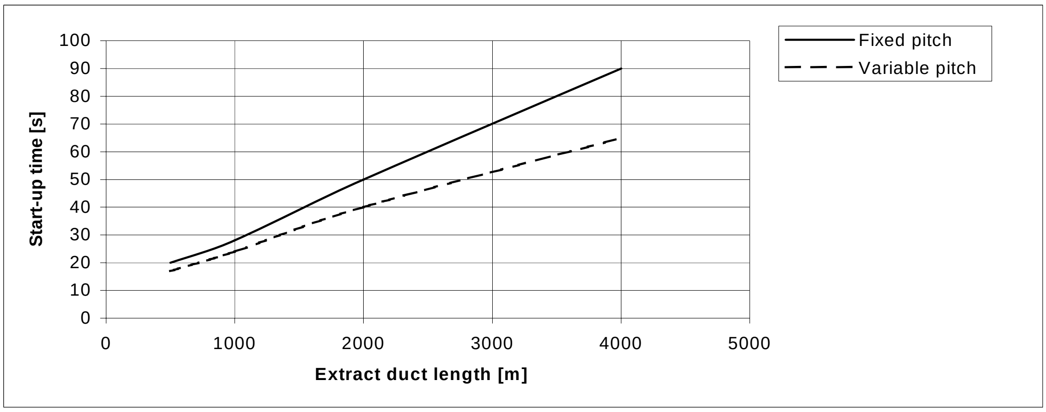

Figure 9: Influence duct length on start-up time

Note that the start-up time is proportional to the length of the extract duct.

4. CONCLUSIONS

- The calculation method gives a good understanding about the start-up of fixed and variable pitch fans in parallel.
- The start-up time of variable pitch fans is shorter than with fixed pitch fans. The difference between the start-up time increases with the length of the extract duct.
- The length of the extract duct has a considerable influence on the start-up time. To be able to start the system within 30 to 60 seconds the extract duct should not be much longer than 2000 m.
- With variable pitch fans parallel start-up or sequential start-up is possible. If due to a fire a second fan has to be started there is no need to reduce the speed of the already running fan first.
- For any fan selection it should be thoroughly checked if and how the fixed pitch fans can be started. If the critical stall margin is relatively small the fans can remain operating in the stall area and do not reach the design volume. This can happen if the static counter pressure due to atmospheric conditions is (temporary) higher than estimated or if during start-up the speed of one fan is higher (in this case 50-100 rpm) than the other fan.

DESIGN CRITERIA AND OPERATIONAL LIMITS FOR AXIAL FLOW FANS OPERATED IN PARALLEL MODE

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ABSTRACT

Axial Flow Fans are the preferred fan types used since about 40 years in modern tunnel ventilation systems. Their advantages against other fan types like Centrifugal fans are mainly that axial flow fans require less space when installed in the tunnel building and ducting systems (especially in case of parallel installation), they typically produce lower 'installation losses' as they can much easier be adapted to the main flow direction thereby avoiding unnecessary 'extra' flow accelerations and decelerations and they normally have a much wider range of high efficiencies when operated off the design point at part load conditions. Off-design operating conditions of axial flow fans are typically controlled by changing the rotor blade angle from 0 to maximum during operation (either hydraulically or electromechanically adjustable) or by using a variable speed drive at fans with fix blade pitch (adjustable at rest). However, when operated in a complex ventilation system in parallel mode with 'connected' ducting systems at inlet and/or outlet, the specific performance characteristics of an axial flow fan and their limits especially with respect to start-up conditions need to be taken into consideration when designing a tunnel ventilation system. Such design criterias are being discussed in this paper.

1. INTRODUCTION

Fans in complex ventilation systems, either in tunnels or other applications, do not only operate at design point conditions, but need to cope with high flexibility with steadily varying system requirements for volume-flow an/or pressure rise and therefore are mostly operating at 'off-design' conditions. The respective fans must be capable to follow any such 'system' requirements without 'operational' limitations and allow for stable off-design operation.

Several methods are used to adopt fans to off-load conditions. Most common methods are either via variable inlet guide vanes, via change of rotor blade pitch angle during operation (very often combined with two-speed motors) or via operation with variable speed drives. From such methods the last two one's (whether used singular or in combination) have proven in many installations to be the most efficient solutions and, depending from the specific system characteristic, normally allow for stable off-design operation.

However, especially when operating axial flow fans in parallel mode (which is a typical application in ventilation systems designed for long vehicle and rail tunnels, see **Figure 1**) in a tunnel ventilation system, specific attention must be given to the required start-up conditions for each individual fan. This is even more vital in today's required 'modern' ventilation system designs with respect to safely handle emergency and/or catastrophic scenarios in a tunnel after a vehicle accidents with a fire inside the tunnel.

Such emergency scenarios developed for vehicle tunnels in the last years are focussed on keeping the smoke in case of a fire as far as possible locally bounded and avoid extraction to other 'clean' areas of the tunnel tube. This shall allow for the people in the fire area to safely

Figure 1: Typical installation of axial flow fans in parallel operation (Plabutsch Tunnel, Austria)

escape into 'smoke free' areas of the tunnel. Dealing with such complex scenarios especially in long vehicle tunnels i.e. requires that normal longitudinal flows in specific tunnel sections needed to be decelerated during a catastrophic case within few minutes to zero and, if required, accelerated into reverse flow direction, that the smoke can be extracted locally with highest degree of exhaust capacity and many more. To cope with such scenarios requires that fresh-air supply and/or exhaust fans in stand-by mode before the accident can be put into operation in shortest possible time and the more are capable to safely and quickly provide the required capacity without any operational limitations. Special attention has therefore to be given to chose the appropriate type of fan regulation for the required specific ventilation system start-up conditions.

2. AXIAL FLOW FAN CHARACTERISTICS

The fan performance charts of axial flow fans operated with rotor blade adjustment or variable speed regulation vary significantly from the other and thereby have a significant influence with respect to the correct application for the intended duties. The aerodynamically basic details of a typical axial fan characteristic curve are shown in **Figure 2**. The axial flow fan performance curve typically consists of a 'stable' and 'unstable' beam. When increasing the systems losses the fan operates at stable conditions between point 1 and 2 with corresponding varying volume flow rates. If the volume flow rate is further reduced below point 2, the inlet flow angle to the rotor blades decreases below a limit value where the blade profile can no longer produce the necessary deflection and deceleration of the flow across the fan rotor. The flow at the profile starts to separate and subsequently moves the fan into stall conditions with further a decreasing flow rate and/or lower pressure increase. At point 3 the axial fan is back at a 'semi' stable 2nd characteristic curve where the volume flow rate can be further reduced and the pressure rise re-increases. An axial flow fan can be operated in such region for a short time, however, it has to be noted that this is still only a 'semi' stable operation with typically higher than normal loads and vibrations at the rotor fan blades. If the system resistance de-

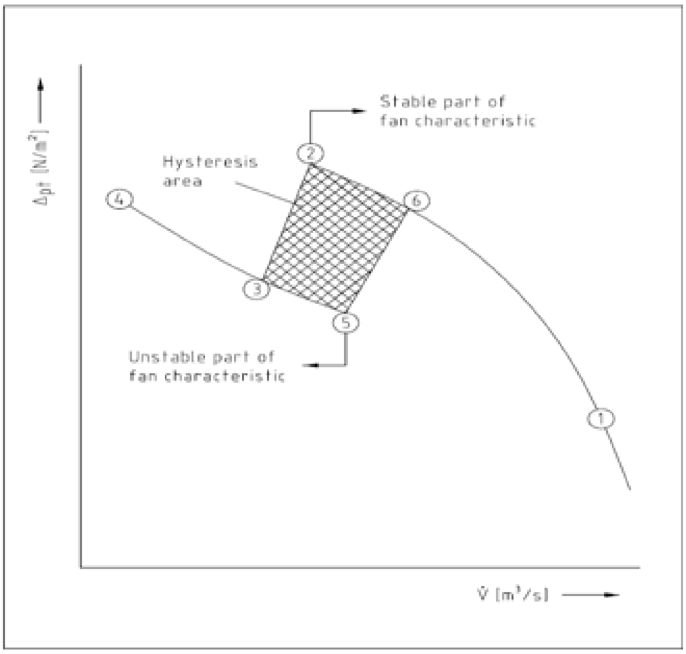

Figure 2: Typical performance graph axial flow fan at fix rotor blade angle and at constant speed

creases and thereby 'unloads' the fan it moves back from point 4 to point 5 (hysteresis point) from which it jumps back to stable conditions at point 6 with further reduced system losses. The area between points 2,3, 5 and 6 is the so-called 'hysteresis area' which marks a field of highly unstable fan operation with undefined flow conditions and possible stresses/vibrations at the rotor blades mostly exceeding the allowable level. Any operation of an axial flow fan in such area needs to be avoided.

Figure 3 shows a typical axial flow fan performance chart for a fan with variable rotor blade angle settings during operation at fix speed. The graphs for 'constant' blade angle are representing the respective 'stable' part of the fan performance curve for a given rotor blade angle up to point 2 as described above. The upper limit line marks the 'stall-line' of all rotor blade angles and should not be exceeded to avoid any fan operation in unstable conditions. If the systems resistance line varies between 0 to maximum the rotor blade angle must be adjusted accordingly to the required operation point at the resistance line (in the following a resistance line according to $\Delta p_t \sim k\ V^2$ was assumed). The most important part of such performance chart refers to the region at very low flow rates (so-called 'saddle-point') where rotor blade settings at low grades still allow to achieve a relatively high fan pressure rise with stable fan operation conditions. This will identify later as a significant advantage against speed regulated fans when discussing various fan start-up scenarios for parallel operation.

Figure 4 shows the corresponding axial flow fan performance chart for a fan with same hub/tip size and rotor blade geometry but operated with a variable speed drive. The graphs for a chosen fix blade angle again show the respective 'stable' part of the fan performance curve up to point 2 as described in **Figure 2**. As one can easily identify, such speed regulated fan typically provides a much higher fan efficiency along the identical systems resistance line compared to the variable blade pitch performance graph (this refers to the fan performance only, for full and correct power consumption comparison one need to take the motor and drive efficiencies into account as well, however, this is not the purpose of this paper). The most important difference compared to the performance graph for fans with variable rotor blade settings at constant speed appears when taking a look at the fan stall line. Such stall line, mostly following the $\Delta p_t \sim k\ V^2$ characteristic, clearly indicates that for a chosen rotor blade angle such fan can only be limited operated left from the stall line and at least not at higher speeds (almost above 30 ÷ 35% nominal speed) as this means operating the fan under ‘stall’ conditions. This therefore has a significant impact on fan start-up procedures in parallel operations.

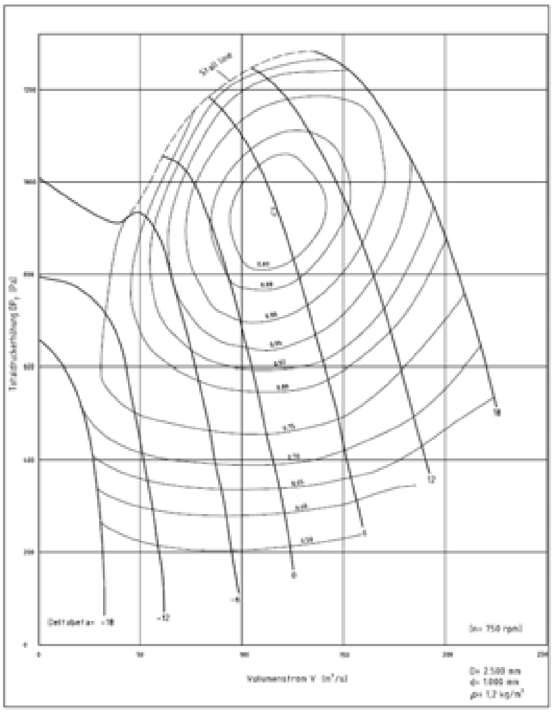

Figure 3: Fan performance chart for variable rotor blade adjustment during operation

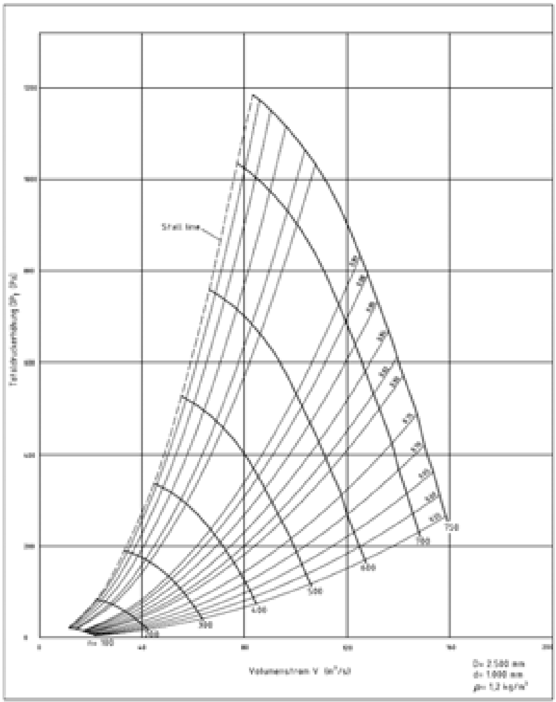

Figure 4: Fan performance chart for axial fans operated at variable speed

3. FAN START-UP SCENARIOS IN PARALLEL OPERATION

The discussion of fan start-up scenarios for axial flow fans in parallel operation assumes the following configuration:

a) 4 speed regulated fresh air supply fans (Ø 2,5m, n = 0 ÷ 750 rpm) are operated in parallel mode.
b) All 4 fans are connected at their ‘suction’ side, sucking the fresh air via a common ‘fresh air stack’ (**Figure 5**).
c) Each fan is designed for a maximum capacity of 100 m³/s fresh air with a corresponding ‘external’ pressure rise of Δp_t = 750 Pa at ρ = 1,2 kg/m³.
d) It is assumed that the stack produces a constant lift of Δp_t = 100 Pa against flow direction from top to bottom
e) The ventilation systems resistance characteristic is assumed to follow $\Delta p_t \sim k\ V^2$
f) Each fan is equipped with a stall sensor monitoring fan operations at stall conditions. Such control system automatically terminates any fan operation at stall after a given limit time is exceeded and the fan still operating at stall.

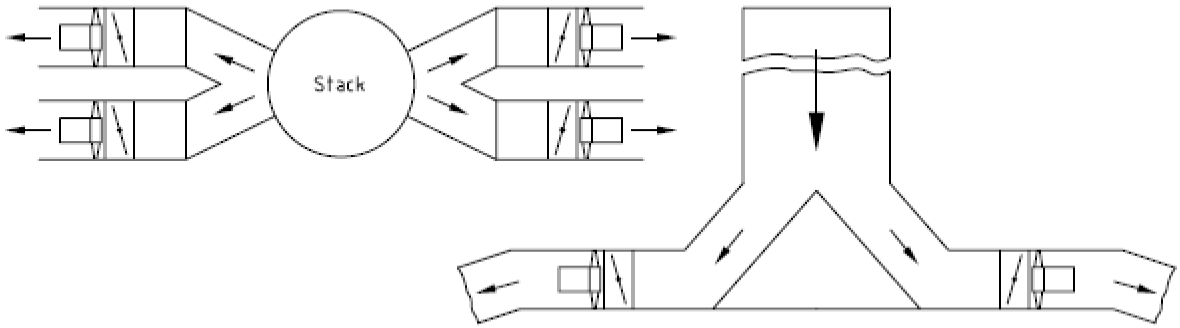

Figure 5: Fan installation in parallel operation

The respective fan performance chart for variable fan speeds and a constant rotor blade angle $\Delta\beta_s = 6°$ is shown in **Figure 6**. The corresponding system resistance curves for 1 fan in operation from start-up to maximum and the possible maximum operation of 4 fans in parallel are shown as K_1 and K_4. The following analysis of the start-up process assumes one fan starting after the next while each of the fan already in operation works at its maximum operating point at $V = 100$ m³/s. Such scenarios are each marking the most critical conditions for the start-up process of the next following fan. Certainly a large variety of other scenarios with one or more fans working at part load conditions when putting the next fan into operation could be discussed, however, all such combinations are somewhere in between the limit conditions with three fans at full load and start-up required for the last fan. The investigation of the start-up conditions therefore concentrates on such boundary conditions.

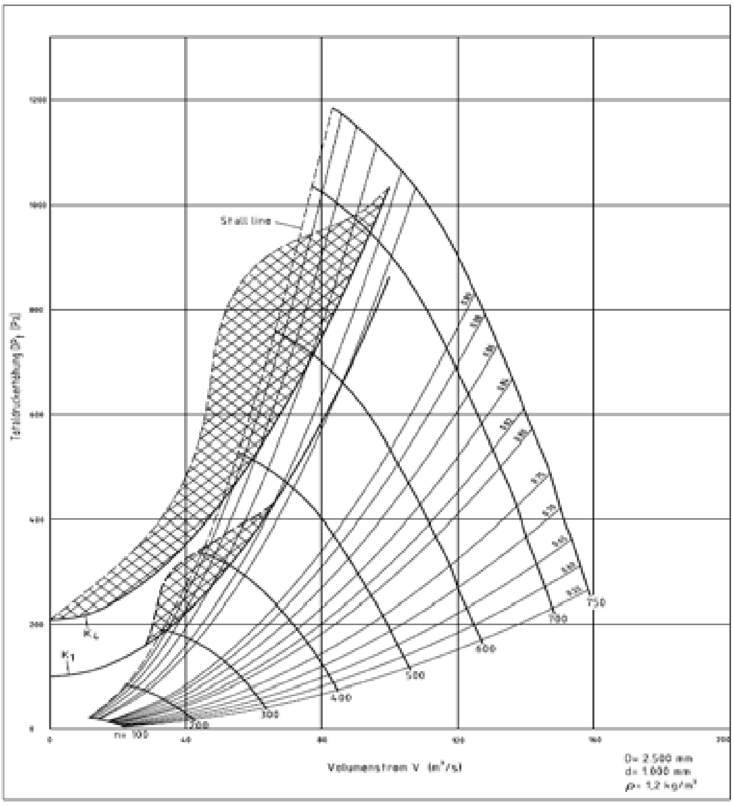

Figure 6: Fan performance chart with systems resistance characteristics K_1 and K_4

Putting the first fan into operation means starting at zero flow against the stack lift of Δp_t = 100 Pa and closed shut-off damper at fan suction side. When further accelerating the speed against closed damper, the fan firstly operates at the 'unstable' beam of its fan characteristic (left from the 'stall' line, see also **Figure 2**) at its respective actual fan speed. At about 300 rpm the shut-off damper is fully opened which allows the flow to start to accelerate through the fan and subsequently the tunnel tubes into the tunnel. About in between 320 ÷ 370 rpm the fan touches the stall line and switches over to stable flow conditions right from the stall line. Such point, although theoretically clearly defined, can't be determined exactly under real conditions as in such region the fan operates at transient conditions where small variations in the ventilation system influence the 'real' point where the fan switches from unstable to stable conditions. However, from such point onwards the fan speed can be increased further while the fan constantly operates under stable conditions up to its required maximum load.

The time of operating such fan at its 'unstable' characteristic beam depends on the time needed to accelerate the flow from stack top to bottom against the stack lift and the increasing pressure loss in the stack when reversing the flow direction by starting to supply fresh air into the tunnel. From operational experience such time is about 30 ÷ 50 sec. (depending on stack lift and tunnel geometry). However, when keeping the fan acceleration time at low speeds relatively long ('smooth ramp' at the drive system) the blade loads and respective subsequently resulting material stresses from the blade vibration under stall conditions can be limited to a level not exceeding the allowable material fatigue limits and therefore are not critical for the fan operation.

When now putting a second fan into operation against fan no.1 operating at its maximum duty point, means that fan no. 2 has, apart from the stack lift, also to overcome the additional pressure losses in the stack and any other connected airways resulting from the flow produced by fan no. 1 in operation. However, the additional pressure losses are still relatively small and therefore the resulting systems resistance line is close to such for fan no.1 (K_1) and a similar start-up process would appear for fan no.2 which indicates that under assumed circumstances fan no. 2 could mostly be put safely into operation at any time and with no major aerodynamically restrictions.

This starts to significantly change when trying to get the third fan into operation and even more worse, if not totally impossible, to start the fourth fan with all foregoing fans running at their maximum output. As one can identify from **Figure 6** the additional pressure losses from the first three fans in operation totally providing 300 m³/sec at full load each together with the stack lift require from the 4th fan to start along the resistance curve K_4. This would theoretically mean that the 4th fan has to go up to about 500 rpm before the 4th fan may switch from unstable to stable flow conditions. However, as described before, operating an axial flow fan at the unstable beam of its flow characteristic and against other fans already in operation and thereby providing fluctuating flow conditions means operating such fan in an area with highly transient conditions. Operational experience gained with such installations have shown that such 4th fan does not follow the theoretical resistance line K_4 but operates somewhere in the transition area (between the dashed line and K_4). This could mean that the 4th fan is moving up to its maximum possible speed and it is even not capable to switch over to stable operation but remains in the transient area. Operating an axial flow fan in such 'high' unstable area produces vibrating blade forces and material stresses by far exceeding the material limits and therefore is not an allowable operation mode. As the given time limit by the stall sensor is typically exceeded under such conditions, the fan is mostly switched off automatically to avoid any distortions to the rotor blades before it reaches 'stable' flow conditions.

In summary this therefore clearly indicates that such a configuration of 4 speed regulated axial flow fans in parallel as presumed in this discussed example can't be flexible operated and switched on/off without considering possible severe restrictions to the operation of such a tunnel ventilation system. This the more as the above example mostly assumes ideal circumstances, while this doesn't yet take into account any variations in the meteorology with higher than the assumed stack lift values, changing traffic conditions in various tunnel section with i.e. total break down of any traffic and respective blockages inside the tunnel, any other local and/or intermediate deviations/changes, etc., which could cause further unforeseeable additional restrictions to the required operation ability of the tunnel ventilation system.

There are obviously other scenarios possible to overcome such restrictions (i.e. reduce the capacity of the fans already in operation, start the third and/or fourth fan and then move up with all fans in parallel, etc.), however, all such combinations at least create more or less limitations to the flexibility of the ventilation system which especially in an emergency case are not allowable.

The necessary degree of flexibility with no obvious restriction for such a complex ventilation scenario can be obtained by using axial flow fans with variable rotor blade angle settings during operation instead of speed controlled fans. The respective fan performance chart at a fix speed of 750 rpm and same fan size as above is shown in **Figure 7** which also includes the equivalent resistance curves K_1 and K_4 for 1 fan in operation from start-up to maximum and the possible maximum operation of 4 fans in parallel.

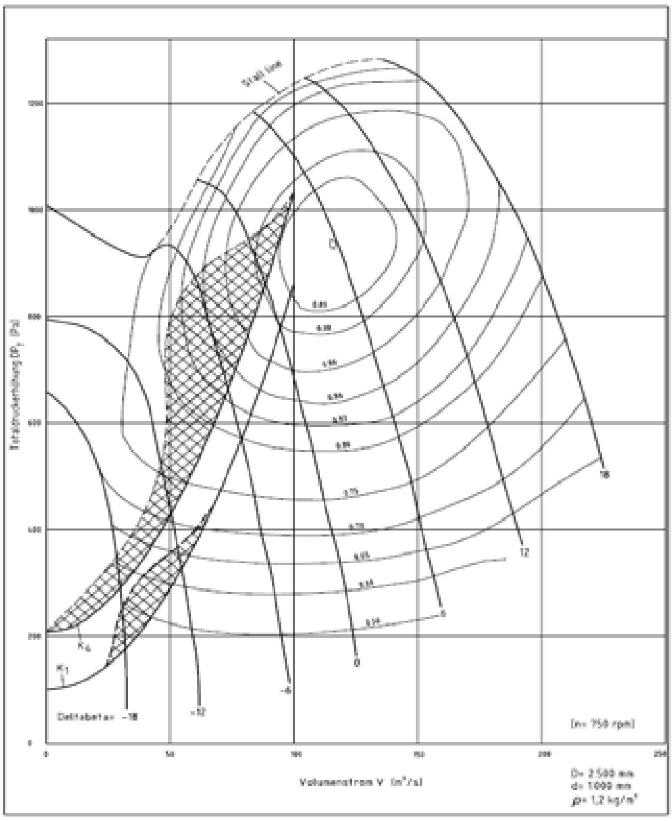

Figure 7: Fan performance chart with systems resistance characteristics K_1 and K_4

The specific advantage of a fan with rotor blade angle control is obviously the course of the respective stall line which in comparison to the performance chart of a speed controlled axial flow fan moves more horizontal and not like a '$\Delta p_t \sim k\ V^2$' curve as for the fan with variable speed. At lower blade angle settings ($\Delta\beta_s \leq = -6°$) the respective fan characteristic does no longer have a specific stable and unstable beam but is more or less stable from maximum to zero flow. This subsequently allows unrestricted stable operation of such a fan from zero to maximum flow and therefore also allows to cope with start-up processes as described above for i.e. 4 fans in parallel and 3 fans already working at their maximum capacity. The specific fan characteristic for fans with rotor blade angle variations also allows to deal with any such transient conditions as they obviously appear during the various start-up scenarios as long as the maximum 'saddle-point' (see Δp_t value at zero flow i.e. for $\Delta\beta_s = -6° \sim 1.020$ Pa = maximum possible pressure difference across the shut-off damper at fan suction side) is above the necessary maximum pressure increase required for i.e. 3 fans at full capacity.

The specific performance characteristic of axial fans with rotor blade angle control also allows to operate those 4 fans in parallel at different Volume flow each (within certain limits) and thereby providing a very high degree of flexible use especially in case of the realisation of specific emergency scenarios (i.e. smoke spread control in case of a fire) where some tunnel areas may need a higher fresh air supply while others only require lower volumes. To achieve this requires that the fan is capable to produce the same level of pressure increase for varying volume flow rates at stable operating conditions. It is obvious that this can't be achieved by a fan with speed control.

4. SUMMARY

A comparison concerning start-up procedures was carried out on axial flow fans operated in parallel mode for either speed controlled fans and fans with continuous rotor blade angle adjustment. The comparison showed that the parallel operation of such fans and the more the start up against other fans already in motion can have some severe restrictions for speed controlled fans resulting from the specific course of the stall line on such fans and the large area of unstable fan operation especially at start-up conditions. A designer of a complex tunnel ventilation system needs to consider in detail such limitations and restrictions during the design phase when planning different ventilation scenarios. The use of axial flow fans with continuous rotor blade angle adjustment during operation does generally not have such limitations on fan operations and therefore provides a much higher degree of flexibility compared to speed controlled fan. In case of uncertainty of the fan operation in parallel mode or other restriction given by the tunnel tube sizes and/or geometries the use of fans with rotor blade angle control should be considered the preferred solution for a safe ventilation system design.

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REFURBISHMENT OF EXISTING TUNNELS AND CONSTRUCTION OF 2ND TUBES – SOLUTIONS TO THE ELECTROTECHNICAL AND SAFETY EQUIPMENT

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ABSTRACT

Among its various projects, the construction of additional tunnel tubes is one of the most difficult tasks that ASFINAG has to deal with. Such projects are highly complex affairs since many diverse factors have to be taken into consideration, i.e. the existing tunnel infrastructure, traffic flow during construction, continuous changes in technological and regulatory conditions, tunnel operating conditions etc. Factors considered decisive for successful implementation are identified here based on an analysis of seven projects involving the construction of a twin tunnel tube. The paper presents solutions found for two projects: the Bosruck tunnel, and the Roppener tunnel.

1. INTRODUCTION

Currently, ASFINAG is engaged in the construction of a second tunnel tube on seven sites in Austria (see Figure 1). By April 2008, the new tubes for the Lainberg tunnel on the A9 motorway, and the Katschberg tunnel on the A10 motorway, will both be in operation. For all seven sites, the opening of second tubes means that existing tubes will have to be adapted accordingly.

Figure 1: Planned construction of second tunnel tubes in Austria

Project teams face several dilemmas when planning second tubes. These are described in more detail below. It was long assumed that existing single tube tunnels could simply be augmented by constructing an adjacent second tube, providing links in the form of cross-connections, and that it would merely be necessary to undertake relatively minor adjustments to the original tube. Unfortunately, we have been forced to learn that reality is much more complicated.

Project implementation has revealed the need for a more holistic approach in second tube construction, i.e. the resulting tunnel system has to be taken into consideration as a whole. The most important reasons for this are:

- The specifications and regulations applying to the construction of new tubes are not the same as those applying to the construction or refurbishment of the existing tubes – several updates or amendments have normally taken place in the meantime.
- Existing tubes impose several constraints on new tubes, primarily in terms of electrical engineering considerations, and not just in terms of construction features.
- Operating conditions are subject to continual development
- Only by considering the system as a whole is it possible to obtain a worthwhile cost-benefit analysis, e.g. by taking simultaneous refurbishment of equipment in existing tubes into account.

2. REGULATORY BACKGROUND

As is well known, the tunnel catastrophes that occurred in the period after 1999 led to major reconsiderations in the field of safety technology. These catastrophes can thus be taken as a prime mover in the development of guidelines and regulations over the past 7 to 8 years.

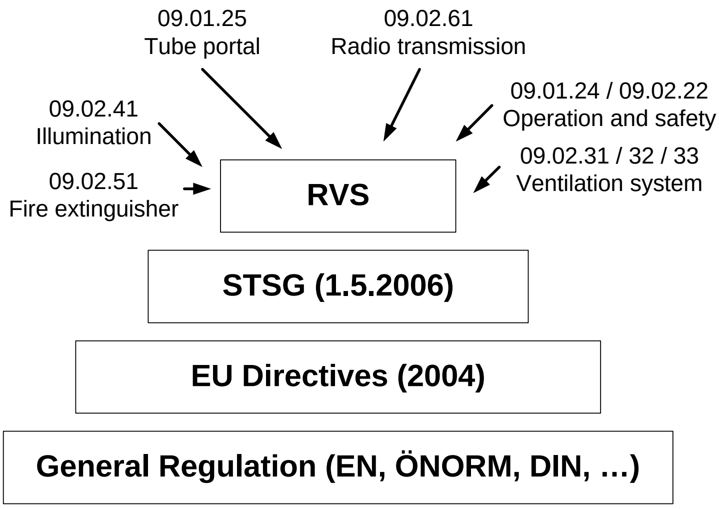

Figure 2: Regulatory levels

Looking at the Austrian regulatory framework relevant for ASFINAG, the 'RVS' (Richtlinien und Vorschriften für das Straßenwesen), we find that a multitude of adjustments have been undertaken since 1999 (at which time the rules of 1989 still applied). With respect to the operating and safety conditions in tunnels, various committees have been working on redrafting official regulations in order to match safety standards with the possibilities of modern technology. It is expected that the new recommendations will become binding during the first half of 2008.

Unfortunately, recent experience clearly shows that revision of regulations can never lead to an end state. Technological progress, particularly in the areas of video or automation technology etc. demands that continuous adjustment be made to existing specifications and regulations. This means that the execution of any large project, e.g. the construction of a second tunnel tube, becomes an enormous challenge. Such projects take many years to develop and have to be continually reviewed and revised in terms of the impact of changes in current regulations. At some stage in every project a point is reached where it no longer becomes possible to take every regulatory change into consideration. Close co-operation with the respective ministry is thus essential, in order to ensure that a tunnel system still receives official approval before it is finally opened to traffic.

Moving away from a mid-term perspective (the last 8 years) and considering the period since the initial construction of the tunnel tubes, the enormous changes that have taken place in terms of the design and outfitting of tunnel systems become immediately apparent. The need for compromise in planning the second tube is especially clear with respect to construction conditions. Table 1 provides an overview of specific regulatory and structural changes that need to be considered with respect to the original tunnel tube.

Table 1: Overview of old and new requirements

	Existing conditions	Present requirements
Cross-connections	▪ Situated according to position of lay-bys in existing tunnel. Connections for pedestrians (PCCs) were not available, connections for emergency service vehicles (ESCCs) every 800m to 1,500m.	▪ ESCCs every 1,000m ▪ PCCs in between at intervals of 250m ▪ Connections for tunnel traffic are no longer planned
Air supply and extraction equipment for transverse ventilation	▪ High capacity of air supply ▪ Extraction equipment is inadequate with respect to capacity and heat resistance (currently at 250°C over 60 mins.) ▪ No influence over longitudinal air flow	▪ Extraction equipment must have capacity of 120m³/s (for all sections in the tunnel) ▪ Heat resistance of 400°C over 120 mins. ▪ Control of longitudinal air flow in the event of fire 1.5 m/s to 2.5 m/s
Internal lighting	▪ Normal luminance of 2cd/m²	▪ For tunnels of risk class III luminance of approx.4.8cd/m²
Ante-portal traffic management	▪ Non-existent apart from in direct proximity to portal	▪ Numerous equipment up to about 500m in front of tunnel
Changes in equipment number and distance	▪ Video cameras every 250m ▪ Illuminated emergency exit indicators every 70m ▪ Emergency call stations every 250m ▪ Fire extinguishers every 250m	▪ Video cameras every 125m ▪ Illuminated emergency exit indicators every 50m ▪ Emergency call stations every 125m ▪ Fire extinguishers every 125m ▪ Increase in number of measuring stations for CO, air clarity, and longitudinal air velocity

3. REFURBISHMENT OF EXISTING TUNNELS SINCE 1999

Changes in regulatory requirements as well as advances in technical standards have both left their mark on the development of safety technology. With respect to the existing tunnel tubes for those sites where a second tube is now under construction, we find that the last time conditions were adapted to reflect new operating and safety standards (OSS) was in the period 1999 to 2002.

Table 2: Safety measures undertaken in existing tunnel tubes

Tunnel	Year	Ventilation	General Changes
Tauerntunnel	1999	Full transverse system	Installation of exhaust flaps; upgrading to OSS
Bosrucktunnel	2001	Full transverse system	Installation of exhaust flaps; upgrading to OSS; emergency exit installation
Katschbergtunnel	2001	Full transverse system	Installation of exhaust flaps; upgrading to OSS
Roppener Tunnel	2002	Semi-transverse system	Total refurbishment of ventilation system; upgrading to OSS
Pfändertunnel	2002	Full transverse system	Installation of exhaust flaps; upgrading to OSS
Lainbergtunnel	2003	Longitudinal	Illumination of emergency exits; kerb reflectors
Ganzsteintunnel	2002	Longitudinal	Illumination of emergency exits; kerb reflectors

As can be seen from the above table, the tunnels under consideration were upgraded to conform to new safety standards following the catastrophes of 1999.

The most important improvements entailed:

- Installation of large exhaust flaps for transverse ventilation systems
- Installation of emergency stations for pedestrians
- Installation of illuminated guidance systems (kerb reflectors)
- Installation of breathing equipment in emergency stations
- Installation of emergency exit indicators
- Installation of video monitoring systems

Consideration of structural adaptations such as rumble strips or the use of crash cushions at the tunnel entrance is beyond the scope of the present paper.

Naturally, during the upgrading of safety installations, refurbishment and maintenance work was also carried out on electrical equipment. This included:

- Refurbishment of emergency power supply system
- Refurbishment of fire detection system
- Refurbishment of equipment for measuring air quality
- Refurbishment of lighting/illumination system

Considering the above measures from today’s perspective, several criticisms may be raised with respect to their impact on or relevance for the construction of second tubes and/or the refurbishment of existing tubes. Two main factors need to be considered:

- Regulatory amendments and revisions (see section 2 above).
  The 1989 regulations still applied in the period 1999-2002. For the current ongoing projects, either the regulations from 2002 or current amendments need to be taken into consideration. There are also numerous new developments and updates which often lead to conflicts during implementation.
- Technological developments.
  This involves much more than conflicts between measures for existing and proposed tubes arising as a result of improved data processing.

Table 3: Examples for relation of systems to respective drivers

<table>
<tr><th colspan="2"></th><th colspan="2">Dependency on central unit</th></tr>
<tr><th colspan="2"></th><th><u>Centralized</u></th><th><u>Decentralized</u></th></tr>
<tr><td rowspan="2">Driver</td><td><u>Technology</u></td><td>▪ Emergency call (Voice over IP)</td><td>▪ LED – kerb reflectors with inductance coupling</td></tr>
<tr><td><u>Regulation</u></td><td>▪ Video detection/monitoring</td><td>▪ Emergency exit indicators every 50m
▪ Jet fans for 400°C over 120min</td></tr>
</table>

In attempting to find an acceptable, well-balanced solution, decision making procedures have to take several factors into account:

- **<u>Availability of specific technical options</u>**: extension of centralized systems e.g. video, radio transmission, tunnel control, emergency power supply, etc. normally calls for the adaptation of existing systems. Quite often the central units have to be completely replaced as for technical reasons they cannot be extended. An example here might be where the energy needed to ensure uninterrupted power supply exceeds the capacity of the existing system.
- **<u>Extension of existing systems is not economic</u>**: while technically speaking the necessary extension of a video detection system to include automatic picture storage may be possible, it is likely to be more economical to replace the whole system.
- **<u>Quasi monopoly</u>**: The market impact of continued use or extension of existing equipment needs to be taken into consideration. For example, where a decision is made to extend a given process control system, the producer is likely to gain a clear competitive advantage since normally only he is in a position to carry out the needed adaptation or extension. This could lead to a subsequent loss in competitive pressure resulting in greater monopoly power and a marked increase in prices over and above normal market levels.
- **<u>Equipment under guarantee</u>**: Where the equipment in need of extension is still under guarantee (e.g. video control unit) liability protection is likely to be lost when the necessary adaptation work is not carried out by the initial installer. A conscious decision will have to be made between contracting out the work to the original installer in order to maintain guaranteed liability cover, or inviting a third party to do the work and losing, partly or fully, guarantee rights.

4. REFURBISHMENT REQUIREMENTS FOR EXISTING STRUCTURES

In addition to the demands arising as a result of changes in the regulatory framework and/or improvements in technology, existing tunnel tubes normally require extensive refurbishment or maintenance work. For example, in the period between 1999 and 2002, in most tunnels employing a transverse ventilation system, large exhaust flaps were installed to improve smoke extraction. The Roppener tunnel was the only site where air supply and extraction equipment were updated in the existing tube in addition to the installation of new exhaust flaps. In none of the other tunnels reviewed here (with transverse ventilation) was refurbishment work carried out. With respect to the construction of second tubes and tube refurbishment for the projects concerned here, we are thus confronted with a situation where axial machines may already have been in operation for 30 to 35 years, and where they may have neither sufficient extractive power nor the requisite heat resistance. The construction of second tunnel tubes together with the necessary refurbishment work on existing tubes is thus a good opportunity to carry out extensive refurbishing. This is mentioned merely by way of example. Other considerations regarding equipment renewal might include medium voltage switchgear, illumination systems, water systems for fire fighting, etc.

5. OPERATIONAL DEMANDS

As is the case in the implementation of any other project, the construction of second tunnel tubes also has to meet the requirements of the operators concerned. The operating concerns described in the table below are those considered to be of general validity. It can be seen as an attempt to list those factors considered most essential.

Table 4: Essential Operating Factors

Uninterrupted traffic access	▪ High level of component reliability ▪ Minimum failure rate for system as a whole ▪ Minimum disturbance during maintenance and inspection
Low operating costs	▪ Use of highly efficient components ▪ Minimum energy consumption through optimization of control procedures ▪ Use of low-cost components (in terms of time, material, personnel, maintenance)
Ease of maintenance	▪ Use of standardized components where possible ▪ Modular construction of comparable sections in various tunnels ▪ Procedural simplicity and clarity.

A close look at the above operating factors quickly shows the potential dilemmas involved in the construction of second tunnel tubes. Normally, one of the main goals during initial planning is to ensure that the potential scope for further use of operating and safety equipment in existing tubes remains as wide as possible. For example, in a case where it is technically possible to continue to use medium voltage switchgear, the operator may understandably set itself the goal of updating the system during the construction of the second tube. Reasons stated for this may include the need to ensure commonality of switchgear panels, or the relatively expensive maintenance costs for existing plant and equipment. A further commonly cited aspect relates to the need to employ higher quality components, which may be more easily available or more effective in operation.

In practice, in order to assess the respective relevance of such questions, it has proved to be of value to first carry out a cost analysis for the whole life cycle – from installation to replacement – and on the basis of this, to make a final decision regarding project execution.

6. SOLUTIONS FOR THE CONSTRUCTION OF SECOND TUNNEL TUBES

On reviewing the points mentioned in section 2 to 5 above, the potential for conflict becomes obvious. Clearly, there is ultimately a large element of compromise involved in many of the considerations relating to project execution, and actual procedures are often far removed from optimal conditions (as might be found, for example, on greenfield sites). A comprehensive description of all compromises necessary for the seven sites under consideration here is beyond the scope of the present paper. The discussion in tables 5 and 6 below is thus limited to a selection of potentially highly successful measures employed in the Roppener tunnel and in the Bosruck tunnel.

- Roppener Tunnel

Tabelle 5: Upgrading of Roppener Tunnel

	Item	Existing	Upgrading
Structural	Cross-connections	▪ 3 Emergency lay-bys at intervals of approx. 1,250m End sections for cross-connections near lay-bys	Additional lay-bys have to be installed in the existing tunnel (current standards and regulations require lay-bys every 1,000m). The distance between lay-bys will thus be halved, resulting in final intervals of approx. 725m.
	Emergency stations	▪ Emergency stations (ES) with pedestrian access at intervals of about 424m.	According to current standards and regulations ES are required every 250m in existing tunnels. Additional ES are thus to be installed halfway between present stations.
Ventilation	Controlling longitudinal air flow in event of fire	▪ Not available	In the first such measure of its kind in Austria, and in agreement with the relevant ministry, fire curtains are to be installed near the tunnel exit (4 in each tube). In the event of fire these close after tube evacuation (it is still possible for vehicles or anyone fleeing to pass through).
Electrical	Medium voltage switchgear (MV)	▪ MV panels at both portals and at the mid-tunnel cross-connection ▪ MV cable throughout the tunnel	Existing plant and equipment is in good condition and will continue in use. The additional units required in the new tube will be integrated with the existing system. In terms of energy delivery and distribution, it would have been better to install two MV units instead of keeping the single existing mid-tunnel panel.
	Video	▪ Video centre upgraded in 2005 ▪ Recording and detection not available ▪ Cameras have been in use since 1989	The existing control centre will continue in use but will be augmented to comply with new regulations (i.e. additional cameras, with possibility of picture storage and detection). The whole support system (camera units and image transmission) will be updated.
	Tunnel control	▪ Most of the control system dates from 1989 ▪ Ventilation control was renewed in 2002 ▪ Data transmission to control centre was extended in 2005	Adaptation of existing equipment to meet increased needs with the new tunnel is not possible. Only the ventilation control system can remain in use . This was set up in 2002 for the axial machine and exhaust flaps, and will be integrated into the new tunnel control system.

- Bosrucktunnel

Tabelle 6: Upgrading of Bosruck tunnel

	Item	Existing	Upgrading
Structural	Cross-connections (CCs)	▪ 12 cross-connections suitable for access by pedestrians (PCCs) ▪ 2 cross-connections suitable for use by emergency services (ESCCs) ▪ 11 Emergency lay-bys (ELs)	Existing CCs will remain in use. Improvements will be made and additional CCs are to be constructed. In future, 17 PCCs and 5 ESCCs will be available. Existing ELs are to be adapted such that a lay-by is sited at each ESCC. The remaining ELs will be taken out of service, and adapted for the installation of jet fans.
	Location of electrical stations	▪ Now in emergency lay-bys together with emergency call station	In future, electrical stations are to be located in cross-connections. This has several advantages, e.g. better cooling, dirt avoidance, etc.
Ventilation	Continued use of axial machines	▪ Extraction equipment, heat resistant to 250°C / 60 min was renewed in 2004 ▪ Air supply equipment is intact	The full transverse ventilation system in the existing tube will be changed to a semi-transverse system, and the existing axial machines can remain in use. In future, air supply equipment will be used to ventilate the cross-connections. New extractors will be installed in the new tube to comply with new heat resistance standards, and these can then be made use of for both tubes.
	Control of longitudinal air flow	▪ Not available	Local meteorological conditions result in a high pressure gradient between the two portals. This means that for each tube, 10 90kW jet fans are required, each with a thrust of about 3,000N. That sufficient space can be made available for this at all is only possible due to the fact that side bays (with vehicle access) can be constructed as part of the new tunnel and that the left-hand emergency lay-bys in the existing tube can be used.
Electrical	Fire detection	Updated in 2000	Detection equipment in existing tube must be renewed/replaced since it no longer complies with current detection standards.
	Medium voltage switchgear (MV)	▪ MV cable replaced in 2001 ▪ Portal MV panels are from initial installation ▪ MV panels in tunnel set up in 2001	Except for the portal unit, the MV system was updated in 2001 as part of safety system upgrading. However, only the MV cable can be used after second tube construction. All MV panels will have to be replaced/updated.
	Emergency exit indicators (EEIs)	▪ Installed in 2001; intervals of 100m	To comply with current standards additional EEIs are needed (spacing of 50m required). Existing lighting can re-main in use, but will need to be adapted to new emergency exit conditions.
	Radio transmission	▪ Newly installed in 2001; digital ready	The existing system, including central units, can remain in use, but must be extended to cope with new equipment in the second tube.

7. CONCLUSION

In future, ASFINAG will no doubt be engaged in further projects dealing with the construction of second tunnel tubes. The Dalaas, Perjen, Gleinalm and Karawanken tunnels – just to mention a few possibilities– are all currently still bi-directional. In terms of safety considerations there will clearly be a need here for adaptation and refurbishment in the coming years. It is thus important to collect and analyse as many of the preceding project strengths and weaknesses as possible, and to use these to engage in a continuous process of improvement. By way of conclusion, the following points may be made:

- **Long-term planning:** In future, ASFINAG will need to place greater emphasis on the long-term when planning projects. This will entail not just construction considerations but also related adaptation and refurbishment equipments. At present, the implementation of an inventory management system for operating and safety equipment is under consideration.
- **Standardization:** An essential point here concerns the implementation of standards relevant for ASFINAG. Various working groups have been given the task of drawing up clear technical specifications. These should be based on, and of course meet, existing guidelines and regulations. The aim is to establish the widest possible common standards (to ease the burden on operating units), and to generate a broad market for procurement purposes (to avoid potential monopolies).
- **Deceleration of regulatory implementation**: From the point of view of road operators, greater continuity in project management would be highly welcome. This is not meant to imply that developments must progress more slowly. However, it would certainly be exceedingly helpful for project implementation if amendments to road regulations were not always immediately published and if they did not require immediate application. Once a year, for example, might suffice.
- **More conscious and deliberate use of new technology**: This is a matter requiring great care and attention on the part of business strategists. In future, much more consideration will have to be given to decisions relating to the acceptance or rejection of new technologies and technical improvements. It is essential here that a more holistic perspective be adopted. In the past, too much attention was placed on meeting the relatively narrow demands of specific ongoing projects. In this respect, ASFINAG needs to reposition itself in order to initiate a greater number of projects and bring them to fruition (more active innovation). Innovation has been too much of a passive process in the past, i.e. too many developments were left to suppliers.
- **Costing over the life cycle**: In future, the costing of project plant, procedures, materials structures etc. over the whole life cycle will be an essential measure in evaluating the relative costs of various alternatives for implementation (this applies particularly to refurbishment).
- **Increased use of risk analysis in optimising equipment**: Risk analysis need not be used solely for checking compliance with tunnel safety standards. In fact, it already finds great application in the more general aspects of project planning since it provides an ideal instrument for assessing the relative risks of alternative safety programmes.

UPGRADING OF THE VENTILATION SYSTEM OF THE GLEINALM ROAD TUNNEL

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ABSTRACT

The Gleinalmtunnel is part of the most important traffic ways in Austria. The daily traffic numbers of 25.000 vehicles confirm the importance of this „trail“. The tunnel ventilating system was build 30 years ago. It will be renewed under the guidance of “ASFINAG Baumanagement Gesellschaft”.

Keywords: Gleinalmtunnel, CFD, ICEM, CFX, ventilation

1. INTRODUCTION

The background for this renewal is based on the exchange of ceiling dampers which were applied four years ago. This application was done having in mind to change to new fans a short time afterwards. They should be adopted with the right volumeflow and crossing speed through the damper openings.

The dampers were installed to fullfill the national safety regulations RVS. The dampers have a size of 9m². The new dampers should be adopted to new fans in order to achieve a full working temperature resting system. The existing fans are not provided for working in smoke exhaust and hazardous situations.

To conclude:

- The existing axial fans are not prepared for high temperature operation
- Volume flow rates and air speeds should be adjusted to the new dampers

In front of this background EAS was charged to prepare the tender on behalf of the ASFINAG Baumangement AG for the renewal works.

EAS is an engineering service provider which cares mainly for Flow Simulation CFD (computational fluid dynamic) and design of aerodynamic influenced systems.

2. CFD INVESTIGATION

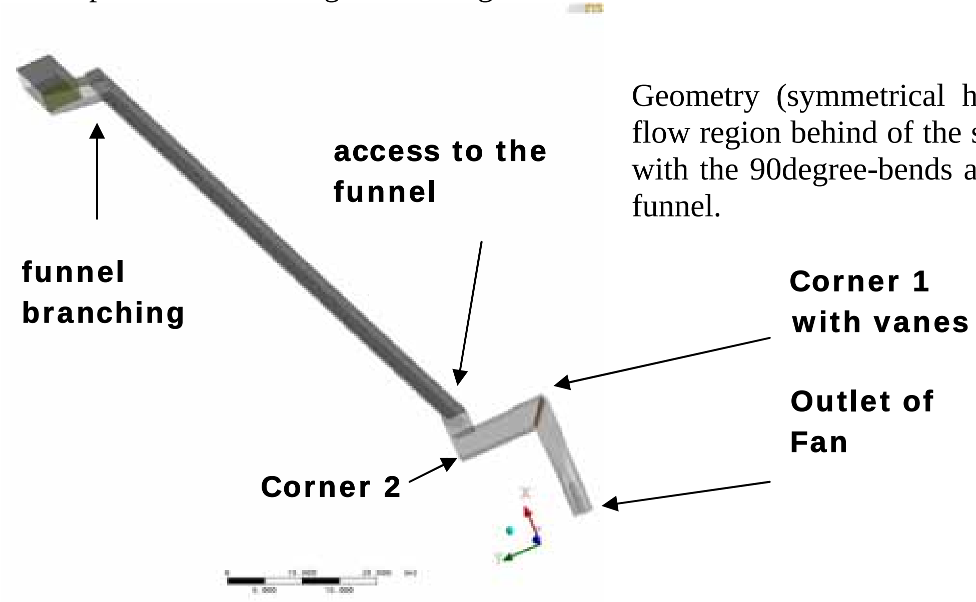
At a first visit of the Gleinalmtunnel it was recognised that the ducts between the fans and the access to the some hundred meter high funnels were not optimised concerning a low pressure loss of the air. Behind the smoke exhaust fans the air has to pass two horizontally 90degree bends and enters through a sidely access with a vertically 90degree bend into the funnels. In the first corner guiding vanes were installed, whereas in the second corner and in the access to the funnel no guiding vanes were installed. It was evident that the installing of some guiding vanes could significant lower the pressure loss. It has to be emphasized that the installation of guiding vanes is an old and approved technique to reduce pressure losses. But at geometrically complicated 3D geometries (vertically access to the funnel follows a horizontally 90degree bend) there is no design recommendation available as it is e.g. for simple geometries as a 90degree bend on long air ducts. Nowadays it is a quite simple procedure to determine a suited design for guiding vanes with the 3D simulation technique.

It was decided to perform a 3D calculation of these sections of the Gleinaltunnel, where design changes could be realised with a reasonable effort and where design changes promised to improve the flow situation.

As weakpoint were detected the duct in front of the fresh air fan and as mentioned above behind the smoke exhaust fans. For performing simulation it was necessary to have build up the geometry of the funnel and air ducts up to the fan inlet of the fan respective from the diffusor of the smoke exhaust fan up to the outlet of the funnel

2.1. Generating of the 3D-Geometry

Due to the fact that the Gleinalmtunnel is more than 30years old only 2D-drawings as paperprint were available. Some important parts as corners, guiding vanes e.g. could not be detailed-true extracted due to the fact that the quality of the paperprints were partially very poor. Therefore the missing geometry information was received by measuring the dimensions with tape-measure and digicam during a second and third visit.

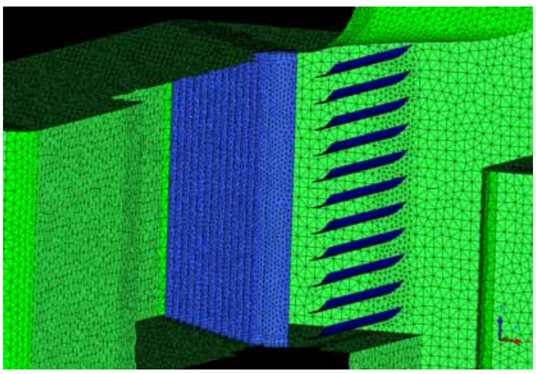


Geometry (symmetrical half-model) of the flow region behind of the smoke exhaust fan with the 90degree-bends and the 360m high funnel.

Fig. 1.: Geometry of the flow region behing smoke exhaust fan

2.2. Meshing

After generating the CAD data (with CATIA V5) the geometry has to be meshed so that the CFD solver can handle the geometry. As grid generator (´mesher´) ICEM Hexa and ICEM Tetra with Prism layers for relevant boundary layer effects were used.



ICEM grid with the new adapted Guiding vanes (blue) in the corner 2 and at the access to the funnel.

Fig. 2.: Cut-out of the ICEM grid of the geometry with the guiding vanes

2.3. Solving of the flow conditions

The commercial code ANYSY CFX 11.0 solves the so called Reynolds averaged Navier Stokes equations, which is an adaequate technique to investigate flows regarding pressure losses. The flow is stationary (steady state) and turbulencce is regarded as a scalar value.

Before improving a flow situation it is necessary to determine the status quo.

The boundary conditions were set as:

Volume flow rate for both smoke exhaust fans each 120m3/s

This corresponds to the normal fresh air ventilation.

In case of fire incident only one smoke exhaust fan would deliver about 180m3/s.

The flowfield in the funnel is highly swirled due to the fact that a 90 degree horizontally bend is followed by a vertically 90 degree bend. In Fig. 3 the streamlines of the current design are shown on the left side, whereas the improved design is shown on the right side. The streamlines are now nearly parallel in the funnel. For the streamlines in the funnel area the same effect is to be seen: The large detachment area is now reduced, so that the pressure loss is reduced.

Both design improvements are corresponding to a pressure loss reduction of more than 35%. To give a rough estimation for absolute pressure losses:

We expect at 180m3/s a pressure loss reduction of about 400Pa (up to 20% total) respective 10 % increase of air flow volume.

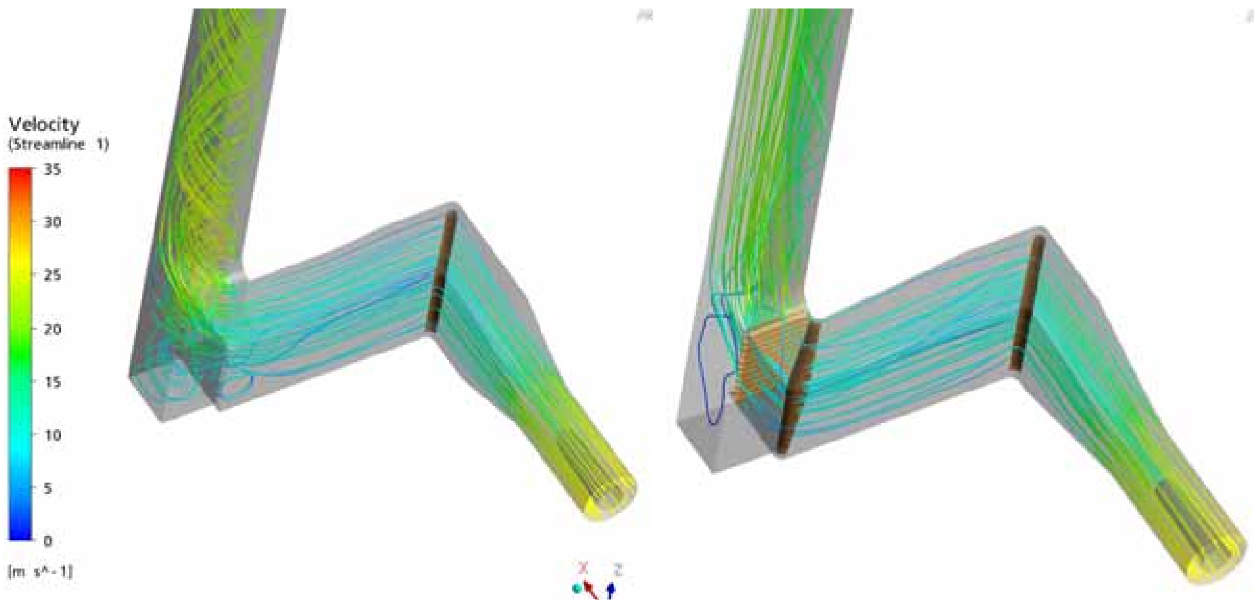


Fig. 3.: Streamlines of current design (left) and after (right) integrating the guiding vanes. The colours of the streamlines correspond to the velocity

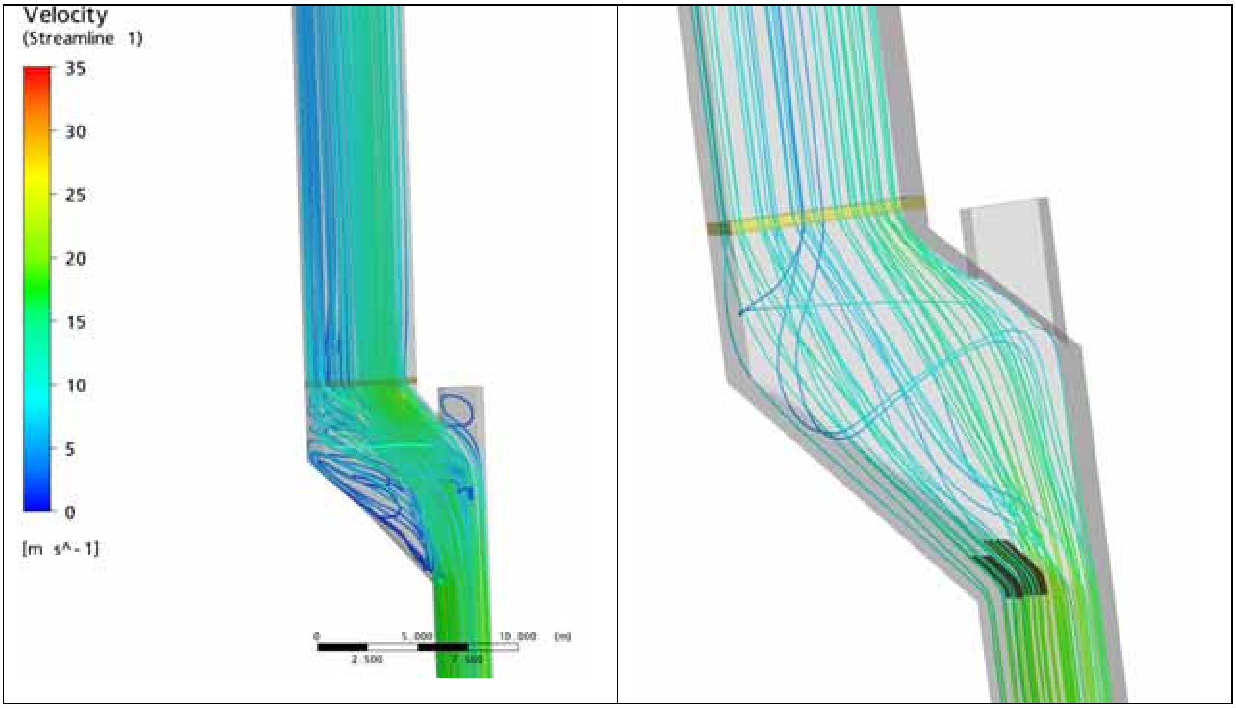


Fig. 4.: Streamlines of current design (left) and after (right) integrating the guiding vanes in the funnel branching. The large detachment area is minimized by applying two guiding vanes.

3. SUMMARY

It was shown that regions of air ducts could be improved with reasonable effort and invest to reduce the pressure losses. Under normal ventilation conditions either higher air volume is transportated at same electrical power consumption as before or the energy consumption decreases at the same air flow.

In case of fire incident the increasing of maximum flow rate is a plus for the safety.

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QUANTIFICATION OF THE LEAKAGES INTO EXHAUST DUCTS IN ROAD TUNNELS BASED ON IN-SITU MEASUREMENTS

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ABSTRACT

In recent years many countries have changed their requirements for ventilating road tunnels in an emergency. Traditional linear exhaust systems are no longer permitted; the smoke has to be exhausted from the tunnel close to the fire. The design of this new ventilation system requires different treatment in many ways. One aspect is the leakages flow into the exhaust duct away from the exhaust point, which can have a significant impact on the required ventilation power and must be considered in the design.

Nowadays only a very few established basis to quantify leakages are available. For this reason a Swiss research project has been set up to extensively investigate leakages into exhaust ducts in road tunnels. A main element of this research covers in-situ leakage measurements using the tracer-gas method.

The paper gives a general overview of the research project, covering aspects like theoretical background, choice of tunnels, construction and sealing methods, measurement method as well as data analysis to define a dimensionless leakage numbers for easy use in the practical application.

Furthermore the results and experience of the first measurements are presented and discussed. Although at the time of writing just four measurements are available, these results are already informative.

Keywords: Road tunnels, Tunnel ventilation, Smoke extraction, Leakage, Leakage measurement, Ventilation design, Design tool

1. INTRODUCTION

The ventilation system was and still is a major part of the road tunnel's safety system, however, the design case for the system has completely changed. The principle aim of the ventilation was to maintain the required air quality during normal operation, whereas today it is the smoke extraction in the emergency case. In longer tunnels a mechanical ventilation system to locally extract the smoke at the fire site is required by the guidelines in a number of countries.

The goal of such a system is to help the passenger escape out of the tunnel by preventing smoke spreading over the trapped vehicles. To avoid smoke spreading, an air flow towards the extraction zone from one side (one way traffic) or both sides (bidirectional traffic) with a velocity of 2 – 3 m/s is normally required. With typical tunnel cross sections of 50 – 60 m^2 the exhaust flow can easily become 150 – 250 m^3/s. With such an air flow the underpressure in the exhaust duct rises rapidly to values of 1'000 – 3'000 Pa.

The underpressure in the exhaust duct causes a leakage flow through the closed dampers and through the structure. This additional flow can have a significant impact on the efficiency of the ventilation system and therefore must be considered in the design. The main difficulty today is to quantify the expected leakage because very few established bases are available.

Underestimating the leakage flow means the required exhaust flow cannot be achieved. Providing additional exhaust capacity can become very complicated and expensive.

In case of overestimating the leakage flow, the installed ventilation power is much too high. A further problem is less obvious, but can cause serious problems. Because of the fact that a lower leakage results in a steeper system characteristic, the operation point travels towards the stall region (Figure 1). Fans without variable blade angles are at risk of stalling.

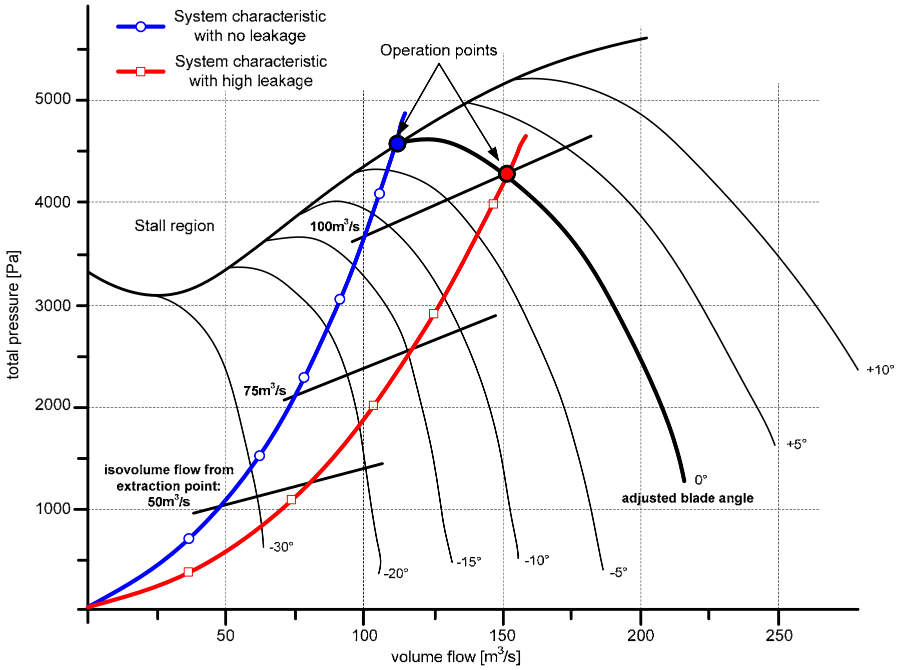


Figure 1: System characteristics regarding leakage

Established data to quantify leakages is required for a more accurate design of appropriate ventilation systems. Leakages into or out of ducts are a general issue in many other technical fields (e.g. air ducts, HVAC systems). A lot of work on air flow with leakages in tubes can be found in the literature. These approaches can in part also be applied for road tunnel ducts. The main difference is the way to calculate the relevant parameters, particularly the ones relating to the leakage. Unlike the leakage into air ducts with well defined vents, the leakage into road tunnel exhaust ducts is somehow random, temporal and special inhomogeneous and difficult do determine. Relevant parameters are very numerous and can for example be the geometry, the construction method as well as the age of the duct. Very few references can be found covering this part.

In 2007 the Swiss Federal Road Authority ASTRA initiated a research project with the title *"Quantification of the leakages into exhaust ducts in road tunnels with concentrated exhaust systems"*. The project is planned to be complete by 2009.

The research work aims to extensively investigate leakages into exhaust ducts in road tunnels. The results should be used in the future as a basis for the design of tunnel ventilation systems. The main part of the research covers in-situ leakage measurements in several road tunnels and the analysis of data. The measurements will be carried out by an accredited laboratory using the tracer gas method. With a careful choice of the tunnels (type, age, refurbished/new) a maximum coverage can be achieved. The analysis of the measurement data should end up with dimensionless numbers for easy use in the practical application. Furthermore a "Best Practice Guide" will be prepared covering recommendations regarding prevention (e.g. reduction of leakages) and intervention (e.g. increasing ventilation capacity).

This paper focuses on the leakage measurements, the analysis and first results. Although the research is in full progress, the first results are already very informative.

2. LEAKAGE MEASUREMENTS

For the evaluation of the leakages in exhaust ducts the volume flow and the underpressure in the exhaust duct must be identified at different locations.

The measurement of the underpressures in the exhaust duct is done with standard pressure measurement devices. The leakage measurements are more complex. The method needs to be accurate and well-proven for volume flow measurements. Furthermore the duration of the measurement procedure must not exceed one night, as some tunnels could not be closed for longer time.

With the tracer gas method the requirements could be achieved and it was chosen for the research project to measure the volume flow. The concept of this method is to inject a constant mass flow of SF6 (sulphur hexafluoride) into the exhaust air at the open dampers. After about 60 duct hydraulic diameters downstream the tracer gas is well mixed with the exhaust air. With the measurement of the concentration of the tracer gas the volume flow can be calculated. A sketch of a typical set-up in a tunnel is shown in Figure 2. At every measurement point (Nr. 1 to 4) the volume flow and the static underpressure in the duct are measured.

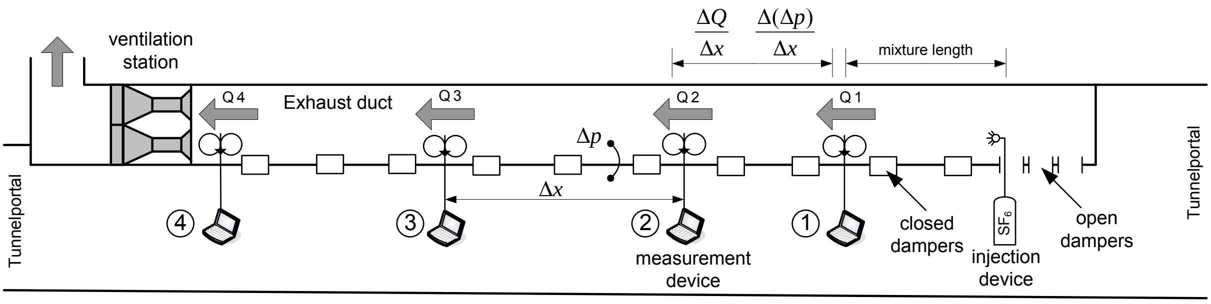


Figure 2: Sketch of the tracer gas measurement set up

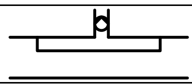
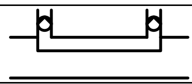
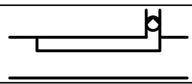
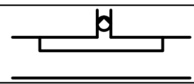
The main advantages of the tracer gas method over a velocity based method (e.g. system measurement) are:

- no undisturbed incident flow required (no problems with installed equipment, e.g. dampers)
- no dependency of the duct geometry and the duct cross section area
- easier and simpler in the set up (just 1 – 3 extraction points per measurement section compared to about 36 anemometers for a system measurement)
- very low impact on the pressure losses in the duct
- accurate, especially in complex and arbitrary ducts

As shown in Figure 2 a small sample of the exhaust air is removed from the exhaust duct and pumped to the measurement units (based on photo acoustic infrared spectroscopy) located at the road level. To route the necessary cables and tubes from the exhaust duct to the road level no extra leakage should be created.

All the measurements are carried out by an accredited laboratory. At the time of writing the leakage flows in four tunnels have been measured (Table 1). For every tunnel the measurements were carried out for different fan operating points (normally four). For the Flimserstein and Raimeux tunnels the volume flow in the dead branch (exhaust duct side with closed dampers) was measured as well.

Table 1: Description of the measured tunnels

Tunnel	Flimserstein	San Bernardino	Giswil	Raimeux
Exhaust duct type				
Tunnel age	< 1 year	app. 30 years	app. 3 years	< 1year
Exhaust duct length	2'300 m	2'200 m	1'550 m	2'658 m
Exhaust duct area	11.45 m^2	11 m^2	11.2 m^2	9.91 m^2
Q_{max} from exhaust point	180 m^3/s	210 m^3/s	155 m^3/s	140 m^3/s
Δp_{max} (end of duct)	1'600 Pa	450 Pa	1'650 Pa	2'300
Dampers distance / Area	100m / 4 m^2	96m / 4.8 m^2	75m / 2 m^2	50 m / 2 m^2
Visible duct tightness	good	poor	very good, (nothing could be found)	moderate (drainage holes every 50m)

3. ANALYSIS

Basically the absolute leakage value of an exhaust duct or duct section is not very meaningful due to the fact that it is dependent on many parameters. The impact of some parameters are known and predictable (e.g. underpressure, length). The impact of other parameters are rather random and unpredictable (age, sealing method). The goal of the analysis is to find a method considering the known parameters as they are, combining all the others with dimensionless values and quantifying the leakages to enable their comparison and extrapolation.

The approach used is to describe the behaviour of the flow in a mathematical way and define the unknown parameters via the measurement results. The concept thereby is to consider the leakage flow in a macroscopic way, accounting for no detail, as numerous attempts to calculate the leakage in a detailed manner failed.

The results for the relevant parameters come out of a limited number of measurements. Hence they must be considered as orders of magnitude and used as bandwidth. Even though the present method is not suited for a precise prediction of the leakages, it can be used during the design process.

For the exhaust duct the pressure and the volume flow can be described theoretically. The approach used is well known and described in several papers (SIA 196, 1998 or ISETH Mitteilung Nr.19, 1978). With f* as the effective leakage area the pressure [Eq. 1] and the volume flow [Eq. 2] are given by two differential equations:

$$\frac{d(\Delta p)}{dx} = \lambda \cdot \frac{1}{D_{hyd}} \cdot \frac{\rho}{2} u^2 \qquad \text{Eq. 1}$$

$$\frac{du}{dx} = \frac{P \cdot f^*}{A} \left(\frac{\rho}{2 \cdot \Delta p} \right)^n \qquad \text{Eq. 2}$$

where:

- A: Cross-section area [m²]
- P: Perimeter [m]
- D_{hyd}: Hydraulic diameter [m]
- λ: Wall friction factor [-]
- Δp: Pressure difference [Pa]
- ζ: Pressure loss coefficient [-]
- n: Exponent
- x: Coordinate in exhaust duct direction [m]
- ρ: Air density [kg/m³]
- u: Exhaust air velocity [$m\ s^{-1}$]
- f*: Effective leakage area [m²/m²] $f^* = f'/(1+\zeta)^{0.5}$
- f': Leakage area ratio [m²/m²] (geometric ratio of the leakage area compared with duct surface area)

The known variables in Eq. 1 and Eq. 2 are the geometric variables (D_{hyd}, P, A) and the change in underpressure and change in air velocity. The geometric variables are defined by the tunnel itself; the other two through the measurements. The unknown variables are λ, f* and n. n is dependant on the leakage flow type (per definition n is 2 for turbulent flow and 1 for laminar flow). The Reynolds Number of the leakage flow can vary from very low (small cracks) to high (big holes), thus the flow type cannot be defined a priori.

The three unknowns must be solved for each tunnel for every segment and operating point. In contrast to the three unknowns one can just write two equations (Eq. 1 and Eq. 2). The missing equation must come from another measurement of the same segment.

After solving the defined equation system for every segment and operating point one gets several results for the unknowns for each tunnel.

4. RESULTS / DISCUSSION

This section presents the results and the conclusions up to the time of writing this paper. More measurements will follow shortly and may change or refine some statements.

In Figure 3 the results for f* and λ for all measurements are shown. Furthermore the leakage value according the Swiss Guideline (ASTRA, 2004) and damper manufacturers have been expressed as f* and added in the plot. To divide the leakages into groups a break down with 5 levels is suggested.

The f* value includes all leakages (dampers and construction) and the λ value expresses the wall friction including all the pressure losses due to installed equipment like damper actuators and illumination.

The results show a dependency on the age of the tunnel. For new tunnels the λ- value varies between 0.013 and 0.020 and the majority of the f*-values are in the group "low" or "moderate". Interesting are the results for "Raimeux Sued". They are significantly higher compared with other new tunnels and with the north branch of the Raimeux tunnel.

Although the San Bernardino tunnel has been recently refurbished the f*- and the λ- values are significantly higher than for a new tunnel. The majority of the f*- values are in the group "high" and "very high".

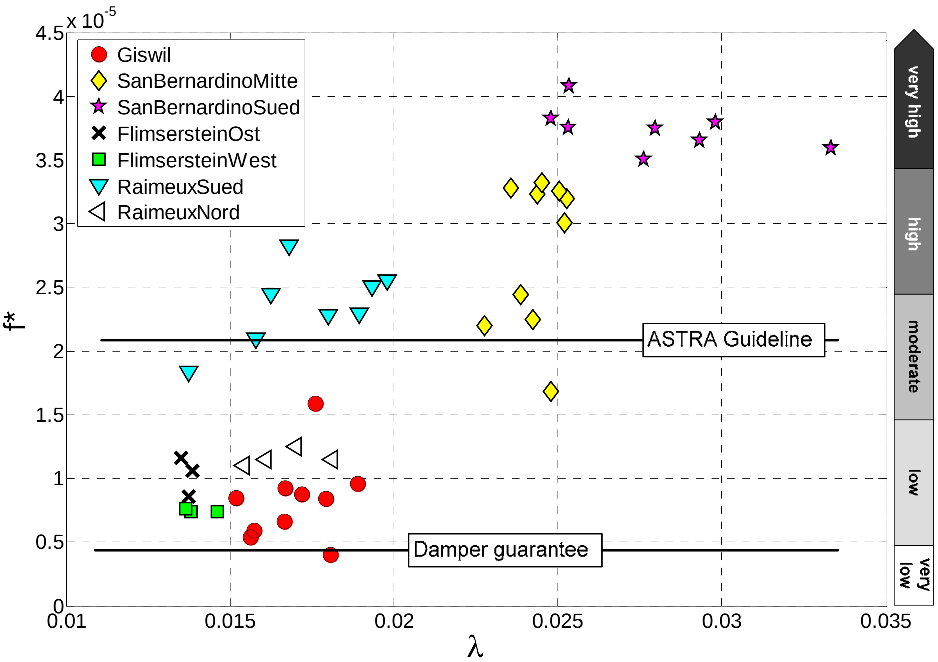


Figure 3: f* and lambda values for all measurements

Based on the analysis of the measurements, the exponent “n” of [Eq. 2] was worked out. Figure 4 shows the distribution of the calculated values of “n”. It can easily be seen that the exponent is very narrowly distributed about 2. The analysis combined tunnels with very low and high leakages. Hence it can be concluded that the leakage flow is mostly of the turbulent type, independent of the amount of leakage.

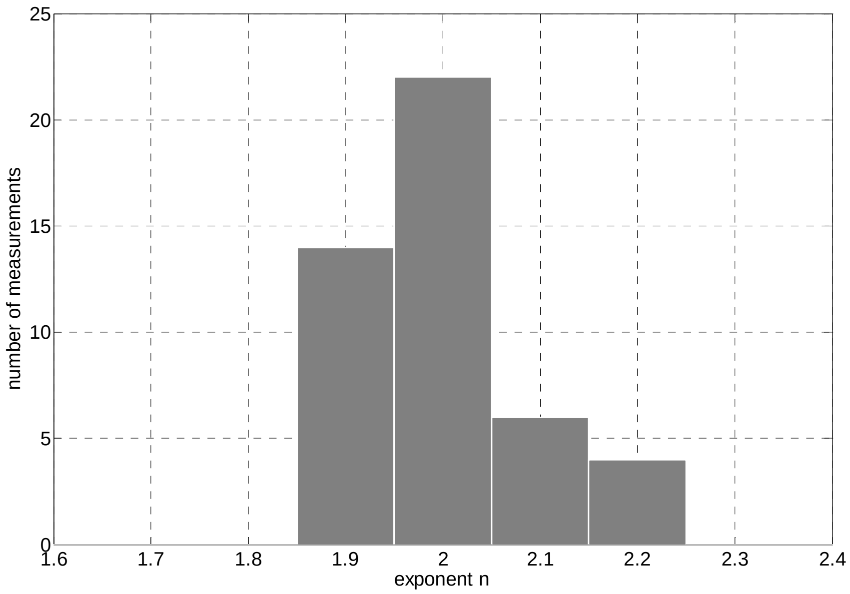


Figure 4: Distribution of the exponent n over all measurements

Figure 5 shows a plot to estimate the expected leakage flow using two dimensionless parameters. The Γ- value combines the important duct parameters and can be seen as a characteristic duct dimension. The Ω- value represents the ratio of leakage flow in respect of the flow through the open dampers and can be seen as a dimensionless volume flow. The two dimensionless parameters are defined as:

$$\Gamma = \frac{L^3 \cdot P^3}{8 \cdot A^3}$$ Duct characteristic

$$\Omega = \frac{\dot{V}_{Fan}}{\dot{V}_{Damper}} - 1$$ Dimensionless volume flow

Other parameters like air density, lambda value and pressure loss over the open dampers may have an impact on the leakage flow. From experience it can be seen that the variation on these parameters from tunnel to tunnel are in a small range and the impact is rather minor. For the graph in Figure 5 the parameters are defined as follows: air density: 1.15 kg/m^3, wall friction factor: 0.020, pressure loss over open dampers: 5 times the dynamic pressure in the exhaust duct regarding the exhaust volume flow.

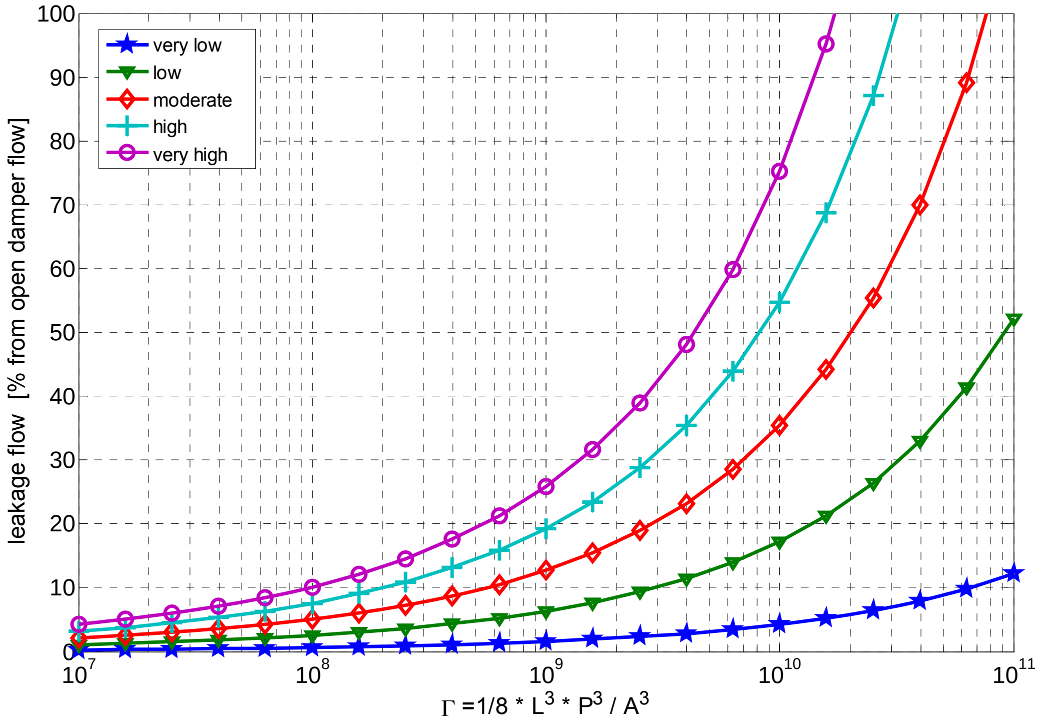


Figure 5: Graph to estimate the expected leakage flow

Before each measurement the exhaust duct gets inspected visually to find potential leakages. One reason therefore is to find a dependency between the visual inspection and the leakage level. Although just a few tunnels are measured one can conclude that the level "low" or "very low" can only be achieved for sealed ducts when almost no gaps or holes are visible. In contrast the level "high" represents an exhaust duct with lots of visible leakage points and no or poor sealing.

Another reason is to catalogue the types of leakages. So far it can be seen that most of the visible leakages are caused by the same reason which can avoid easily:

- drainage
- cabling between road level and exhaust duct
- doors and manhole in weak construction
- interfaces between damper frame and the concrete block out

The tracer gas method is theoretically a convenient and accurate method for leakage measurement. However in practical use some difficulties must be considered:

- cross sensitivity for vapour, temperature and atmospheric pressur
- leakage into the gas sampling tubes
- measurement of the volume flow is very sensitive to measurement errors
- sensitive measurement equipment in a rough environment
- routing cables and tubes through the intermediate ceiling may cause problems

Accordingly it's very important to seriously control the plausibility of the measurement results.

5. OUTLOOK

The project is intended to be completed by spring 2009. Before the end the following actions are scheduled:

- 5 more measurements in new and existing tunnels in 2008.
- Definition of f* values for particular types of tunnels (e.g. new, refurbished)
- Evaluation of different construction and sealing methods.
- Comparison of other approaches used to treat leakages in other countries.
- The whole experience of the project will be written down in a "Best Practice Guide".

6. CONCLUSION

- Modern tunnel emergency ventilation systems extract the smoke close to the fire. In such systems the underpressure in the exhaust ducts is relatively high.
- Leakages into the exhaust duct can have a significant impact on the air quantities to be extracted and must be considered in the design.
- Nowadays just very few established bases are available to quantify leakages, therefore a research project to extensively investigate leakages in exhaust ducts has been started in 2007.
- A main element of this research covers in-situ leakage measurements. At the time of writing 4 tunnels have already been measured.
- An analysis method using a dimensionless value to cover the leakage was presented. This method enables one to directly combine and extrapolate the data to other tunnels.
- Regarding the f* and the λ- values, a strong dependency on the age of the tunnel can be seen.
- The leakage flow can be considered as a turbulent flow, even if the leakages are very low.
- A noticeable amount of leakages is caused by drainage holes, cabling, doors and manholes, which may be reduced in number or avoided.
- The tracer gas method to measure leakages in exhaust ducts is suitable but delicate

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OVERCOMING EVACUATION LIMITATIONS OF THE UČKA TUNNEL BY IMPROVEMENT OF FIRE SAFETY MEASURES

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ABSTRACT

This paper considers a possible upgrading of existing single-tube tunnel with the primary objective of the fire safety improvement. The practical application is illustrated on the Učka Tunnel (5062 m), built in Croatia in 1981, which is undergoing a process of intensive modernisation, in order to overcome evacuation limitations due to single-tube design.

The approach relies on complementary safety measures which include both replacement of old tunnel equipment with new one as well as the implementation of new technologies and software solutions in the area of ventilation control, smoke management, fire detection, video imaging etc. Upgrading of tunnel safety level is done mainly in the area of "active" measures, without any serious reconstruction of the civil engineering characteristics of the tunnel, what will be done in the second phase of modernisation.

Keywords: road tunnel, modernisation, fire safety measures

1. INTRODUCTION

The Učka Tunnel was built in 1981 as a single-tube tunnel with bi-directional traffic, located on the road connecting Istria, the largest Croatian peninsula, with the remaining part of Croatia (Figure 1). At the time of building, it was the longest tunnel in Croatia, having a length of 5062 m. The most advanced solutions at that time were applied concerning both the construction measures and the tunnel equipment.

During the past ten years Croatia has experienced one of the most intensive roads building periods, when the major part of the existing motorway network has been built. On these motorways new tunnels have been constructed, some of them being longer than the Učka Tunnel, e.g. Sveti Rok Tunnel (5680 m) and Mala Kapela Tunnel (5760 m). The beginning of this construction was preceded by a period of detailed analysis of the world and in particular European practice and regulations on road and tunnel building. Finally, the Austrian RVS directives for tunnel construction and tunnel equipment were selected as the main basis for the designing of road tunnels in Croatia. Also, since 2004 the *Directive 2004/54/EC of the European Parliament and the Council on Minimum Safety Requirements for Tunnels in the Trans-European Road Network* has been applied.

In the light of new regulations and safety requirements, the Učka Tunnel today needs overall modernization. Recognizing the need, the tunnel's concessionaire started in 2007 with the interventions that should after a few years result in a two-tube tunnel equipped in accordance with the existing regulations and the regulations getting into force with the accession of Croatia to EU. During the first phase, in order to achieve the improvement of the degree of tunnel safety as early as possible, and in accordance with the investment dynamics, the safety will be raised to a higher level without radical construction interventions. That will be done primarily by modernization of the equipment and related software support of tunnel technical systems which participate in fire protection (ventilation system, fire detection system, CCTV etc.).

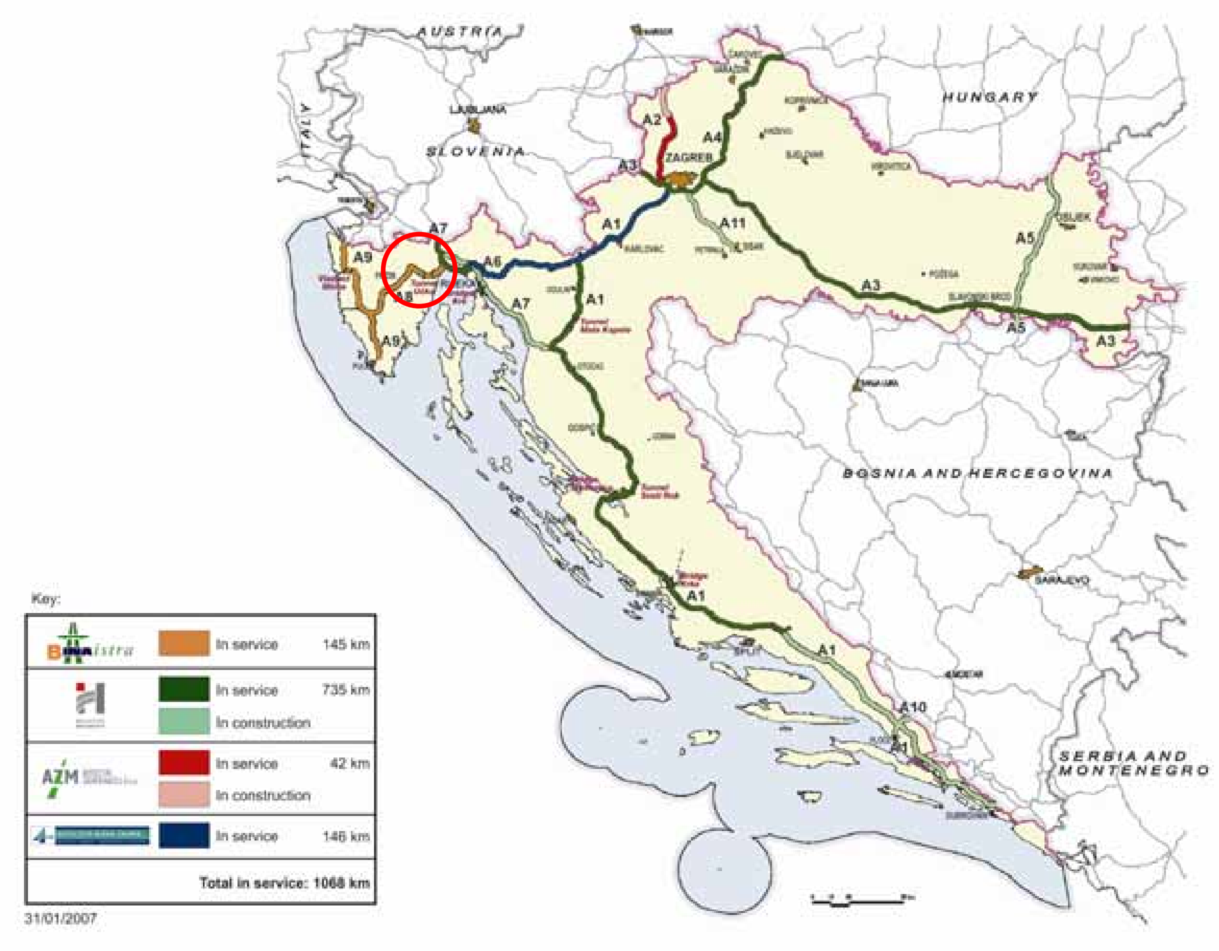

Figure 1: Motorway network in Croatia

2. OVERVIEW OF THE CURRENT STATE

2.1. General

As already mentioned, the Učka Tunnel is a single-tube tunnel with bi-directional traffic, with one traffic lane for each direction. There are 17 SOS niches on each side of the tunnel tube at a distance of 250 to 420 m, and 3 turning points on the right side of the tube, if driving from the direction of Rijeka to the direction of Pula. There are no separate escape routes connecting the tunnel tube and the exterior of the tunnel. The SOS niches are equipped with emergency phones located within the tunnel space. Power supply system includes 6 transformer stations within the tunnel, and one transformer station at each tunnel portal.

2.2. Ventilation system

The tunnel is equipped with a longitudinal ventilation system, with ventilation units (batteries) containing 3 impulse, non-reversible jet fans per unit. The ventilation batteries are arranged in two groups, each in one third of the tunnel with respect to the related tunnel portal (Figure 2). There are 24 jet fan batteries (3 jet fans per each battery)) in each group, the batteries are alternately oriented with respect to the jet fan's air flow direction. The distance between individual jet fan units is 70 m. The jet fans delivered by SOFRAIR, France, have a power of 30 kW, and a thrust of 810 N. The control of ventilation is done via jet fan battery; one unit with 3 jet fans is started as a whole so that jet fans within one unit are automatically started one after another within the time of 12 seconds in order to avoid overloading.

At the same time, while one jet fan battery is being started, it is not possible to start another jet fan battery within the same distribution because of power supply restrictions. Power supply of the jet fans is divided into 2 distributions, each at one side of the tunnel; the middle does not always match the geographical midpoint of the tunnel. Described solution of ventilation system is pretty old and conservative but common for that period.

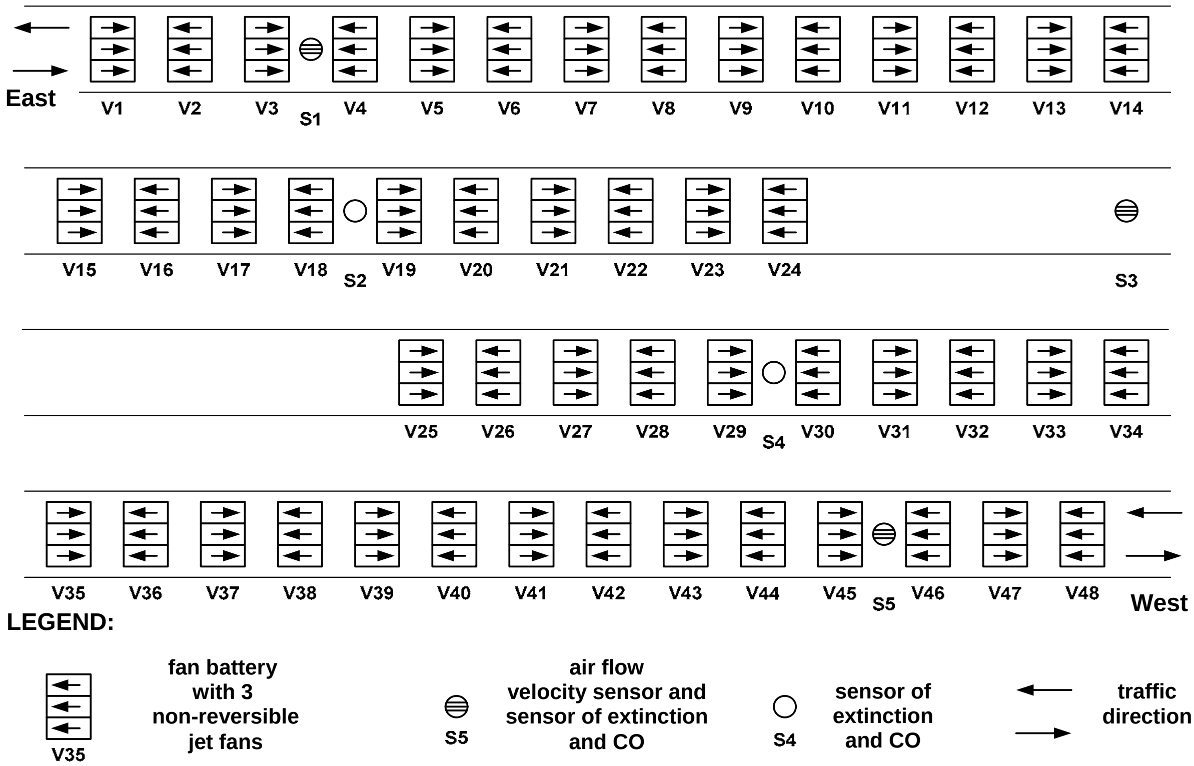

Figure 2: Schematic presentation of the arrangement of jet fan batteries, air flow velocity sensors and sensors of extinction and CO

2.3. Sensors system

The tunnel sensors include air flow velocity sensors and sensors of extinction and CO. Their location in the tunnel and arrangement in relation to jet fan units can be seen in Figure 2. There are 5 sensors of extinction and CO, and 3 air flow velocity sensors mounted in the tunnel. There are also 2 meteorological stations located at the tunnel portals for the measurement of air temperature, pressure and humidity.

2.4. Signal acquisition system

The air flow velocity sensors and the sensors of extinction and CO are first connected in the tunnel with the local base stations. From them the signals are fed to the measurement stations (acquisition system's sub-stations) which forward the signals to the central station located in the control centre (Figure 3). The connection between the measurement stations and the central station is realized via a copper conductor, the maximum rate of transmission is 600 baud, and thus for the sampling of data from all measurement stations minimally 2 minutes are necessary.

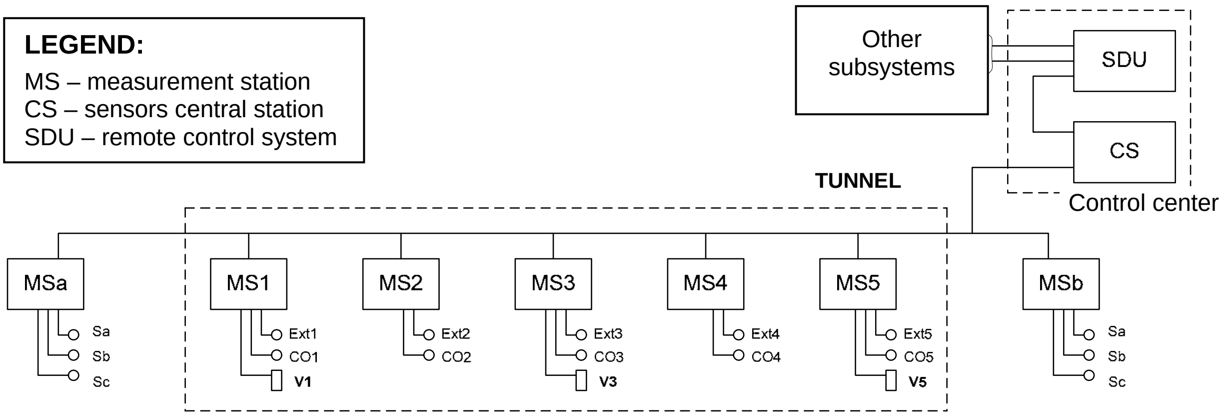

Figure 3: Schematic presentation of the sensors system and signal acquisition system

2.5. Fire alarm system

The fire alarm system includes 9 fire detection stations (VC), arranged along the tunnel. The main tunnel tube is monitored by the loops of the collective point thermal detectors. The transformer stations are monitored by point smoke detectors, while the SOS niches and the tunnel portals are fitted with manual call points that are not connected with the fire alarm system, but are connected with the remote control system.

The tunnel is divided into 35 fire detection zones and 7 traffic zones. All fire detection loops are implemented in the collective logic, which means that activation of any detector in a particular loop (the length of one loop is about 150 m) in the main tube is alarmed as a signal that is uniform for that particular loop irrespective of the fact which particular detector has been activated. Due to such logic, there are several cases of overlapping of one fire detection zone with two traffic zones, and in the case of fire detection zone No. 34 with three traffic zones, and thus the activation of a detector in such fire detection loop does not provide unambiguous information in which traffic zone a fire has broken out. The schematic presentation of the fire alarm system is given in Figure 4.

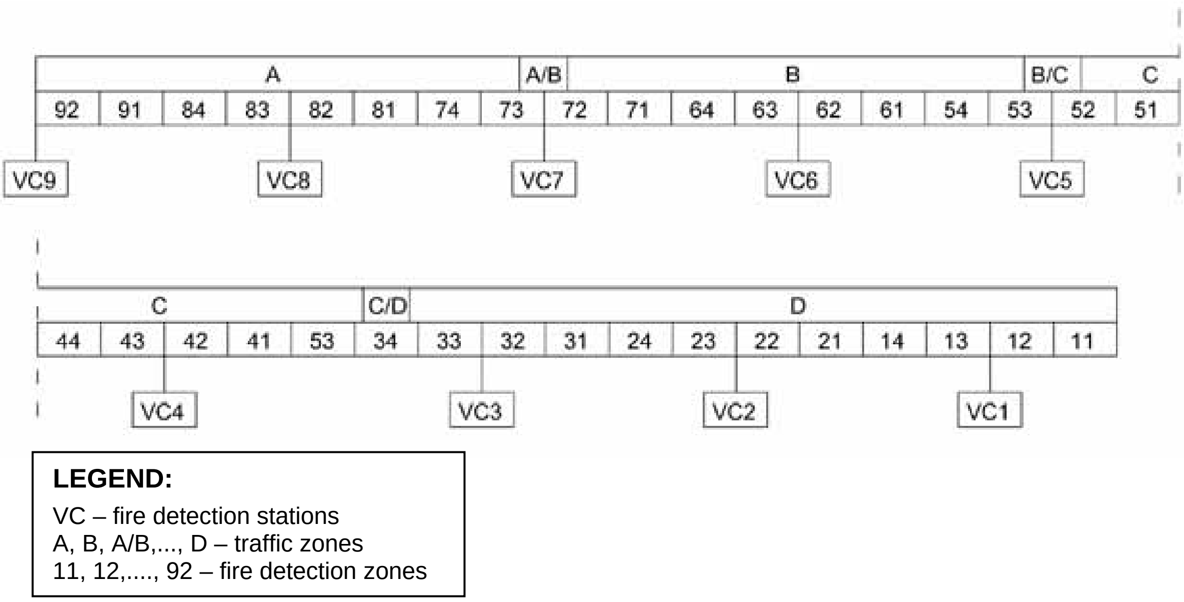

Figure 4: Schematic presentation of the fire alarm system

3. CHANGES AIMED AT THE IMPROVEMENT OF TUNNEL SAFETY

3.1. Ventilation system

- The major change is the implementation of the computer program for the active control of longitudinal air velocity by means of the tunnel ventilation system.

  The program will operate in 3 automatic independent modes:

  a) ***Normal mode*** - preventive stabilization of air flow velocity to 2 – 2.5 m/s, in the case of dangerous goods transport or seasonal high traffic intensity.

  b) ***Fire mode (evacuation)*** - stabilization of air flow velocity to 1 – 1.5 m/s, as soon as it possible, in order to establish smoke **stratification,** important for successful evacuation process.

  c) ***Fire mode (fire extinguishing)*** – keeping air flow velocity at critical or higher value (3.5 m/s), in order to prevent smoke "**backlayering",** which can endangers fire fighters.

- Provide the possibility of independent control of each individual jet fan within a particular jet fan battery. This improvement enables the fine resolution of ventilation control both in the normal and fire mode.

3.2. Fire alarm system

- Introduction of modern fire alarm system for the main tunnel tube based on a linear fibre optics sensing cable.
- Replacement of the collective logic with the analog addressable logic.

3.3. Sensors system

- Sensors of CO of the old generation (electrochemical), are to be replaced by new optoelectronic sensors (CO and extinction in a set).
- Two more air velocity sensors shall be put in the main tunnel tube, in order to acquire more detailed sampling for program for the active control of longitudinal air velocity.
- Sensors S1, S4 and S5 are relocated because of inadequate location; they are positioned between adjacent jet fan batteries which blow the air toward sensors, and that degrades measurement accuracy.

3.4. Signal acquisition system

- Existing measurement stations shall not be used any more because of too slow sampling. Program for the active control of longitudinal air velocity requires air velocity and direction sampling with the time period up to 5 s, so velocity sensors shall be connected directly to the remote control system sub-stations through adapting modules.

3.5. Video surveillance system

- Installation of the new generation video surveillance system with "video imaging" function enables incident recognition (e.g. traffic halting, driving in the wrong direction) and smoke recognition as early ("first") alarm. This system can give very fast information for the tunnel operators to start computer program for the active control of longitudinal air velocity.

3.6. SOS niches

- New SOS calling devices shall be installed in order to make distance between SOS calling devices around 150 m.
- On every location of the new SOS calling devices cabinets with 2 hand held fire extinguishing apparatus shall be retrofit; cabinets shall be equipped with “micro-contacts” for signalling rising of fire extinguishers.

4. CONCLUSION

All measures described previously represent active fire safety measures. For that reason they have to be put in adequate operation modes to fulfil the design goals regarding the fire safety improvements. Prescribed measures plan to be tested carefully in order to adjust operational parameters during the commissioning phase of the Učka tunnel. Authors of this paper, as fire safety designers, hope that synergy effect of those measures can temporarily overcome evacuation limitations due to the actual construction characteristics of the Učka tunnel, but can not exclude need for finalizing the second phase of tunnel modernization (twin tube tunnel configuration!).

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UPGRADING AND REFURBISHING VENTILATION SYSTEMS IN ROAD TUNNELS - ENGINEERING WITH CONFLICTING INTERESTS

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ABSTRACT

A large number of road tunnels have been build in the last decades. In response to serious tunnel accidents recently, the normative requirements for safety in tunnels have increased significantly. This is reflected in the tunnel design guidelines of the EU (2004) and adaptations of national guidelines thereafter.

Due to intense traffic, the structure of many road tunnels show signs of fatigue. Electro-mechanical equipment becomes outdated or needs replacement. Traffic forecasts keep increasing, despite the demographic development and the hikes in oil prices. Due to technological improvements, tunnelling is now quicker, more affordable and more secure than several years ago.

All these factors oblige tunnel operators to review existing tunnels and, while doing that, to consider building new tubes to enhance security, availability as well as traffic capacity.

Hence, there is a highly actual field of activity for tunnel engineers and planners of electro-mechanical equipment: upgrading and refurbishing existing tunnels, eventually coupled with the construction of an additional tube.

As in all projects, there are conflicting interests. However, in this type of project, there is one more group of people involved as compared to the creation of a new tunnel: all those, who are engaged in the operation of the existing tunnel and who have to ensure the security and availability of the road during the entire construction period. This causes that there are less degrees of freedom than for new tunnels built in the past. It is therefore time to prepare for a new type of challenging and awarding engineering task in the decades to come.

The present paper addresses this issue with reference to the actual tunnel projects Bosruck-tunnel (5.5 km) in Austria.

Keywords: tunnel ventilation, refurbishment, 2nd tube, RVS 09.02.31

1. INTRODUCTION

The Bosruck tunnel is a 5.5 km long road tunnel crossing the Pyhrn Pass between the states Styria and Upper Austria. The first tube (east tube) has been opened in 1983 and is since operated with two-way traffic. Due to particular geological conditions with heavy seepage and saline inclusions, the main tunnel is paralleled by a de-watering tube, which is also used to supply fresh air to the fully transverse ventilation system.

Since 2006, the planning for the extension of the Bosruck tunnel to a twin-tube tunnel with directional traffic has begun. It has been awarded to the Planungsgemeinschaft Bosrucktunnel (PGB) consisting of Laabmayr&Partner ZT GmbH / Salzburg and the ILF ZT GmbH / Innsbruck. The new west tube is scheduled to be operational in late 2012. After that moment the existing east tube will be refurbished. Both tubes will operate in directional traffic in the summer of 2014.

The overall project also includes two bridges at both ends of the tunnel and comprises a stretch of 7 km in total.

Even though the tunnels will primarily be used in directional traffic, the ventilation system fully accommodates for two-way traffic. Two-way traffic is necessary during the refurbishment of the east tube (2013-2014) and in case of intentional or accidental closure of one of the tubes.

Availability was one of the major targets in the conception of the ventilation system. This is because the pass is closed for heavy vehicles and alternatives involve significant de-routing.

The starting point was the ventilation concept from the general project for the first tube in 1979. It already contained elements for an extension to a 2nd tube. The ventilation concept basically mirrored the existing system. Cross-vents were built so that they could be extended to the 2nd tube. Portal stations for the 2nd have been built as well.

During the main project, it was found that vehicle emission values have significantly been reduced in the mean time, resulting in much lower fresh air rates than predicted 30 years ago. Also, the requirements of local smoke extraction as well as the consideration of unfavourable weather conditions (pressure, wind) gave rise to a change of priorities. Therefore, the ventilation concept from the initial study needed to be revised.

This revision has led to several discussions involving operational aspects and investment costs. Parallel to the new conception, several draft revisions of the Austrian road tunnel guideline RVS 09.02.31 have been issued. These revisions addressed improvements to safety requirements and contained clarifications to former versions. The following will outline the concepts which have been looked at. Reasons why they have been discarded or followed are discussed. It must be emphasized that this discussion refers to one particular project. The parameters and client preferences in other projects may be different and may lead to other conclusions. Nonetheless, the type of compromises observed here is likely to recur in similar projects, i.e. projects where an existing tunnel is extended during operation.

1.1. Planning Guidelines

The basis for the ventilation concept is the Austrian road tunnel security law from 08/05/2006 and the Austrian guideline for basic principles of tunnel ventilation (RVS 09.02.31). It defines criteria for the required ventilation concept, sets aims for normal and emergency ventilation, specifies flow control parameters and contains the procedure for a simplified risk assessment.

2. INITIAL VENTILATION CONCEPT

The ventilation concept in the general project from 1979 contained provisions for the 2nd tube. The extended concept was the onset for the main project and is therefore shortly described.

2.1. Scheme

The ventilation scheme for the 2 tube system as anticipated in the general project is pictured in Figure 1. It will also be used to describe the current configuration of the tunnel.

The system in the blue rectangle embraces the existing system with fully-transverse ventilation in the east tube. The main components are: the east tube with split false ceiling, the ventilation and de-watering gallery and the fan stations for supply and extract at the tunnel portals. Adjustable exhaust dampers have been added to the east tube in 2002 in order to increase tunnel security.

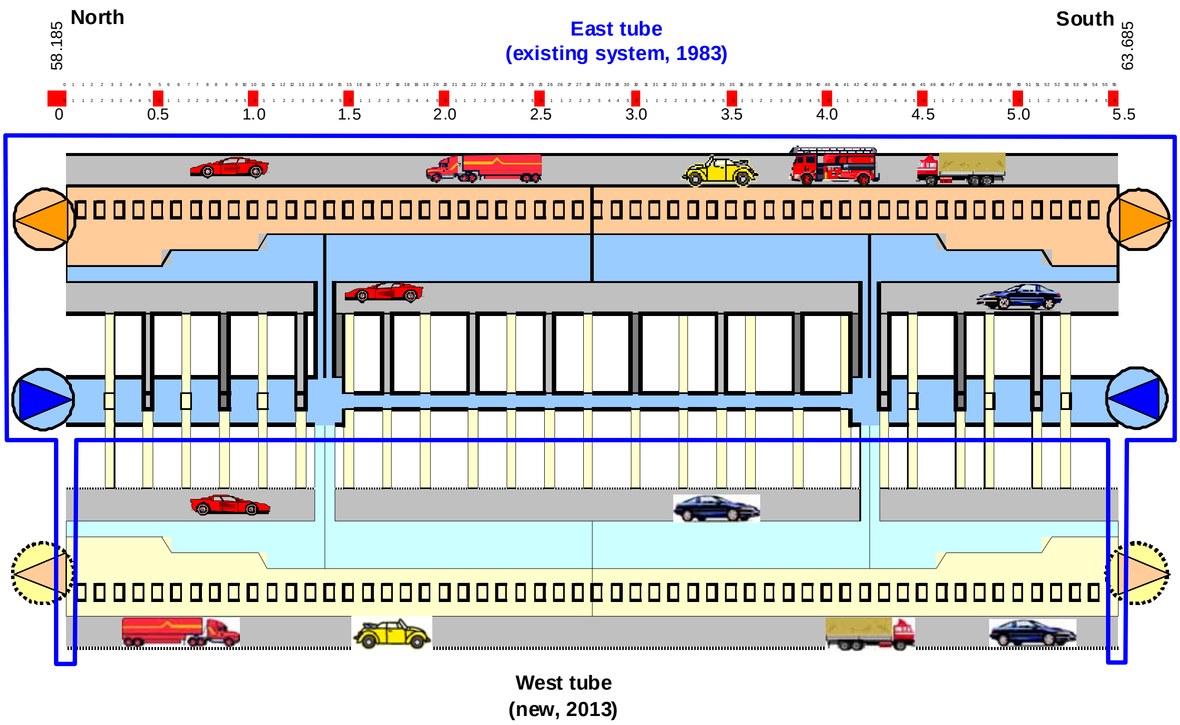

Figure 1: Ventilation concept as anticipated in the initial project (existing system in rectangle)

The scheme shows a fully-transverse ventilation system. The general project anticipated to mirror the existing system keeping the supply fans and adding two new exhaust fans. The portals for the east tube and the ventilation caverns have actually already been built.

Fresh air enters by the tower between the tubes. The supply fans are connected to the central ventilation gallery. The ventilation gallery ist connected to the supply portion of the false ceiling by ventilation cross-vents in the quarter points. In the false ceiling, the flow splits into one branch towards the tunnel center and a second branch toward the portals. Its distribution can be adjusted with dampers in the ventilation cross-vent.

In the Bosrucktunnel, the area of the supply portion of the false ceiling reduces between quarter points and portals continually (the steps in the scheme represent in reality a continuous area change). Between the quarter points, the respective areas of supply and extract portion remains constant. This way, the variation of the flow velocities in the false ceiling is reduced and operational costs optimized. It must be considered that the ventilation system is currently in operation most of the time as there is two-way traffic.

The exhaust fans are directly connected to the end of the false ceiling. The exhaust air leaves the tunnel by additional exhaust chimneys which are connected laterally to the building.

Figure 2 shows 2 vertical cuts with the existing tube and the ventilation gallery as well as the new tube (right hand side, green) as anticipated in the initial project. The upper image corresponds to the zone between the quarter points and the lower image to the portal zones. As the gallery serves also for de-watering, it is below tunnel level over the entire tunnel length.

The current rescue concept foresees that tunnel users seek shelter in the cross-adits, which are designed as waiting areas (seats, telecommunication, and cameras). Rescue personnel enter by the ventilation gallery. The cross-vents between the quarter points and the portals (see Figure 2 below) are accessible by a narrow shaft with a ladder through which tunnel user are evacuated.

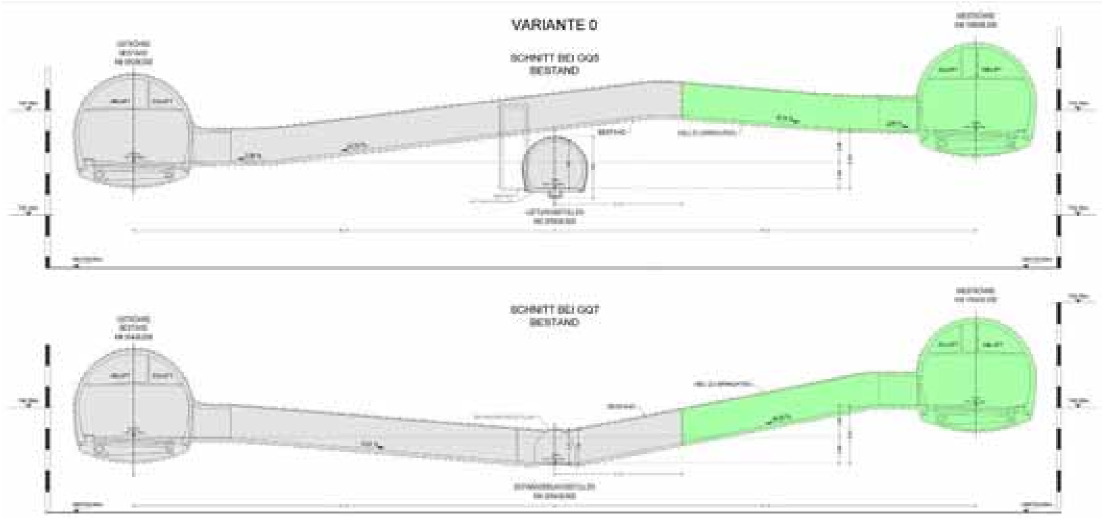

Figure 2: Position of the existing cross-vents (grey) and the continuation according to the general project from 1979

2.2. Discussion

The initial concept is a straightforward extension of the general project. However, as many main parameters have changed in the mean time, the requirements for the new system are different now:

1. The general project in 1978 projected a required fresh air rate of 135 m³/(s.km) on the basis of 1800 PWE/h. Even though the projected vehicle flow fits very well to the actual data, the fresh air requirement is now only 20 m³/(s.km). This reduction is due to significantly reduced emission levels of modern vehicles, which exceeded by far the predictions from the 70s. → This means that normal operation can be covered with longitudinal ventilation, in most cases even with self-ventilation by the vehicles themselves. A fully-transverse system is not required any more.
2. The relevant tunnel guidelines now impose different standards than 30 years ago. For example: The maximum distance of cross-vents exits is now set to 250 m plus the maximum slope is 10% (existing cross-vents have up to 12%) → This leads to a complete re-distribution of all cross-vents.
3. The relevant ventilation guidelines are quite different than in the 70s. The main point is that ventilation systems are now designed with a focus on the emergency ventilation. → This lead to re-dimensioning the ventilation system for the existing and the new tube plus additional installations to influence longitudinal flow needed to be added.
4. From the experience with the existing tunnel, the operator has developed ideas which help to increase the availability of the tunnel in case of maintenance works and to reduce operational costs. → this lead to new requirements with respect to redundancy, accessibility as well as maintenance costs

For all these reasons, the concept was revised.

3. PGB CONCEPT

In the first phase of the project, the planner of the Bosrucktunnel, the PGB, suggested a ventilation concept which fulfilled the following main targets:

1. Full compliance with RVS
2. Unified ventilation concept for both tubes
3. High security level
4. Powerful extraction capacity considering smoke expansion due to heat
5. Easy to operate
6. Redundancy (not required by RVS, but necessary to achieve high availability)
7. Switching from the current ventilation system to the operation of the west tube in two-way traffic without major traffic disruption possible
8. Providing ventilation for the refurbishment of the east tube
9. Low investment costs
10. Reasonable maintenance costs

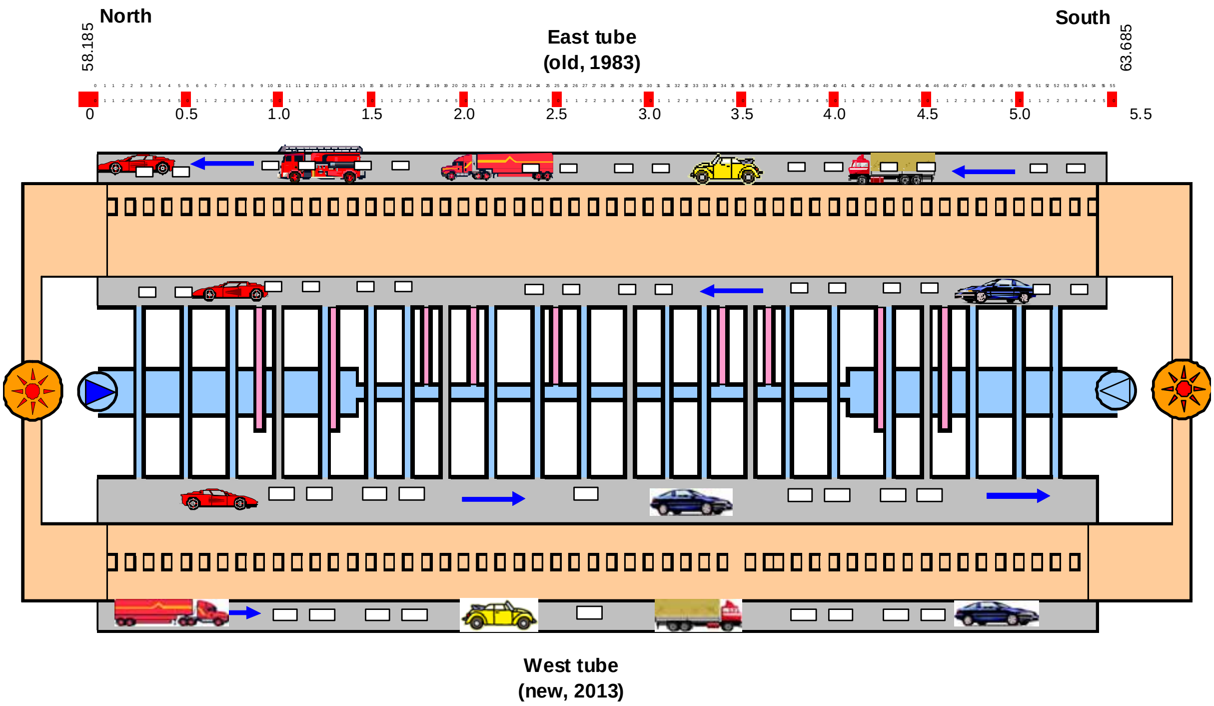

Figure 3: Initial Concept of the PGB

3.1. Scheme

The result can be seen in Figure 3. Its main ideas are:

- rededication of the air supply chimney to an exhaust chimney
- smoke extraction fans placed vertically at the bottom of the chimney
- suction-side connection of both tunnels to the exhaust fans inside the head building (no mined ventilation cross-vent required)

- unmake the north / south separation in the false ceilings
- false ceiling only for smoke extraction, i.e. connection of the two ventilation ducts in the east tube (at this time, it was not clear whether the false ceiling needed replacement)
- jet-fans in the main tunnels, adaptation to required cross-section
- new cross-vents passing above ventilation gallery
- pressurization of cross-vents via supply fans and adjustable dampers connecting from the ventilation gallery

Even though the control system foresaw that smoke is extracted to the nearer fan, it was suggested to dimension the extract fans in a way that they could handle fires over the entire tunnel length. This way, the proposed system would provide full redundancy with only little extra costs (remark: redundancy is not required by the RVS). The jet fans were dimensioned so they could reach 1.5 m/s for the fresh air along the entire tunnel even against the maximum pressure differences, which amounted here to 225 Pa. Expansion of air due to heat was considered.

3.2. Discussion

Even though the concept was fist acknowledged by the project team, some scepticism came up about the following points:

- the newest draft of the RVS 09.02.31 required exhaust lengths not exceed 2’500 m
- it was found that the real leakages may exceed the values required by the RVS, hence the full redundancy was questioned
- the jet fans in the driving tunnels were criticised with respect to traffic disruptions for maintenance and their maintenance costs
- it was criticised that the exhaust fans may not provide full exhaust capacity when one exhaust fan is out of order (e.g. due to maintenance)
- as the existing exhaust fans are still in good shape (even though only for temperatures of up to 250°C), it was found that they should not be abolished
- maintenance of a vertical axial fan was found too complex
- it was claimed that consideration of air expansion due to heat for dimensioning of the extract fans (required max. power: ~1 MW) exceed the requirements of the RVS and lead to unnecessary investment costs

In the sequel, a number of alternative ventilation concepts were examined. The main focus was on the aim to avoid jet-fans in the driving tunnels. The most promising suggestion on that path was to use the very powerful supply fans as injectors. This concept was studied in detail by the PGB, even with multiple injector locations. It was discarded due to the unusually high relevant pressure differences, which could not be handled with the injector, and reservations with respect to the control strategy of such a complex system.

4. FINAL CONCEPT

The final concept was then found performing a thorough economic analysis including costs for civil engineering, M&E equipment as well as operational, maintenance and opportunity costs for traffic disruptions over 25 years. Even though the main candidates gave very close numbers, the maintenance costs as estimated by the Asfinag were significant and it was found that this item is the least desired one.

4.1. Scheme

Thus, the PGB concept, which required small jet-fans, was abolished in favour of an option where fewer, but larger units are used. In turn, additional niches needed to be built. These ventilation niches are build as an extension to the lay-byes. Also, it was the wish of the operator to keep the existing exhaust fans and to add new ones in horizontal portal stations above the new tube. The ventilation RVS does not require a temperature upgrade for the refurbishment of existing tubes. However, in favour of an improved security level, it was decided that the new exhaust fans rated at 400°C over 120 min. should be able to handle fires in the east tube as well. To this end, ventilation cross-vents connecting the false ceilings of both tubes will be built at the quarter points.

The operational points of the extract fans have been determined assuming a volumetric flow rate of 120 m³/s (cold) at the incident location plus the doubled leakages as required by the new draft version of the RVS 09.02.31. The power of the new exhaust fans is about 300 kW.

The jet fans are now able to generate longitudinal flow of 1.2 m/s over the entire tunnel length in a completely filled tunnel in 2-way traffic against a maximum meterological pressure difference of 235 Pa.

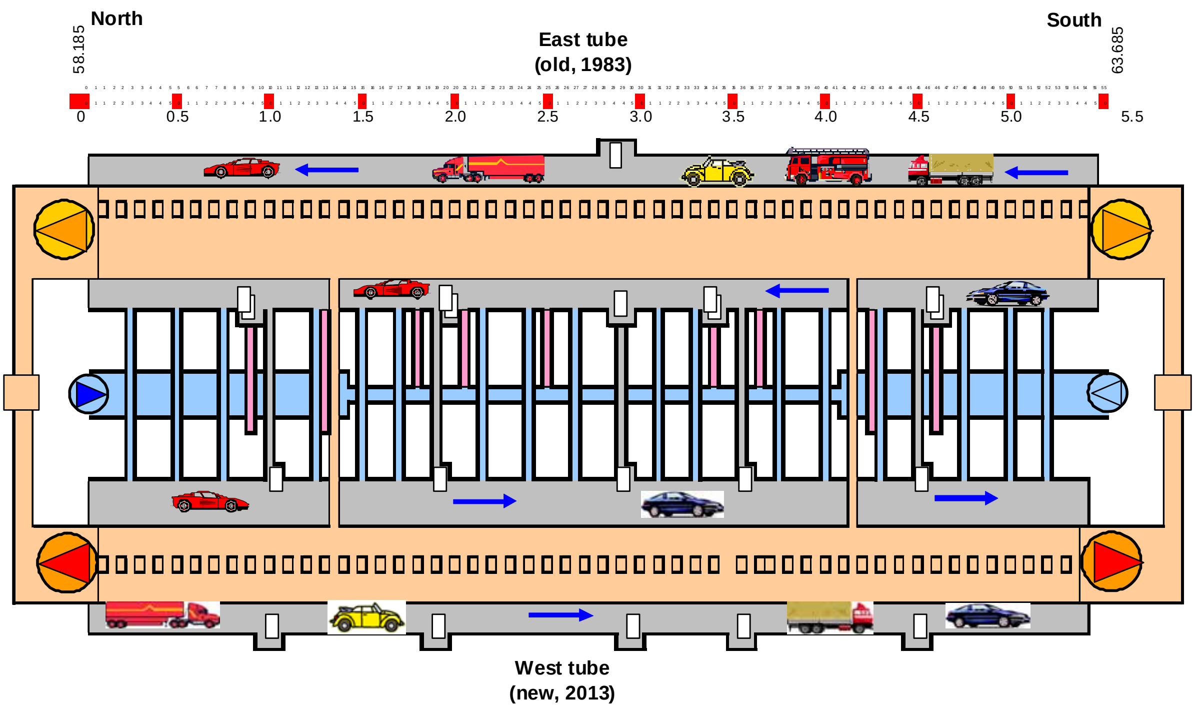

Figure 4: Final concept as chosen by the Asfinag

4.2. Discussion

As compared to the system in chapter 0, there are now less jet fans and smaller axial fans. This makes up for savings of investment and maintenance costs. In turn, niches and the ventilation cross-vent have to be built plus the power supply for 4 smaller instead of 2 larger fans needs to be put in place. The reduction in exhaust power does not lead to significant offsets in the original security level as the existing fans will remain in place. These can not handle the today required high temperatures but will be useful in most cases. This is particularly true in the case of maintenance works where operational restrictions can be imposed (e.g. reduced speed limit) in order to mitigate risk. But also when only one of the new exhaust fans is in operation, the 2nd exhaust fan of the west tube and both axial fans in the east tube provide additional extract capacity to compensate unexpected leakages and if larger exhaust capacities are required (e.g. for larger fires or if desired by the fire brigades).

Most importantly, this was a solution where all participants from different departments of the Asfinag could live with.

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SINGLE TUNNEL AND STILL SAFE
THE FELBERTAUERNTUNNEL

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INTRODUCTION

Do you know the children's story "The Ugly Duckling"?
You ask: What do children's stories have to do with tunnel safety?
You are right. There is no relationship!

However, let us retain the "ugly duckling" and keeping this picture in mind turn to the subject of incident monitoring in existing road tunnel systems. Let us replace "ugly" with "40-year old technology", with "non-reversible supply air semi-transversal ventilation" and "meteorologically caused longitudinal air flow speeds up to 8.0 m/s", with "escape route lengths up to 5,300 metres", with "detection possibilities missing", with "only limited video monitoring system present", with "central controller not available" and let us replace "duckling" with "Felbertauerntunnel with mid-1990s safety status".

BACKGROUND

At that time, the primary concern of all operators of underground traffic systems was the optimisation of the operation. Therefore, infrastructure maintenance and reduction of operating costs were also in the foreground for Felbertauernstraße AG for all the adaptation plans for the Felbertauerntunnel realised until 1995. If safety was also increased, this was seen as a welcome added bonus. However "more safety" was never the direct initiator for the investments.
Analyses of an accident and fire incident in the Pfändertunnel, Vorarlberg were the starting point for changes in the approach to safety. These changes were not suddenly completed, but gradually as everywhere. Considerations of the possible liability aspects for "route liability" and "contractual liability" between tunnel users and the operating company followed the shock of the tragic personal injuries. New light was also cast on the possible material and operation interruption damage.

Therefore, the accumulation of the personal, material and liability damages had to eventually lead the decision makers for the toll tunnel to the question: Are actions for improving the risk standard required by adapting to the current "state-of-the-art" as regards safety? The inventory analysis subsequently performed by comparison with the current new construction guidelines *(assumed state-of-the-art at that time)* was rather sobering. The above negative points listed under "ugly" could still then be enhanced in any way although the system inventory and mainly the construction conditions provided options for future improvements. But the time for this was not yet ripe in 1996. A risk analysis was applied to the sobering actual-new construction target comparison and the result was finally a need to take action.

The determined need for action was reflected in the development of a comprehensive adaptation concept for the Felbertauerntunnel whereby the current new construction guidelines were indeed included from the start as standards however not binding in the sense of restricting. In establishing "what is the current technical state?", "what are the possibilities?", it was necessary to collaborate closely with the Austrian Road Safety Board

and the emergency services – mainly the fire brigades -, and last but not least also to check commonly used standards abroad and to incorporate all of this into the design considerations.
There was an initial result at the end of 1996 which still largely reflected the current new construction guidelines. The first phase of the concept implementation started one year later. A time frame of 10 years until final completion was envisaged.
The catastrophic damage experienced in the year 1999 ignited the proverbial "implementation turbo" for Felbertauernstraße AG as well as for all other operators of road tunnel systems. Suddenly "tunnel testers" were on the move and certified the Felbertauerntunnel bad safety standard. However, the market was also suddenly in action. Many technical safety solutions on a scale hitherto unknown were suddenly available.

In the year 2000, the operating company, with a concept revised in many details, together with the ambitious plan, started to approach the status "safety swan" by 2007 from the status "ugly duckling" for the single Felbertauerntunnel and doing this without building a new tunnel. It became quickly clear in the concept revision that a satisfactory safety result would only be achievable with significant modification of the requirements of the new construction guidelines. Alternative solutions, practically a made to measure safety solution for the Felbertauerntunnel, had to be found. To everyone's surprise, there were many promising and above all, realisable, ways to the safety objective after removing the rigid adherence to the guidelines by using unconventional solution approaches.

However, at that time, the objective was opposed to the general "tenor" of the tunnel experts: *"As a single road tunnel, the Felbertauerntunnel can never achieve the "very good" safety level"*.

Experts who know the Felbertauerntunnel make a different judgement today. Why?

1. FELBERTAUERNTUNNEL VENTILATION SYSTEM

The ventilation system of the tunnel – we remember: a non-reversible supply air semi-transversal ventilation, divided into four ventilation sections – has been converted to a multifunctional ventilation system. It was specified in the dimensioning of the new system to maximise use of the infrastructure *(tunnel geometry, sewer cross sections, connected loads, …)* and to produce an accompanying realisation concept that allowed implementation with moving traffic. The system was completely adapted to the requirements in several phases. Full transverse, partial transverse, exhaust air semi-transverse and longitudinal ventilation operation are now possible.

Figure 1: Exhaust air flap in the verification test

The features of the ventilation system in the Felbertauerntunnel include

a) the system performance – a total of 220 m^3 per second exhaust air capacity for unfavourable position in the tunnel using three exhaust air flaps for a length of 144 metres is achieved by concentration of the total available exhaust air capacity *(exhaust air blowers in both portal stations)* by flexible connection *(mechanical cover flaps)* of the respective assigned exhaust air sections *(moving vertical closures in the exhaust air duct);*
b) the exhaust air flaps *(a total of 72 exhaust air flaps spaced at approx. 72 metres designed as baffles with a maximum open cross section in each case of 8.95 m^2 at 90° angle and with an actuator motor in the secure supply air duct)* with the possibility of turning the baffle fins depending on the main exhaust flow direction *(flap setting angle from 0° to 125°)*;

The adapted ventilation system has been available since Spring 2004.

2. FELBERTAUERNTUNNEL ESCAPE SYSTEM

The escape route lengths in the tunnel were previously max. 5,300 metres – we remind ourselves: the traffic space was the only escape route and thus the tunnel length was the maximum escape route length – shortened to max. 230 metres. Strictly following the principle of self-rescue, the integration of the emergency call recesses in the system, a functioning interaction with the adapted ventilation system, the optimum use of infrastructure and the “implementation while traffic is moving” condition, were the direction of the requirements for the design. In other words: Whoever has to raise the alarm and/or escape must be given the possibility of making the emergency call in safety – in the protected emergency call recess -, together with the same local escape option without having to make a detour again across the “unsafe” traffic space. Among other things, the local grouping of emergency call and escape route access was reflected in the positive assessments of the escape psychologists consulted and also of the Tirol association for the disabled.
Possible alternatives were checked in the course of the preliminary work. A parallel escape route tunnel and a connection to an existing pipeline tunnel of TAL were ruled out for technical and economic reasons. The task was solved using the existing supply air duct divided into two sections.

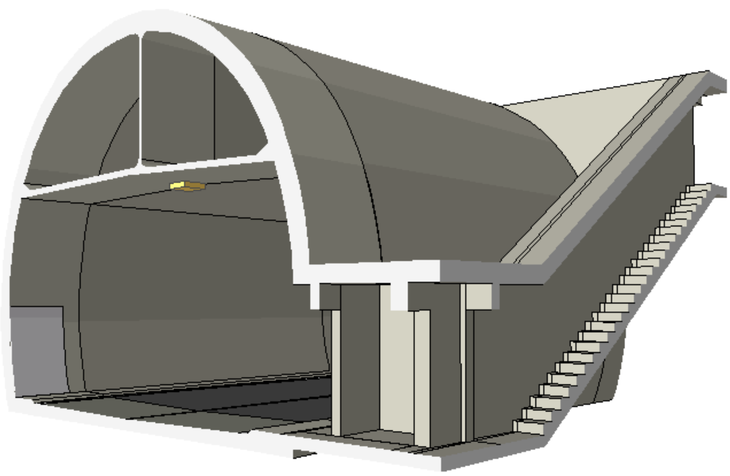

Figure 2: Felbertauerntunnel escape route system diagram
Traffic space-Emergency call recess-Escape route staircase-Supply air duct

In the operating case, two supply air fans deliver fresh air as required into the portal stations above the duct into the tunnel. In the case of an incident, this supply air duct which can be walked on *(cross section height up to 2.60 metres)* will be connected and integrated for the safe escape route. In both portal stations, so-called "escape route bypasses" are conducted out of and past the supply air duct to the supply air fans and the flaps of the flow brake into the open air. The escape system can be accessed from the traffic space via 23 emergency call recesses and directly at the escape staircases connected to the recesses spaced at 230 metres apart. Thus for the most unfavourable incident position *(incident directly in front of an emergency call recess)*, the maximum escape route lengths in the tunnel are 230 metres. The escape system also provides possible access in the opposite direction for the emergency services. These reach very close to the incident location safely and very quickly *(engine powered small emergency vehicles).* The necessary emergency equipment is located in the fire extinguisher recesses directly opposite the emergency call recesses.

The features of the escape system in the Felbertauerntunnel include:

a) 416 motor-operated supply air flaps for secure closure of the supply air duct against the traffic space for the incident operation *(standard position "closed")*;
b) Pressurised ventilation of the complete escape system by using the "free" – not in use for the flow brake – idling capacity supply air fan;
c) Access to the escape system via "safe" emergency call recesses *(F 90 and T 90 or REI 90 and EI2 90 c closure to the traffic space)* and gates *(2 x T30 closures or 2 x EI2 30 c closures)*;
d) Pressure relief of the emergency call recess doors in the case of overpressure in the escape system in order to maintain the maximum counter pressure requirements for the escape doors;
e) Automatically effective escape guidance system coupled with the system for incident detection based on the core idea of "displayed escape direction always leads away from the incident";

The new escape system has been available since the beginning of 2005.

3. FELBERTAUERNTUNNEL PROTECTION SYSTEM

Suitable possibilities for extended protection for persons, structural elements and systems for the Felbertauerntunnel have been researched and available variants compared in parallel with the 5 years of intensive work on the ventilation and the escape system. The comparison of achievable risk reduction to economic cost produced clear benefits for an active protection system. The passive high temperature protection of the structure by means of cladding with fire protection plates and by high temperature insulation of the partition wall in the exhaust air duct proved to be inferior. The requirements for the protection system were defined in the next step. In doing do, it was first necessary to optimally integrate the infrastructure and infrastructure relationships in the concept development and to ensure the unimpaired interaction with the ventilation and the escape system. The length of the groups *(36 metres)* and thus the lengths of the protection zones *(3 x 36 metres)* of 108 metres emerged from the infrastructure. The infrastructure relationships also resulted in the requirement for reliable system functioning for temperatures down to -30 °C. A further essential requirement for this system was the protection of the suspended roof, mainly the suspended roof support and thus last but not least the protection of the escape system. This resulted in the requirement to protect the system assuming 1,200 °C within 180 seconds after ignition against a maximum temperature of 250 °C at a distance of 5 metres from the source of the fire. Furthermore, the

maximum temperature at 20 metres distance was established at 50 °C with the emergency services and the requirement was developed also to be effective for large area liquid fires using wetting agent additions.
Available systems on the market were assessed on the basis of the requirements and sorted according to the state of development and suitability for practical use. The functional and documentation claims of many providers proved to be unsustainable for the tunnel already in this phase. The preselection followed joint efforts for further development and for further harmonisation of the systems with the requirements set.
The result, a stationary water spray system usable over the complete tunnel length for reducing the effects of fire incidents in the tunnel traffic space, was installed in one extreme tunnel section with respect to temperature differences, entrained water entry and contamination and continually stressed for one and a half years, jointly tested with the emergency services and thus tested for Felbertauerntunnel suitability.

Another tunnel test was also carried out Europe-wide in the Spring of 2005. With the rating of "good", the Felbertauerntunnel is in the safest category for single tunnel systems. This is not a reason for the operating company to lose sight of the objective.

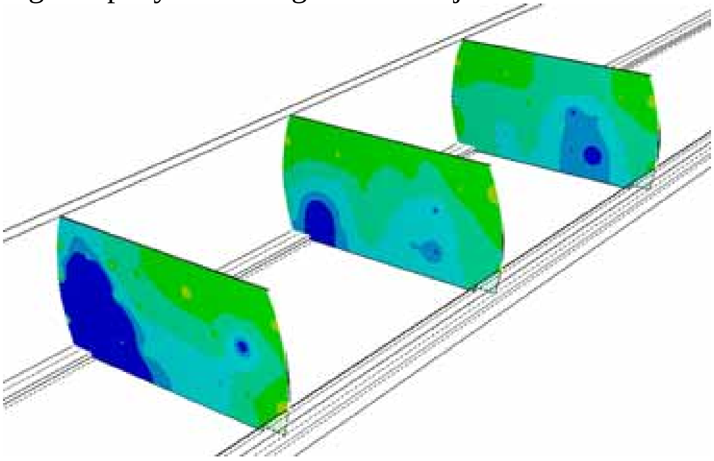

Figure 3: Result for water spray distribution in the cross section dark blue > 1.49 l/m³ min, red < 0.62 l/m³ min

The final component in the safety concept for the Felbertauerntunnel, "the protection system" was finally ready for installation at the beginning of 2006. The selection was made for a stationary "extinguishing system" designed as a high pressure water spray system with a wet and insulated main line and with group valves in the supply air duct and with dry distribution and nozzle lines in the traffic space. The difference to conventional sprinkler or water spray systems: the finest water droplets *(water mist)* emitted by high pressure using special high pressure nozzles act with direct destructive energy in the truest sense of the word due to the enormous surface area.

Fires at any location in the traffic space of the tunnel can be tackled with the protection system using water mist – the water output is approx. 3.800 litres per minute, distributed over a section length of 108 metres.
The fire output can be reduced or restricted to a "tolerable" level with the system. In this way, the smoke output is reduced and the temperatures in the incident surroundings are reduced so that fire expansion – the fire spreading to other vehicles in the tunnel – and destruction of the surrounding parts is inhibited. This results directly in the protection of persons involved. Safe escape conditions are maintained in the traffic space for a long time and the essential system functions such as video system, lighting, radio signal transmission, traffic lights and

emergency call equipment remain intact at least until clearance of the affected area. This makes it possible for the fire services to reach the incident location. They can intervene quicker and finally extinguish the fire.

The features of the protection system in the Felbertauerntunnel include:

a) the position of all essential installation components in the safe supply air duct;
b) the "feed-in protection" realised by the so-called "in-pipe nozzles";
c) the proven effect, both for solid as well as for liquid fires, up to fire outputs of 180 MW and the proven function also after long exposure by the system to temperatures of more than 1000 °C;
d) the proof that the operation of the exhaust air system in fires is not adversely affected irrespective of whether the opened exhaust air flaps are inside or outside the triggered section. In the course of the associated proofs, even positive effect on the distribution uniformity of the water mist in the traffic space cross section could be documented.
e) multiple system redundancy based on, e.g. pump stations in both portal stations, spare pumps in both portal stations, …;
f) the available running time of the system which with more than 3 hours safely covers the required lead times of the emergency services;
g) the possibility of adding wetting agents to the extinguishing medium;

The system, which could also generally be called a high pressure extinguishing system, has been ready and in operation since late autumn 2007.

SUMMARY

Incident safety in the Felbertauerntunnel is a customised interaction of many components. "Prevention" using information of the tunnel users is certainly in first place. The Felbertauernstraße can also build on the available potential in the interrelationship. The high proportion of the so-called frequent drivers also opens the way for information using multiple direct contacts. However "prevention" and preparatory "emergency management" due to the contact with the responsible fire services must also be seen in the interrelationship. There is close collaboration which was and is extremely important for Felbertauernstraße AG. The portal fire brigades were intensively incorporated in the development and continuing adaptation of the safety concept and in preparatory actions for emergency management. Many of the preliminary tests for the ventilation conversion and the protection system have been performed and assessed jointly. Therefore, the status of the system knowledge must be designated as at least "high". The safety brigade – a small tunnel fire brigade equipped with a special vehicle – which is reserved for the operating company for rapid first deployment around the clock directly at the south portal station of the Felbertauerntunnel, also has a preventive effect.

The many components today also include self-evident technical requirements which are essential for the function of the systems described above. The fact that suitable programmable logic controllers for them, a corresponding process control system, measuring and detection systems with current technical standards and many other things were required goes without saying.

To summarise, we see the Felbertauerntunnel today at the current state-of-the-art after completion of the essential points in the safety concept. We have certainly come nearer to providing the desired "swan" end result or rather the "maximum possible safety for the users in the Felbertauerntunnel.

SAFETY REQUIREMENTS & TRANSPORT OF DANGEROUS GOODS THROUGH THE 53 KILOMETER RAILWAY TUNNEL THROUGH THE ALPS BETWEEN LYON AND TURIN

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ABSTRACT

This project concerns the border crossing part of the new high speed link between Lyon and Turin. This high speed link is an important connection in the pan-European railway network. In 2015 the first trains will run. The tunnel will be used by high speed passenger trains, freight trains and "Autoroute Ferroviaire" (trucks on the train). ARCADIS has studied the transport of dangerous goods and the functional requirements of the safety equipment.

Keywords: transport of dangerous goods, tunnel safety, railway tunnel

1. INTRODUCTION

The Lyon-Turin rail link between France and Italy, crossing the Alps, is one of the major projects in Europe. This high speed link is an important connection in the pan-European railway network. In 2015 the first trains will run. The link will be used by high speed passenger trains, freight trains and "Autoroute Ferroviaire" (trucks on the train) and will consist of a 53 km long tunnel crossing the border between France and Italy as well as the 12 km long Bussoleno tunnel. For such a project, the safety expectations are very high. Before starting the detailed design of the tunnel, it is therefore of importance which safety measures are to be integrated in the tunnel to meet the defined safety principles.

2. EQUIPMENTS

In order to provide for the required level of safety in the tunnel, several security systems and security equipment has been foreseen in both tunnels (Tunnels du base and the Tunnels du Bussoleno.

2.1. Emergency philosophy

The emergency philosophy for trains with a fire onboard has to, if possible, continue to a 'safe haven' and to evacuate all passengers there. For all other trains not directly involved in the incident the rule is to a) leave the tunnel(s) as quickly as possible or to b) stop before entering the tunnel.

2.2. Emergency installations and equipments

The following emergency installations are used in the tunnel and connected areas:

- Detection equipment for:
    - Smoke and fire
    - Derailment
    - Train stop
    - Gage
    - Fumes and gasses

- Containment and extinguishing equipment in case of fire:
  - Ventilation systems in tunnels, inter tube tunnels
  - Ventilation of safe areas
  - Ventilation of technical rooms
- Control systems:
  - Lighting system
  - Video system (CCTV)
  - Central command post (PCC)
  - Communication equipment
  - Telephone system
  - HF communication system

The following equipment is foreseen in the tunnels, intervention stations and safety stations and surrounding elements:

- Evacuation of passengers:
  - Emergency platforms:
  - In the tunnels (min. 1.2 m width)
  - In the emergency stations and station (3.0 m width, 750 m length)
  - Cross passages (every 400 m, in Modane station every 50 m)
  - Collection rooms for the injured in every intervention and emergency station
  - Directions signs for emergency escapes
  - Audio system
- Accessibility and equipment for emergency services:
  - Emergency accesses at the highest point of every emergency tunnel, connecting to local infrastructure. The accesses are provided with a helicopter platform, parking space, and a command post
  - Emergency tunnels
  - Fire extinguishing equipment:
  - Hydrants (6 – 10 bar, every 133 m, French and Italian system)
  - Fire mitigation system in every intervention station and in the safety station
  - Automatic fire extinguishing system in technical rooms
  - Emergency water reservoirs (with a capacity of 120 m^3) in each station.
  - Central command post (PCC), one in France and one in Italy.
  - Drainage system liquids (alpine water, extinguishing water)
  - Storage tanks for dangerous liquids (6 in total, storage capacity 240 m^3 per tank)

Three systems in particular will be described in following paragraphs, namely the foam water system, the emergency tunnels and the drainage system.

2.3. Fire mitigation system

Fires with a capacity of 50MW can occur in the tunnel, due to the properties of transported goods and air speeds in the tunnel. These fires cannot be reached physically by fire fighters and therefore cannot be put out in a traditional way. For this reason, all goods trains will have to make a safety stop at an intervention station or safety station when exiting the tunnel is not an option. Each intervention and emergency station in the tunnel is provided with a sprinkler like system, using a specific mixture with water onto the fire from nozzles located on either side of the tunnel roof. Two systems have been modelled and tested: a Foam Water system and a high pressure Water Mist system. With a ventilation speed of 2 m/s, the following results are found.

The figure shows that the FW system reduces a fire to 20% of its original intensity within 70sec and to 10% within 150sec. The WM system mitigates a fire to 40% and 35% for the same time intervals respectively. These results are obtained when the system is called into action immediately after the start of a fire. There are however scenarios in which it takes up to 15 min before a train is located in an intervention station provided with a FM or WM system and the system is switched on. This way, 100MW fires cannot be excluded.

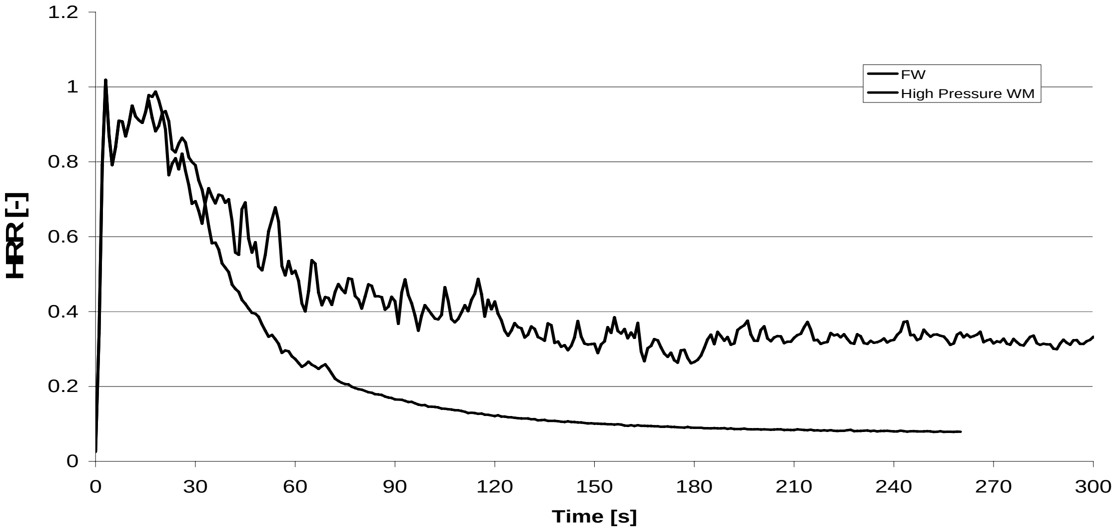

Figure 1: Test results from Foam Water and high pressure Water Mist systems to a 50MW fire.

2.4. Emergency tunnels

The intervention stations of Saint-Martin, La Praz and Venaus, as well as the emergency station of Modane are connected to the outside world by means of emergency tunnels. In total there are 4 emergency tunnels, with a diameter of 10m and lengths varying from 500 to 4,500m. The emergency tunnels will be used by emergency services in case of an emergency. The enormous length of the emergency tunnels led resulted in a one-way regime for traffic, with passage sites every 400m, dividing each emergency tunnel into sections. The passage sites have a length of 200m and a width of 20m. Traffic lights will be used to indicate a free passage per section.

2.5. Drainage system

In the tunnel, a drainage system is applied to drain the alpine water from the tunnel the slope of the system is 2%, following the tunnel slope. In case of fire in a goods train leaking dangerous liquids, extinguishing efforts with water will result in a pool fire, possibly increasing the capacity of a fire. Therefore, the drainage system consists of lateral and longitudinal canals that collect in central collection points with siphons, to prevent progression of a fire in the closed drainage system. The liquids are collected in storage tanks, located at every station and at the heads of the tunnel.

3. DANGEROUS GOODS

One of the reasons the tunnels are being constructed is the transport of freight. From current transport of freight we know that a substantial part of the international transport can be classified as dangerous goods. Effects of an incident with dangerous goods in the tunnel may be serious for both persons present and the structure of the tunnel. Before allowing transport of dangerous goods in the tunnel, it has to be determined whether the possibility of an accident in relation to the effects is acceptable.

3.1. The methodology

The UN working group WP15 on the transport of dangerous goods has been developing a methodology to categorize tunnels. Through tunnels of different categories, different groups of dangerous goods are allowed for transport. For the LTF project this methodology has been the base to define safety measures and to determine whether transport of dangerous goods can be allowed in the tunnels. For each group is determined whether the possibility of an accident in relation to the effects is acceptable and if safety measures can be taken to ensure that the required safety level is reached.

3.2. Possible effects and proposed safety measures

3.2.1. Group A

Dangerous goods in this group are prohibited for transport and are therefore not analyzed in the studies for the project Lyon Turin Ferroviaire.

3.2.2. Group B

3.2.2.1 The effects

Dangerous goods in this group can provoke a big explosion. LPG is the product most transported good within this group. For this reason the effects of an accident with LPG are taken as normative to analyze the effects of a possible incident with goods of this group.Two types of incidents have been considered: a leak of limited size leading to a vapour cloud explosion after ignition and a catastrophic failure of a LPG vessel leading to a BLEVE (Boiling Liquid Expanding Vapour Explosion).A combination of a steady leak and steady ventilation flow may result in a homogeneous cloud in the tunnel downstream of the leak. For stoichiometric clouds of 10, 20, 50 and 100 meter length (it is never certain when a cloud may be ignited), the blast effects up to a distance of 5000 meters on either side of the cloud have been modelled.

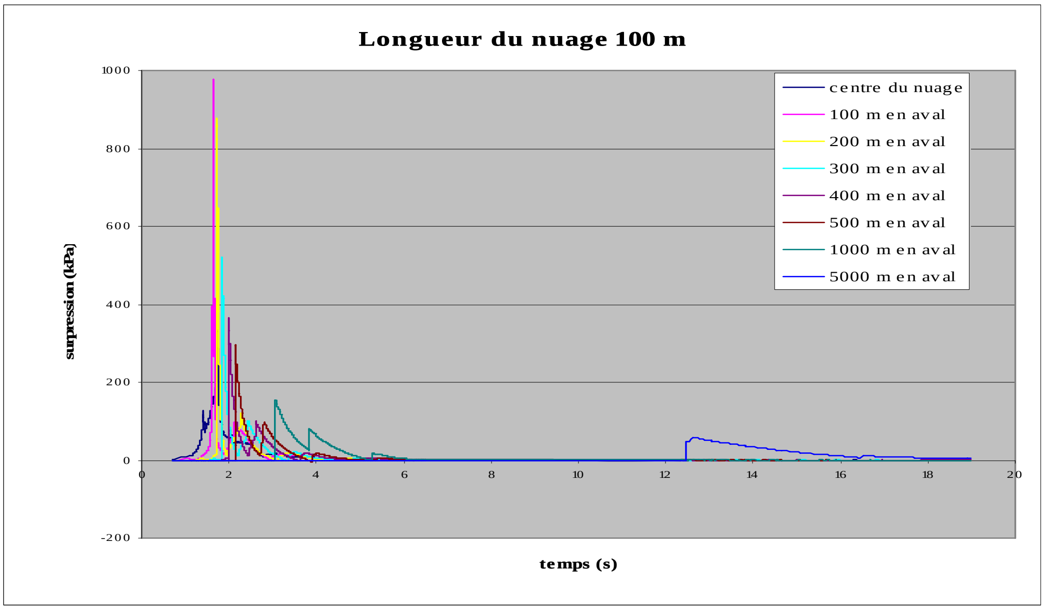

Figure 2: The blast effects after ignition of a cloud with a length of 100 meter

A vapour cloud explosion as simulated can generate a blast that can cause victims up to 4200 metres.

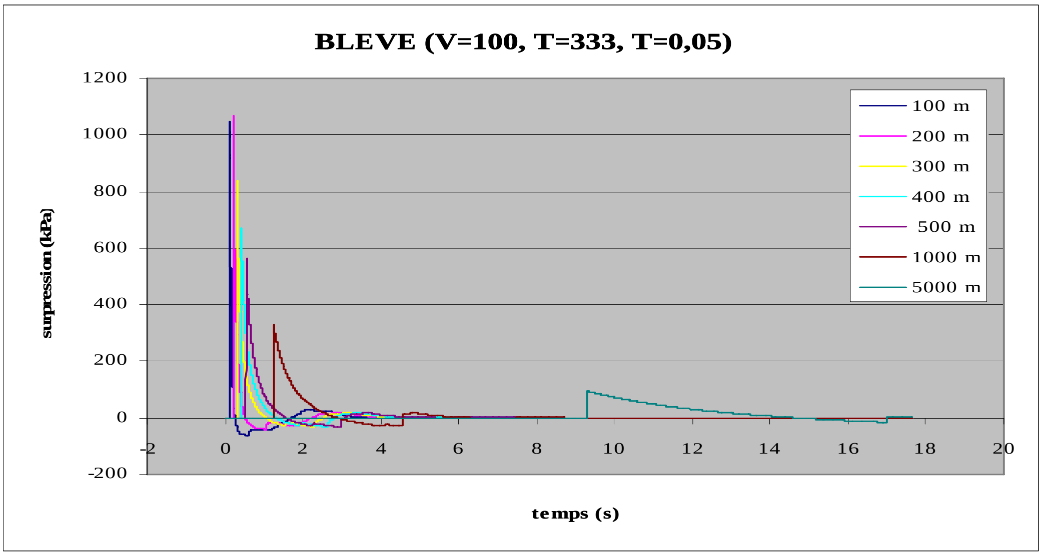

Figure 3: Possible blast after a BLEVE of a vessel of 100m3

The blast of the simulated BLEVE can cause victims up to a distance of 4200 meters in the tunnel on both side of the incident.

3.2.2.2 Proposed safety measures

The prognostics show a large amount of possible transport of flammable gases. For this reason, both protective and preventive measures are proposed for the tunnel.

Since effects of an explosion reach up to 4200 meters in the tunnel, the first measures is to keep a distance of at least 4200 meters between a train carrying this products and a train with passengers. Furthermore the truck train combination is not allowed for this group since there are too many drivers present in the train, thus within the 4200 m range.

3.2.3. Group C

3.2.3.1 The effects

Dangerous goods in group C are goods that can provoke an explosion or a toxic leak in the tunnel. To analyse possible effects of possible incident with goods in this group, dispersion of ammonia and chloride in the tunnel is modelled.

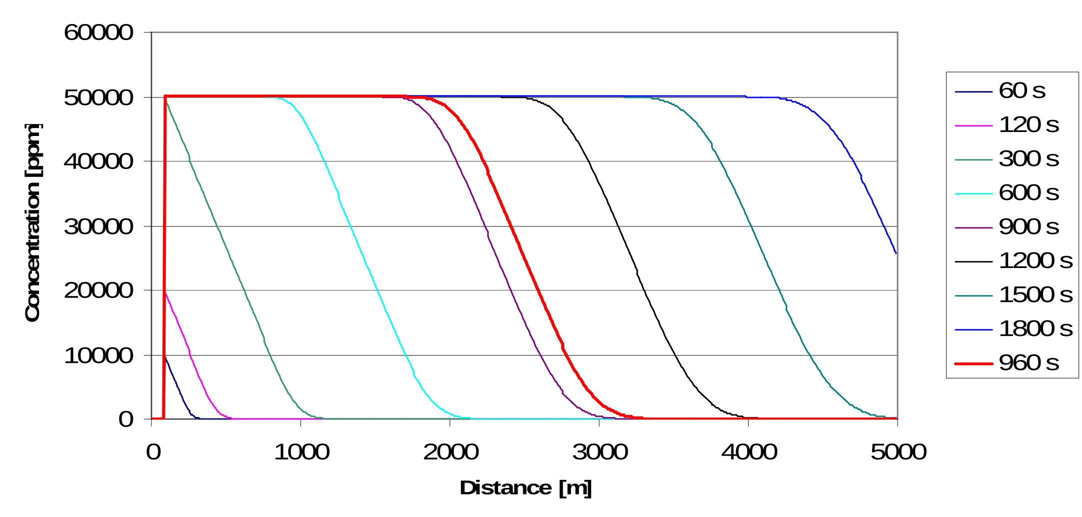

Figure 4: Dispersion of chloride in the tunnel after a leak (50mm) of a vessel (ventilation speed 3 m/s).

With the probit function (probit functions give the mortality rate depending on concentration and exposure time) for chloride it is calculated the toxic cloud reaches up to 3500 meters from the incident after 16 minutes.

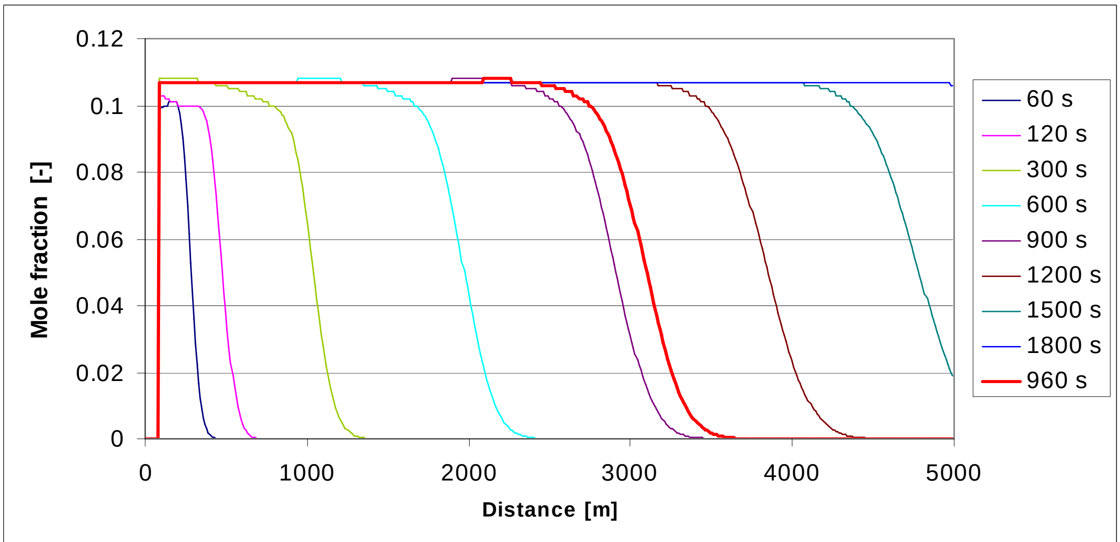

Figure 5: Dispersion after a leak (50mm) of ammonia (taken ventilation speed 3 m/s).

The lethal concentration of ammonia will not reach as far as the chloride cloud.

Toxic vapour clouds from toxic liquids have also been analysed. Since evaporation from a liquid pool is a lot slower than evaporation of a pressurized gas, effects will not carry as far as the effects of pressurized gases.

3.2.3.2 Proposed safety measures

Since some of the goods in this group can provoke an explosion, a distance of at least 4200 meters (3500 m for truck-trains) between a train carrying this products and a train with passengers is introduced.

To reduce toxic effect of gases, the ventilation system should be able to influence the velocity and the direction of a toxic cloud.

To reduce the effect of toxic liquids it is proposed to limit the surface of a possible pool to minimise evaporation. As for the flammable liquids a maximum of $100m^2$ is proposed (see above). The evacuation system has the possibility to separate toxic liquids and water (they can provoke a chemical reaction in some cases).

Further on, the ventilation systems of trains passing through the tunnel should be closed unless toxic clouds can be detected before trains with groups of passengers enter the tunnel.

The Sonia vehicle does also have this possibility to ensure that drivers of the trucks can get away in this vehicle.

3.2.4. Group D

3.2.4.1 The effects

Dangerous goods in groups D are those that can provoke a major fire. To analyse possible effects of possible incident with goods in this group, the effects of a fire of 100 and 200 MW in the tunnel have been modelled.

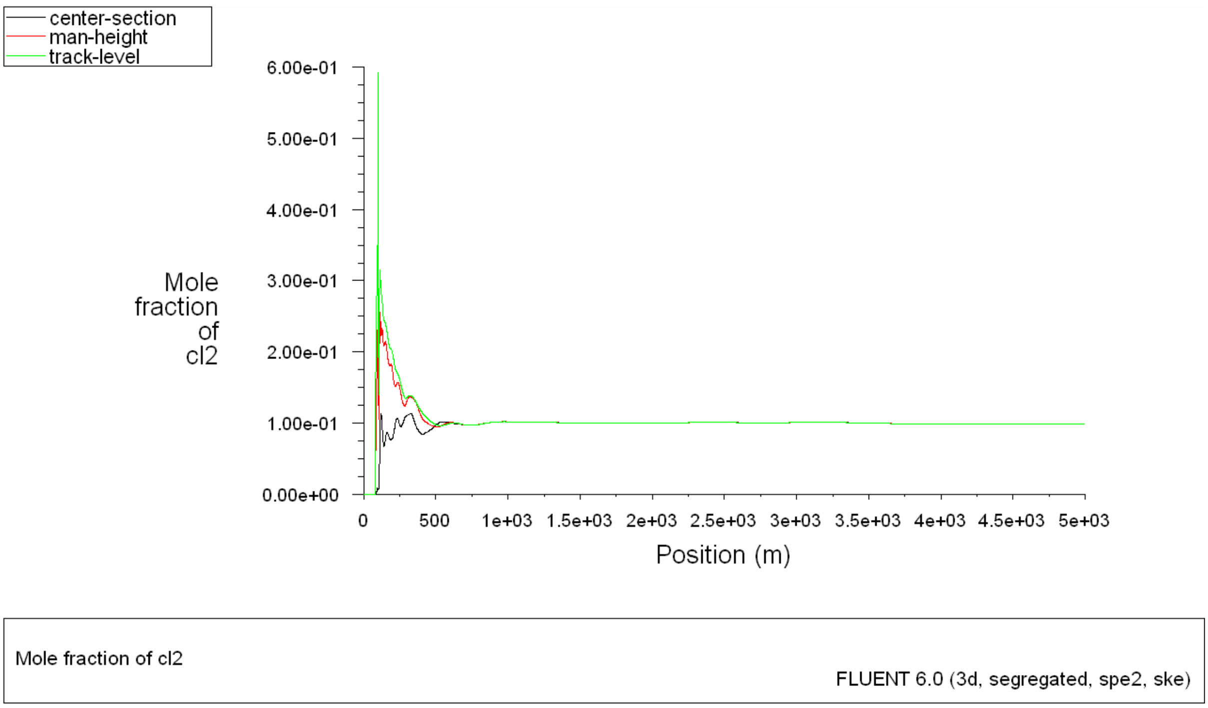

Figure 6: Temperature of 100MW in relation to distance in the tunnel.

Furthermore the effect of a fire in case of another train present was analysed.

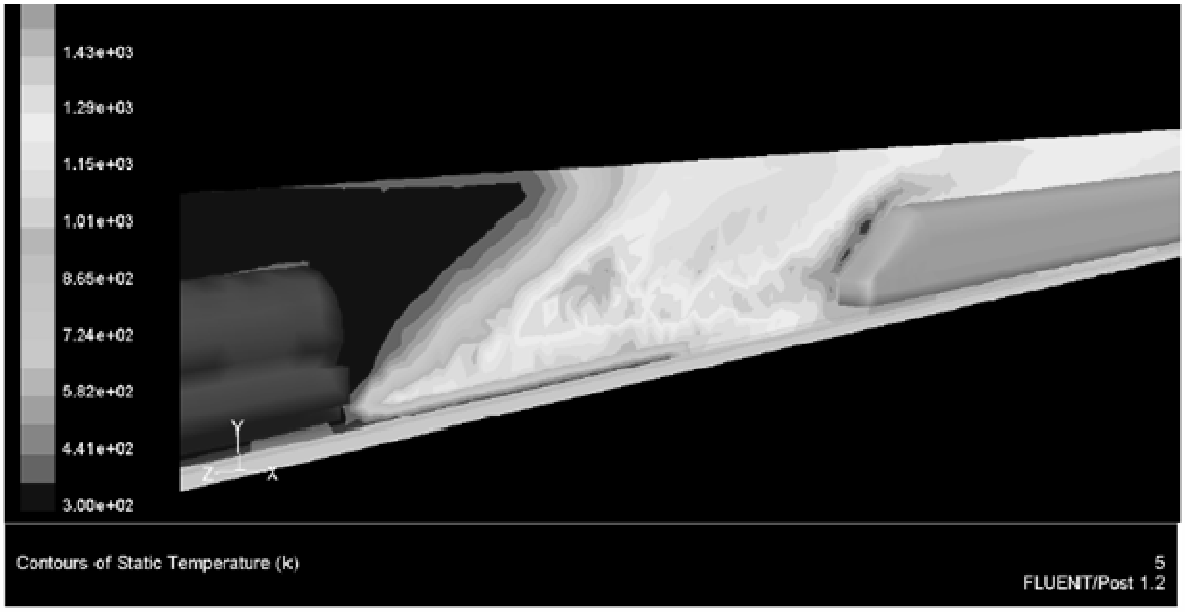

Figure 7: simulation of a major fire next to a passenger train

It has been concluded that the temperature reaches up to 50 °C at 3500 meter after 15 minutes. Since the air in the tunnel will be moist, this the level which can be dangerous to persons present in the tunnel.

3.2.4.2 Proposed safety measures

Since temperature and smoke can reach dangerous levels up to a distance of 3500 meters, this distance should be kept between a train carrying flammable products and a train with passengers. The interdistance of 4200 m caused by group B makes this one oblivious.

To prevent a fire from growing to fast and to limit effects, the ventilation system should be able to influence the velocity and the direction of the air in the tunnels.

To make sure a pool fire will be limited in magnitude, the surface of a possible pool should be limited to a maximum of $100m^2$ (gasoline generates about 2 MW/m^2).

The Sonia vehicle must be able to leave as fast as possible after an incident, before the effects of a fire reach the vehicle where the drivers are present.

3.2.5. Group E

Since the products in group E are either less dangerous or transported in smaller quantities this group has not been analysed. Measures taken to reduce risks for the other groups are supposed to be efficient enough to take away the risks of this group.

4. CONCLUSION

- The safety studies have been carried out in order to determine the Functional Requirements Specifications of all safety measures and precautions in the tunnels to minimize the risks.
- The outcomes are input for further technical studies of the project as well as for the definition of the layout and design of the tunnel. It is up to the design engineers to incorporate all proposed measures in the tunnel.

AERODYNAMICS, CLIMATE AND VENTILATION OF THE LÖTSCHBERG BASE TUNNEL: FIRST RESULTS OF THE MEASUREMENTS CARRIED OUT DURING THE COMMISSIONING PHASE

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ABSTRACT

The paper includes a short introduction to the Lötschberg base tunnel project and a description of the most important planning criteria for the tunnel climate, the tunnel aerodynamics and the tunnel ventilation in every operation mode. Additionally the concept, the realisation and the substantial results of the elaborate measurement campaign are discussed. Finally preliminary findings of the tests during the commissioning phase are summarized and evaluated regarding future tunnel projects.

Keywords: Measurements, Aerodynamics, Climate, Ventilation, Lötschberg Base Tunnel

1. INTRODUCTION

The 34.7 km long Lötschberg base tunnel is part of the new transalpine tunnels in Switzerland (NEAT). In summer 2007 the base tunnel was taken into reduced train operation. The final opening of the tunnel for the regular train operation took place at the end of 2007. During the commissioning phase of the base tunnel a huge number of tests and measurements were carried out. Amongst others these covered the examination of the tunnel climate, the tunnel aerodynamics and the functionality of the tunnel ventilation. With the help of the tests the most important planning criteria should be verified. In particular the planning hypotheses, the calculation parameters and the simulation codes were to be examined. These comprehensive verifications are not finished up to now.

2. DESCRIPTION OF THE LÖTSCHBERG BASETUNNEL

Due financial reasons and reduced traffic demands the final configuration of the 34.6 km long Lötschberg base tunnel including two fully equipped and operated single track tubes between Frutigen and Raron is not yet completed. The current set of the 34.6 km long Lötschberg base tunnel consists of one single track railway tube between Frutigen and Ferden and (over 1/3 of the overall length) of two single track railway tubes from Ferden to Raron (cf. Figure 1).

In the northernmost section of the base tunnel between Frutigen and Mitholz a service tunnel accompanies the railway tube for water drainage and safety reasons. The two tubes are connected by cross passages in regular distances of 333 m.

Between Mitholz and Ferden two railway tunnels are provided. However only the eastern tube is technically equipped and under train operation. Since both tunnels hold the same cross sectional areas, it is possible to equip the western tube in a later phase. In the current phase the western tunnel serves as a maintenance and safety tunnel. Again the two tubes are connected by cross passages in regular distances of 333 m.

In the southernmost section between Ferden and Raron the base tunnel is operated as a system of two single track railway tubes. The two tunnels are connected by cross passages in regular distances of 333 m.

The access tunnel Steg is foreseen as a connection tunnel to the loading point for car shuttle operation in a later phase.

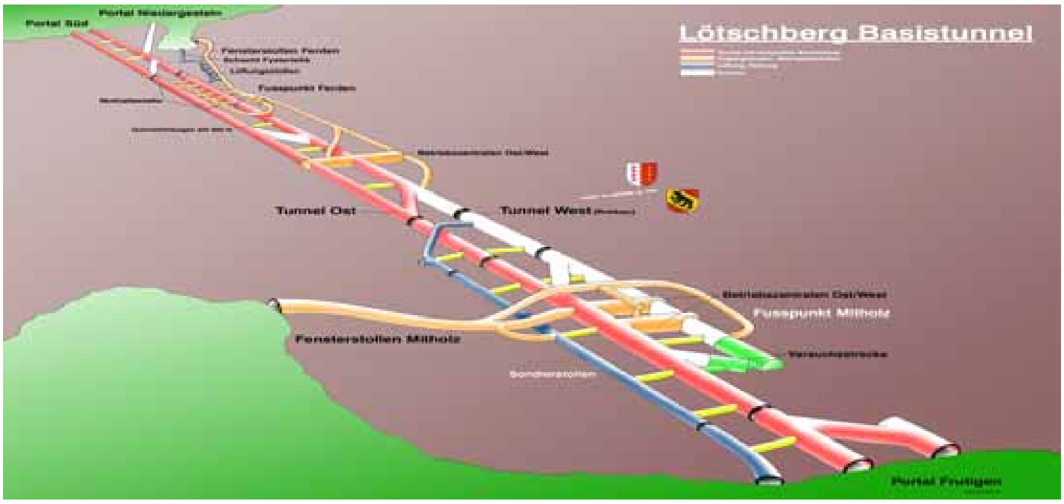

Figure 1: Sketch of the Lötschberg Base Tunnel

A rescue station consisting of two emergency stations is located near the cross over in Ferden. If an incident train is not able to leave the tunnel, it can reach the emergency station either from the eastern or from the western tube.

Starting with the commissioning at end of 2007, 110 trains (passenger trains, piggy back and goods trains) cross the tunnel per day.

3. REQUIREMENTS ON TUNNEL CLIMATE, AERODYANMICS AND VENTILATION

During normal, maintenance and emergency operation distinct requirements must be fulfilled.

3.1. Normal Operation

In normal operation a safe and fail safe tunnel operation must be ensured. The air temperature in the tunnel must be kept under 35°C independent of the season and of the traffic volume in the tunnel. The surrounding rock contributes to the heating of tunnel air. The initial rock temperature reaches 45°C on particular sections in the tunnel. Additionally the heat loss of moving trains and of technical equipment increases the tunnel air temperature. On the other hand the cooling of tunnel air takes place due to air exchange with the outside based on the piston effect of moving trains.

The arrangement of the tunnel portals, the cross sectional area of the railway tubes as well as the changes of the cross sectional areas along the tunnel were carefully chosen to prevent pressure fluctuations in passenger trains over 1.5 kPa/4s. Apart from these structural measures, the high-speed passenger trains must feature a good sealing against pressure fluctuations to fulfil the specified pressure comfort criteria.

3.2. Maintenance Operation

Maintenance work in the tunnel is carried out at operation off hours. During the maintenance operation climate conditions according to the industrial safety regulations must be guaranteed using the tunnel ventilation. The individual operation of supply air and exhaust air fans will ensure favourable working conditions for the maintenance staff.

3.3. Emergency Operation

The critical scenarios of the emergency ventilation are emergency stops of burning passenger trains or burning freight trains in the tunnel. For these cases the following substantial ventilation goals were defined:

- Guarantee of a smoke free waiting area for the escaping passengers in the emergency station (overpressure within the waiting area by air supply).
- Support of self rescue of passengers escaping along the emergency stop (exhaust of smoke along the emergency stop).
- Guarantee of a safe evacuation way in the not affected opposite tube according to the evacuation concept (prevention of smoke propagation into the opposite tube).

Dependent on, whether the incident train stops inside or outside of the emergency station, the following three cases regarding the emergency ventilation must be considered:

- **Stop in the emergency station:** The conditions for the self rescue and evacuation can be optimized by supply air and exhaust air. By extracting smoked air from the emergency station the smoke propagation along the emergency station can be minimized and the escape conditions for the passengers will be improved. The supply of fresh air into the waiting room of the emergency station prevents a smoke infiltration. The passengers can safely await the evacuation train.
- **Stop outside the emergency station in southern tunnel sections:** Using fresh air supply in the opposite railway tube a smoke propagation from the incident tube via open cross passages can be prevented. Passengers waiting in the opposite tube for the evacuation train are protected against smoke and heat.
- **Stop outside the emergency station in the northern tunnel section (one single track tube):** Using fresh air supply in the service tunnel a smoke propagation from the incident tube via open cross passages can be prevented. Passengers waiting in the safety tube for an evacuation bus are protected against smoke and heat.

4. TEST DESCRIPTION

4.1. Concept

After completion of the tunnel construction and installation of the railway equipment the commissioning phase of the Lötschberg base tunnel was carried out in 5 steps:

1. Testing of each technical installation with the goal to verify the technical contractual specifications (dimensions, quality and functionality).
2. Integration of every technical installation and verification of the integrated system functionality. Examination of the interfaces to other technical and operational disciplines.
3. Technical test operation: Examination of the functionality of the integrated technical installations in the tunnel based on realistic operation procedures.

4. Reduced train operation: The tunnel operator achieves an approval for a reduced commercial operation (first only with freight trains and later with some additional passenger trains). The objective of these tests is to prove that the operator is able to ensure the tunnel safety.
5. Beginning of regular train operation: With the implementation of the definitive train schedule at the end of 2007 the operator accomplishes the approval for a regular train operation in the tunnel.

Within these commissioning steps several tests concerning the aerodynamics, the climate and the ventilation in the tunnel were carried out. The goal of these tests was to verify individual specifications of the tunnel construction and of the functionality of the tunnel ventilation for the individual operation modes.

The following table includes an overview of the accomplished tests and individual measurements.

Table 1: Measurements of aerodynamics, climate and ventilation

Aspects	**Measurements**	**Goal**	**Test Phase**
Tunnel aerodynamics	Determination of the pressure and wind loads in the tunnel due to moving trains	Verification of the pressure and wind loading technical equipment in the railway tunnel (doors, walls) Verification of the specified project assumptions	3 - 5
	Determination of the pressure fluctuations in trains during their journey through the tunnel	Verification of the pressure comfort criteria in passenger trains	3
Tunnel climate	Determination of the tunnel climate (temperature and relative humidity of the air)	Verification of the climatic prognoses Verification of the air exchange and the cooling effect in the tunnel due to the piston effect of moving trains	4, 5
Tunnel ventilation	Determination of the technical specifications and functionality of the tunnel ventilation	Verification the contractual specifications concerning the ventilation plants	1
	Integration of the ventilation system and determination of the ventilation efficiency within the individual ventilation scenarios	Verification of the ventilation functions; Verification of the specified ventilation goals	2
	Determination of the ventilation functions based on realistic scenarios for realistic operation scenarios	Verification of the ventilation goals based on realistic operation scenarios	3

4.2. Measuring Systems

The measurement of the air temperature in the railway tubes was performed with permanent measuring instruments fixed along the tunnel in regular distances of about 300 m. The measured data are continuously transmitted to the tunnel control centre.

The measurement of the tunnel longitudinal air flow and the pressure fluctuations in the tunnel and on the trains were accomplished with temporary measuring instruments installed at representative locations in the tunnel and on the test trains. These measuring instruments were removed after the tests, since a continuation of monitoring of these physical dimensions seemed no longer necessary.

Some measuring instruments and the selected measuring locations in the tunnel and trains may be seen in the illustrations in section 5.

5. TEST RESULTS

5.1. Tunnel Climate

The following main results were achieved:

- The tunnel climate (temperature and relative humidity of the air) has a substantial influence on the availability of the technical equipment. In addition the compliance with the defined climatic limits in the tunnel is important for the maintenance work.
- The tunnel climate will be substantially affected by the heat of the surrounding rock, by the heat loss of the technical equipment, by the traction power of the moving trains, by the ambient climate conditions at the portals and by the air movement in the tunnel.
- In Figure 2 the air speed along the northern single track railway tube during a period of regular train operation and during the off hours are illustrated. The air movement and in the tube as well as the air exchange with the outside has a substantial influence on the tunnel climate.
- In Figure 3 the average air temperature in the eastern railway tube is shown for typical days of the first winter months after the opening of the Lötschberg base tunnel. The simulated air temperature complies quite well with the measured data.

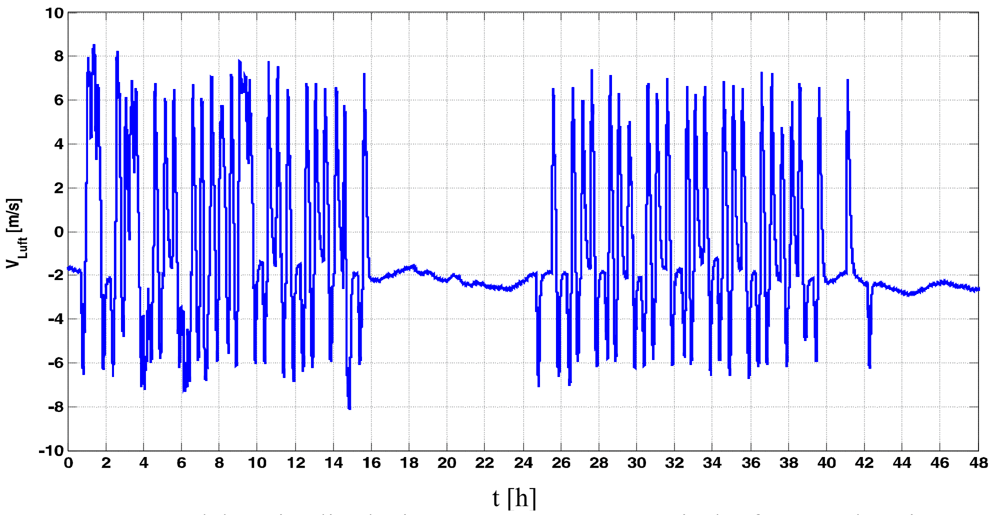

Figure 2: Measured longitudinal air speed during a period of normal train operation in the LBT. During operation off hours (in the night) the residual longitudinal airflow is based on the thermodynamic buoyancy effect of the sloped tunnel and the meteorological boundary condition at the tunnel portals.

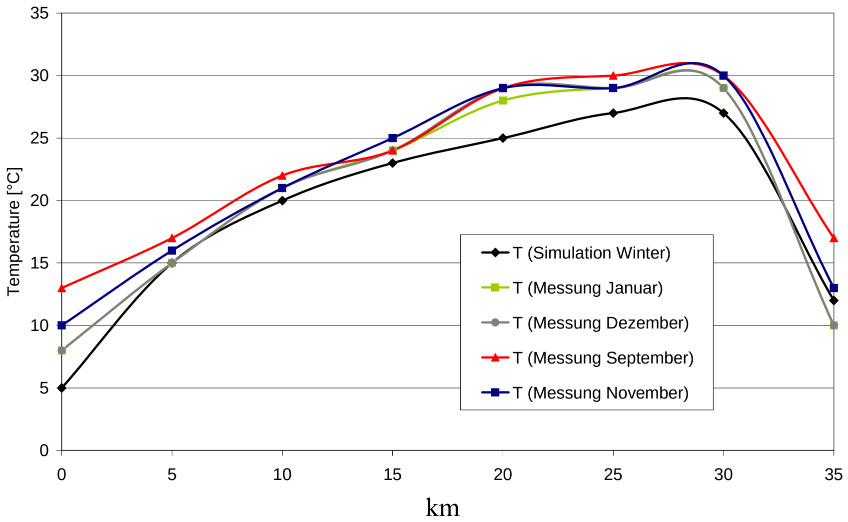

Figure 3: Measured air temperature (daily averages between September 2007 and January 2008) versus predicted air temperature in the eastern railway tunnel.

5.2. Tunnel Aerodynamics

The following main results were achieved:

- The railway equipment in the tunnel has to endure frequently pressure fluctuations and high pressure loads produced by the moving trains. In addition to fast moving passenger trains (up to 250 km/h) especially the aerodynamically unfavourably shaped good trains (high blockage effect) lead to a high pressure load in the tunnel.
- Therefore the examination of the following aspects was of special importance (cf. Figure 4 to 7):
  - The maximum air flow in the different tunnel directions (longitudinal, transversal) for the determination of the wind loads on technical equipment (e.g. jet fans, signage, railway catenaries, etc.)
  - The pressure load on doors, gates, walls, covers, etc. in the railway tubes and on the technical equipment in the cross passages between the railway tubes
  - The pressure fluctuations in a passenger train during its journey through the tunnel. Passengers may experience unfavourable pressure changes induced by the train entry into the tunnel, by the passing of of the cross sectional variations along the tunnel and by the exit from the tunnel. Accordingly smooth cross sectional areas transitions and good sealed passenger trains were specified.
- In the following illustrations some of the measuring systems and collected data are shown.

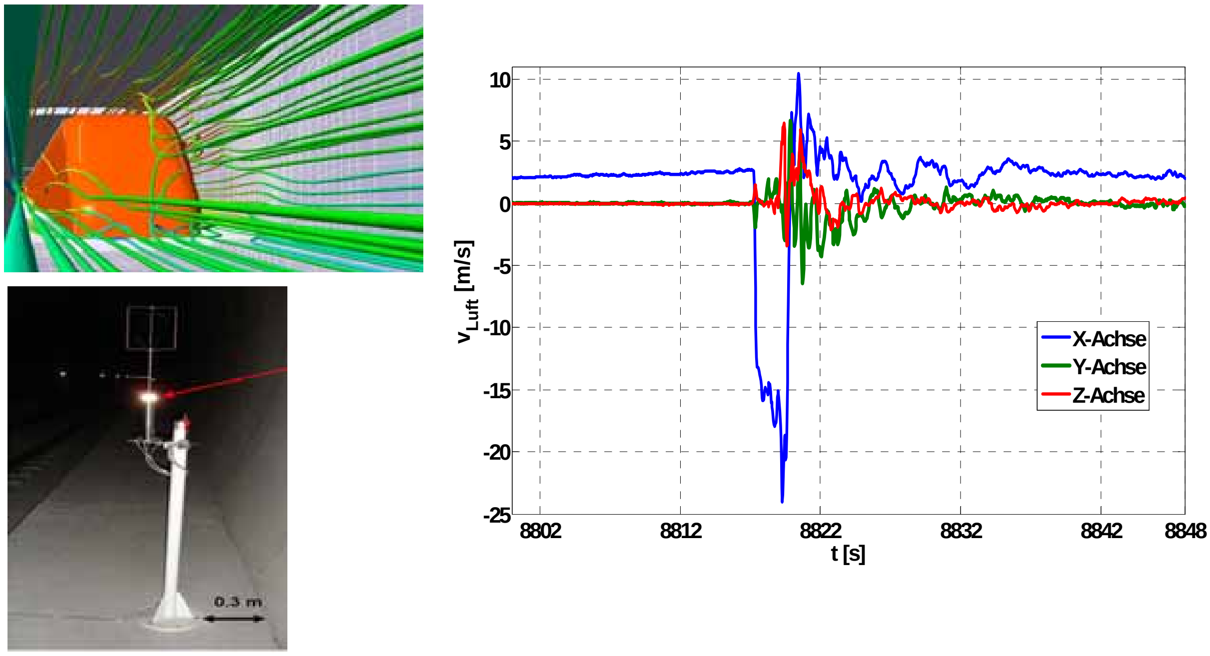

Figure 4: Three dimensional air flow in the railway tunnel. On the upper left side: An illustrative 3D simulation of turbulent air flow along a moving high speed train in the tunnel. On the lower left side: The used ultra sonic air speed sensors to capture the three dimensional air flow in the railway tube. On the right side: Measured 3D air flow on the sideway in the railway tube while a passenger train passes with 200 km/h.

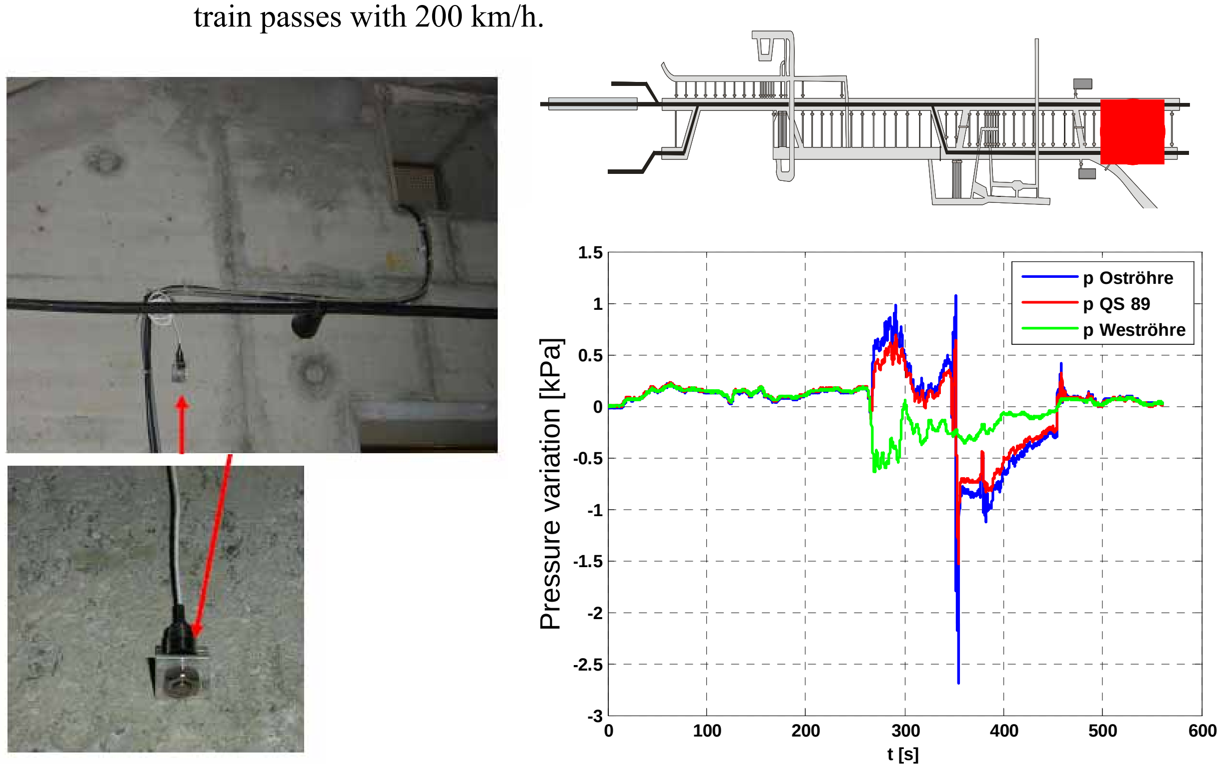

Figure 5: Train induced pressure loads in the south eastern and western railway tubes and in the cross passage between the two single track railway tubes while passing of a passenger train (ICE, Vmax=200 km/h). On the left side: Installed pressure sensors. On the upper right side: Localisation of the measurement. On the lower right side: Measured data

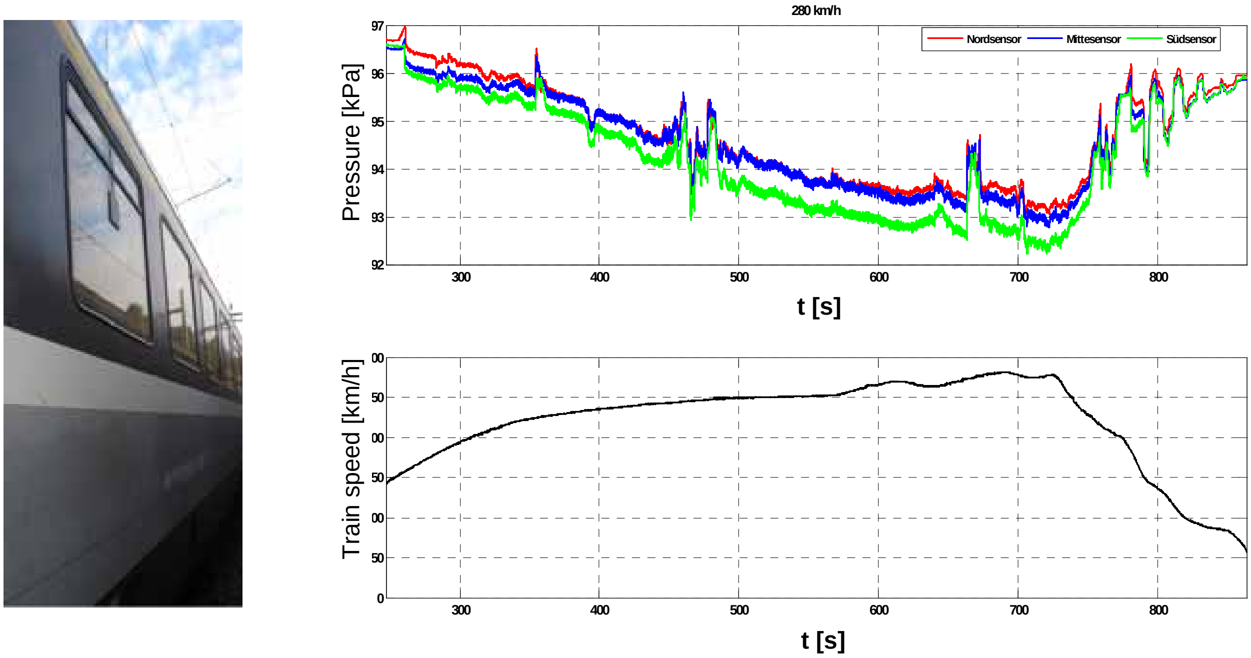

Figure 6: Pressure fluctuation on a passenger train (ICE) at different position on the train while passing the Lötschberg Base Tunnel. On the left side: Pressure sensors installed on the window of the train. On the right side: Measured pressure fluctuation on the train (outside) while passing the tunnel and the correspondent speed profile of the passenger train.

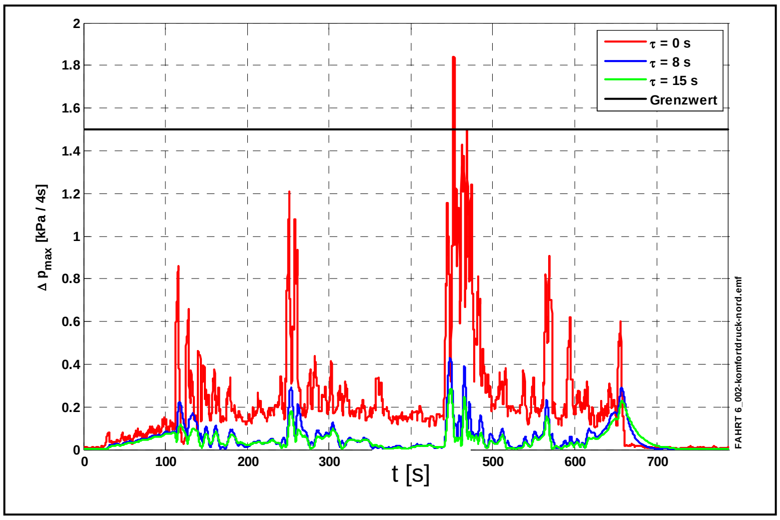

Figure 7: Measured maximum pressure fluctuation within time periods of 4 seconds in the train during its journey through the tunnel (see figure 6). These calculated pressure fluctuations inside the passenger train quote for different sealing factors τ of the train. The dashed horizontal line indicates the comfort criteria of 1.5 kPa/4s. The pressure profiles prove that the comfort criterion is fulfilled only with a sealed passenger train (τ > 0).

5.3. Tunnel Ventilation

The following main results were achieved:

- The objective of the ventilation tests was to verify the efficiency of the ventilation functions for realistic emergency scenarios. Thus the examination of the temporal reaction of the ventilation (in a very long tunnel) and of the influence on the longitudinal air flow in the open escape doors due to the piston effect of the moving trains was of great importance.
- Via cold smoke tests the propagation of smoky air in the tunnel and in the emergency station was examined.
- In the following illustration an example of an emergency scenario applied for the tunnel ventilation tests including leaving trains as well as the entry of rescue and evacuation trains is given. The influences on the longitudinal air flow in the open escape doors due to the piston effect of the moving trains are illustrated.

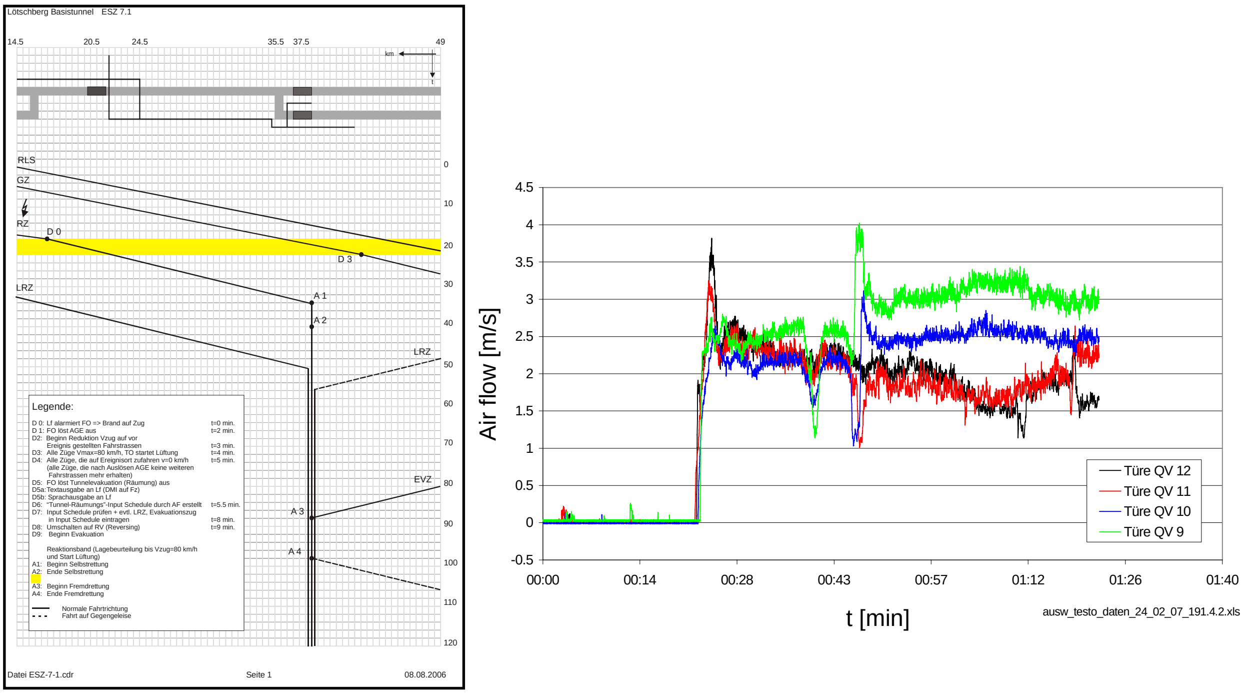

Figure 8: Tests of the emergency ventilation system: On the left side: Typical emergency operation scenario in the tunnel based on the train control system ETCS II. On the right side: Measured longitudinal air speed in the open escape doors of the rescue station as a result of the supplied fresh air of the emergency ventilation system. The temporal fluctuation of the air flow bases on the piston effect of the train movements in the tunnel.

CONCLUSION

The following conclusions can be drawn:

- Detailed measurements of substantial physical parameters such as air temperature, humidity, flow and pressure in each phase of the commissioning of the Lötschberg base tunnel were accomplished.
- These measurements served the verification of the design specifications, of the efficiency of the structural and technical measures as well as of the functionality of the tunnel ventilation.

- Considering the ventilation and tunnel aerodynamics the efficiency of the taken measures could be proven finally. Especially it can be assumed that the tunnel construction and the technical equipment can withstand the high pressure loads during the operation.
- The aerodynamics and thermodynamic specifications for the technical equipment in the Lötschberg base tunnel could be confirmed. Moreover these specifications are transferable to comparable tunnel projects like the Gotthard base tunnel, the base tunnel Lyon – Turin and the Brenner base tunnel.
- The efficiency of the tunnel ventilation for the normal, maintenance and emergency operation could be verified in realistic operation scenarios. It was confirmed that a careful tuning of the operational procedures and ventilation measures are of fundamental importance to assure operational safety.
- Particular comparisons of the of the tunnel climate, aerodynamics and ventilation simulations with the measured data show good agreements. Even though the evaluation of the measuring results is not finished yet.
- In general the measurements help to reduce the planning risks for further tunnel projects with regard to the tunnel ventilation, the tunnel climate and the tunnel aerodynamics.

UPGRADING TORONTO'S UNIVERSITY SUBWAY LINE VENTILATION SYSTEM

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INTRODUCTION

This paper presents the results of work undertaken as part of the Toronto Transit Commission's University Subway Line Fire Ventilation Upgrade Program. The design intent is to upgrade, to the greatest extent practical, the tunnel ventilation system to meet the current National Fire Protection Association (NFPA) 130 Standard for Fixed Guideway Transit and Passenger Rail Systems [1]. The existing tunnel ventilation system is not fire-rated and does not have the necessary capacity for maintaining a smoke-free egress route in the event of any fire larger than a nuisance fire.

The work has involved investigating the potential for both upgrading the existing fans and for installing new fans in existing blast relief shafts. During normal operating conditions the requirement for blast relief in order to alleviate the piston effect of trains is necessary. Hence the installation of fans in blast relief shafts would require that the fans are allowed to 'free wheel' when not in operation, allowing blast relief through the fans themselves.

The University Subway Line was simulated using the Subway Environment Simulation (SES) software [2]. SES was used to determine the required fan size for meeting the critical velocity requirement in the case of a fire in the running tunnels. Having established the fan size to meet the design criteria in the running tunnels, the SES software was then used to simulate station fires, so that boundary conditions could be set for CFD simulations of fires at stations. Hence, the work has also involved the development of three dimensional CFD models which predict air velocities, smoke distribution, temperature and related flow properties for the prescribed cases and boundary conditions. This enables an assessment of the performance of the fire ventilation upgrades during a fire incident inside the station and whether there is a tenable environment for safe egress within the time allowed for by NFPA 130 egress criteria. The standard requires a 4-minute duration for platform evacuation, a 6-minute duration for passengers to reach a point of safety and defined criteria for temperature exposure, visibility, and velocity along the egress paths.

Of the five stations modelled, results are presented for Museum Station; a natural ventilation simulation base case was performed to study the existing conditions, i.e. in the absence of mechanical ventilation. The results from the natural ventilation case are compared with two ventilation schemes, an all exhaust ventilation scheme and a push pull ventilation scheme.

TUNNEL & STATION CONFIGURATION

The University Subway Line entered revenue service on 28th February 1963, extending the Yonge Line from Union Station to St George Station and later linking to the Bloor Line at Bay Station and St George Station, and to the Spadina Line at St George Station. The connection to Bay Station is no longer used for revenue service.

These stations form part of the University Line. Figure 1 shows the section of the TTC subway system.

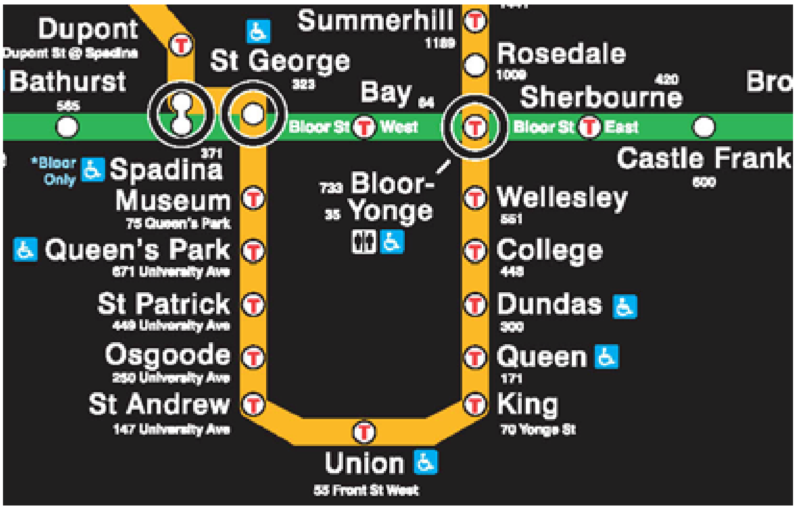

Figure 1: Section of TTC subway system

The University Line consists of five stations, each with 500-foot (152.4 m) platforms. From north to south they are:

- Museum
- Queen’s Park
- St Patrick
- Osgoode
- St Andrew

Each station has a shaft or shafts at each end. Figure 2 shows the general location of these. There are fan shafts at:

St George West
Museum South
Queen’s Park North
St Patrick North
Osgoode North
St Andrew South
West of Union (between Union and St Andrew)

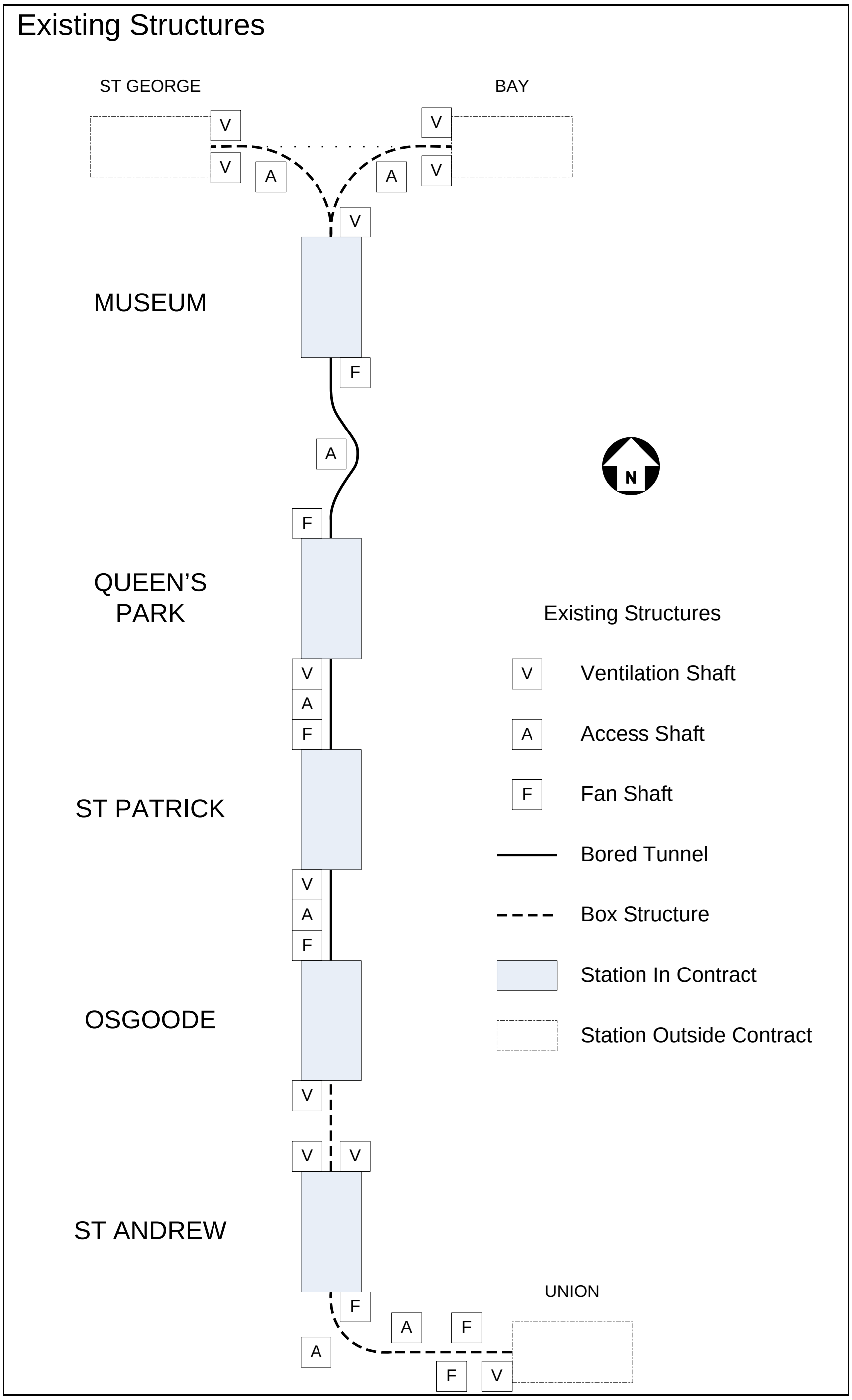

Figure 2: Existing Structures

There are blast relief shafts at:

St George East
Museum North
Queen's Park South
St Patrick South
Osgoode South
St Andrew North

There are also six inter-station access shafts. These are between:

St George and Museum
Museum and Queen's Park
Queen's Park and St Patrick
St Patrick and Osgoode
St Andrew and Union (Two in this section)

There is another access shaft between Bay and Museum. This section is not in revenue service.

The above stations are linked by 1180 m of box structure and 1294 m of bored tunnel. The bored tunnel section is lined with ribbed cast iron liner and runs between Osgoode Station and Museum Station. The rest of the line is box structure. Including the stations, the total length of the University Line between the west end of Union Station and the east end of St George Station is 3236 m. This excludes the section that is out of revenue service between Museum Station and Bay Station

The existing box structure has separating walls between the tracks, except at crossovers. The walls have regular openings of 3.25 m² (35 ft²; 5 ft wide by 7 ft high) at 6.1 m to 7.6 m intervals. There are three cross-overs to centre tracks. The Union centre storage track has crossovers immediately to the west (northbound side) of Union station and immediately to the south of St Andrew station. The centre track south of Osgoode has a crossover immediately to the south of Osgoode station (Osgoode three track crossover). Most of the section between Osgoode and Union is triple-track. The triple-track box section has varying width, being usually about 14.5 m wide in total. The vertical clearance is 3.96 m (13 ft).

There is also a double cross-over between Museum and St George, immediately to the east of St George.

There are three-track box tunnel segments between Osgoode and St Andrew and between St Andrew and Union. The centre tracks are separated from the running tunnels by walls with openings. The openings have an area of 3.25 m² and an interval of about 7 m. The annular area around a stationary train is less than the open area of two of the wall openings.

The centre track between Osgoode and St Andrew is only open for trains at the Osgoode end via a three track crossover (Osgoode three track cross over). The centre storage track between St Andrew and Union (Union storage track) is open to trains at both ends via three track crossovers.

The presence of the openings prevents effective longitudinal smoke control. If critical velocity is to be achieved over a burning train the openings would have to be closed, thus creating separate box segments.

The following alternatives were studied:

A. Leave the openings as they are. Do not attempt to create critical velocity over the incident train. Attempt to keep a tenable environment in the adjacent center track and running tunnel. For the section between Osgoode and St Andrew this could include enlarging the openings at the St Andrew end of the centre track.
B. Close all, or almost all, the openings between the centre track and both running tunnels. This could be done with sliding doors or by walling up the openings. Jet fans would be required if critical velocity was to be achieved.
C. Install fixed fire suppression in the running tunnels and crossovers. This would not require jet fans.

Alternative A was simulated using a local model with greater detail than the line-wide model used for the rest of the simulations. These simulations showed that critical velocity could not be achieved anywhere along the length of a burning train: the whole length of the train could become engulfed in smoke as smoke would spread both ways from the fire. The only tenable environment in the incident track would be at least 30 m upstream of the train. The adjacent tracks would be subject to some smoke contamination, but the opposite running tunnel could remain tenable. Passengers would have to know that it was the route to safety, and be able to get there.

The installation of jet fans with Alternative A would not achieve guaranteed longitudinal smoke control because they could not prevent mixing between the tracks and could not guarantee that critical velocity is met at the fire site.

DESIGN CRITERIA

The fundamental design criterion for the fire ventilation system in the running tunnels is compliance with the relevant parts of the current version of NFPA 130. In terms of the tunnel ventilation system, emergency operations in running tunnels have been modelled based upon a fire scenario on board a transit vehicle. The analyses focused on determining the ventilation required to maintain a single evacuation path from the train clear of smoke and hot gases. Maintaining such a path during a fire emergency enhances passenger safety.

The TVF equipment will be used to produce an air flow rate in the incident ventilation section such that the velocity is sufficient to prevent back layering of smoke. This is often referred to as the critical velocity. NFPA 130 defines the critical velocity as "the minimum steady-state velocity of the ventilation airflow moving toward the fire within a tunnel or passageway that is required to prevent backlayering at the fire site." Back layering is defined as "The reversal of movement of smoke and hot gases counter to the direction of the ventilation airflow."

The critical velocity calculated for each tunnel cross-section and gradient was increased by 10%, and then multiplied by the tunnel train annular cross-sectional area to produce the minimum air volume flow criterion. This air volume flow was used as the basic acceptability criterion for fire ventilation.

In addition to the requirements of NFPA 130, the prevention of smoke spread to adjacent ventilation sections was also a design goal. For example in the event of a train fire in a tunnel, smoke being drawn towards a station should not flow past the extract shaft at the end of the station into the station itself.

For trains on fire at stations and in tunnels, the design must comply with emergency ventilation requirements in enclosed stations and tunnels as per Chapter 7 of NFPA 130. In accordance with Section 7.2, the emergency ventilation in is required to provide a tenable environment along the path of egress from a fire incident and be capable of reaching full operational mode within 180 seconds.

In accordance with Paragraph 5.5.3.2 of NFPA 130, stations are required to be designed to permit the evacuation from the most remote point on the platform to a point of safety in 6 minutes or less. Therefore, in order to allow safe evacuation of the station modelling has been carried out with the ventilation system operated in "push-pull" mode, whereby smoke ventilation fans are operated in supply and exhaust modes at opposite ends of the stations, and in "pull-pull" mode, whereby all fans are operated in exhaust mode. This is done in order to draw fresh air through the station concourse and passenger exits. CFD analysis was carried out to show the most effective of the alternative ventilation strategies.

FAN SIZING METHODOLOGY

The initial series of fire simulations was carried out without regard for the space requirements of the fans; therefore the fan capacity was unlimited. The sole criterion was to achieve NFPA 130 compliance in terms of smoke ventilation. The ideal fan capacity indicated by the successful simulations was then used to select potential fan units. This enabled an assessment of the practicality of the installation of fan plant of sufficient capacity in the available existing space, or in possible future available space. If fans rated at the ideal capacity for NFPA 130 compliance had proved too large for the available space, further simulations would need to be carried out to assess the benefit of the largest fans that could be accommodated.

SES MODEL

To develop the optimum solution, bearing in mind that NFPA 130 compliance might not be possible in all locations, the following sequence was planned:

1) Test runs with base model
2) Fire runs for NFPA 130 compliance, with no limit on fan size.
3) Fire runs with ‘realistic’ fan selections and system modifications, including runs to establish CFD boundary conditions.
4) Environmental runs to assess effect of system modifications, with and without congestion.
5) Cold flow runs for commissioning purposes, once the system design is finalised.

INTERFACE WITH STATION CFD MODELS

In addition to the simulations carried out for fires in the running tunnels, simulations of train fires in stations were also carried out. The SES software is a one dimensional simulation method and due to inherent limitations it is not recommended for the detailed study of station fires. This is primarily because it is not possible to model the flow of smoke as a stratified layer. The SES software can only model smoke movement as a homogenous mixture across the entire cross section. A three-dimensional computational model is more appropriate for simulating the flow of smoke along and across a station platform, up stairs and through a concourse. It would be impractical to include enough of the subway system in a CFD model so that the model itself would be able to be used to simulate the flows in or out of a station during fan operation. An SES model is more suitable for the simulation of the bulk air flows in a system, so an SES simulation can be carried out to determine the boundary condition for the CFD model.

Mass flow rates, in or out of the station headwalls, were used for the boundary conditions at University Line, i.e. at the interface between the running tunnel and the station. Where there was an active fan within the bounds of the CFD model, for example at Museum Station, this was also modelled as a mass flow boundary.

As a check between the SES model and the CFD model, both the SES and CFD models were run for cold flow conditions, and the air flows and calculated pressure drops from each set of results were compared. The SES model was then adjusted and predictions checked so that they were in agreement with the CFD model predictions. The SES station fire simulations were then re-run to provide the final boundary conditions for the CFD simulations.

The SES model was adjusted to match the CFD model because it is considered that the CFD model of the stairways, concourse and entrances, predicts losses more accurately than the conventional method of summing individual component losses from standard references.

Simulations were carried out for all-exhaust ("pull-pull") and for longitudinal ("push-pull") ventilation modes, with the longitudinal mode being tested in both possible directions. CFD simulations were then carried out for the two modes. The boundary conditions established for MuseumStation are given in Tables1and 2.

Table 1: Museum Station Mass Flow Rates – Push-Pull

Museum Station Interface	Mass Flow Rate (kg/s)
North Vent Shaft	-120.0
NW Tunnel	50.4
NE Tunnel	59.3
SE Tunnel	-23.8
SW Tunnel	-24.0

Table 2: Museum Station Mass flow Rates – Pull-Pull

Museum Station Interface	Mass Flow Rate (kg/s)
North Vent Shaft	120.0
NW Tunnel	-51.5
NE Tunnel	5.1
SE Tunnel	-41.3
SW Tunnel	-40.8

PLATFORM LEVEL

Museum Station is split into two levels, a platform and concourse level. A northbound track and a southbound track run on either side of the centre platform. The length of the platform from north headwall to south headwall is 152.4 m (500 ft). The platform has a 0.3 percent slope, where the north end is higher than the south end of the platform. Figure 3 shows a schematic plan view of the platform level where the columns are clearly marked.

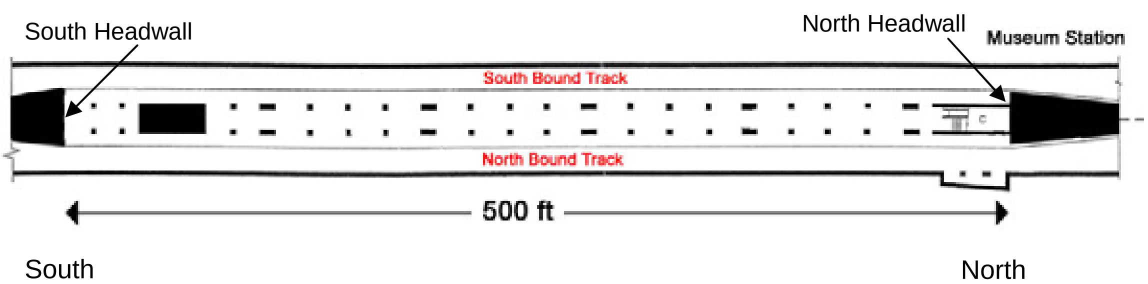

Figure 3: Plan view of platform level

Figure 4 shows a typical cross section through the platform level of the station. The platform width is 6.30 m (29 ft 8 in). The distance between the two centre lines of track is 12.30 m (40 ft 4 in).

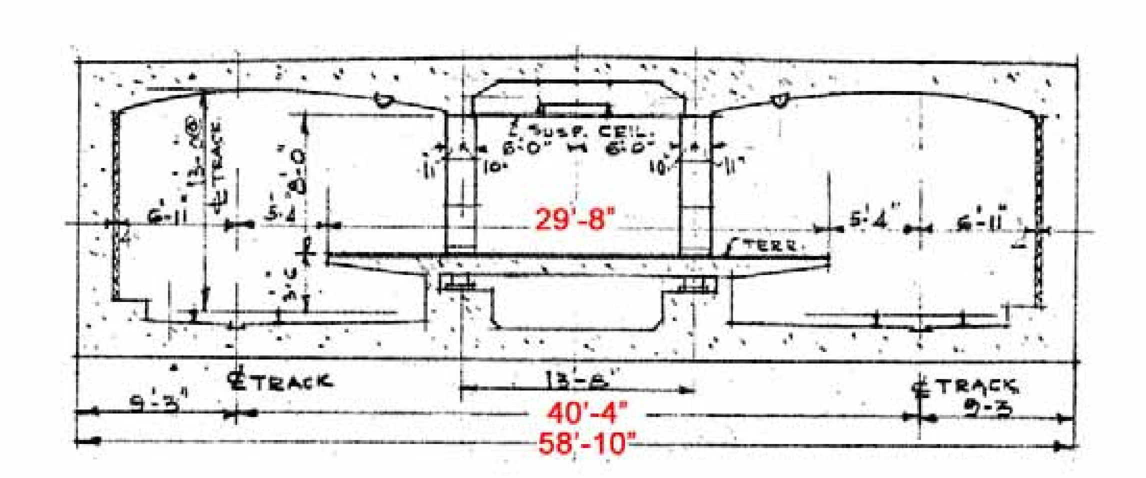

Figure 4: Cross section of station platform

Figure 5 shows a plan view of the concourse level. There are three connections, one to the platform level and two connections to grade. The two concourse level connections lead to grade via an east and west passageway. The passageways contain two sets of staircases, where the staircase doors are open during revenue service. There is a collector's booth in the centre of the concourse level. Figure 6 shows the incident train location for the runs presented in this paper

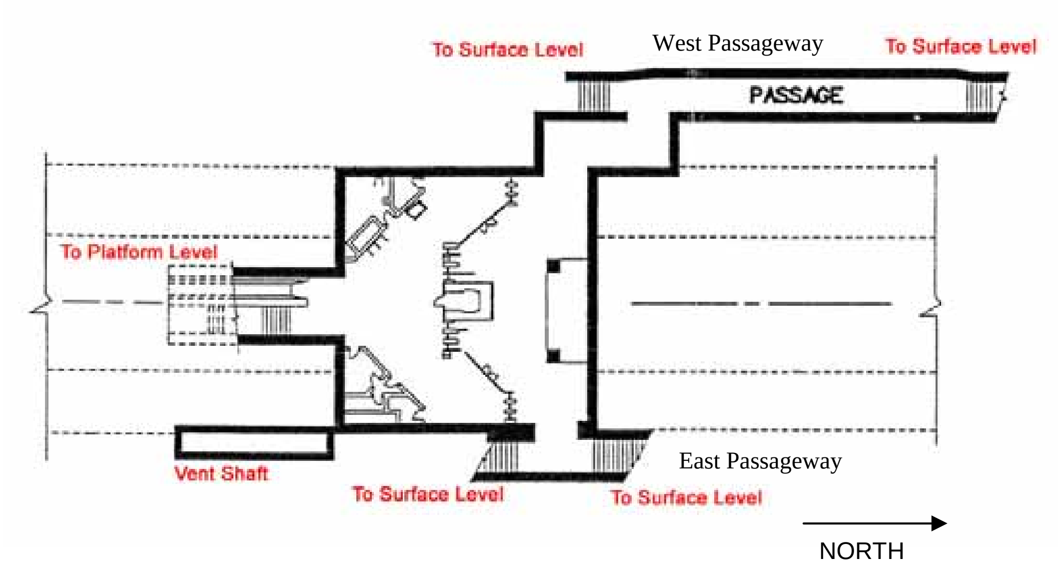

Figure 5: Plan view of concourse level

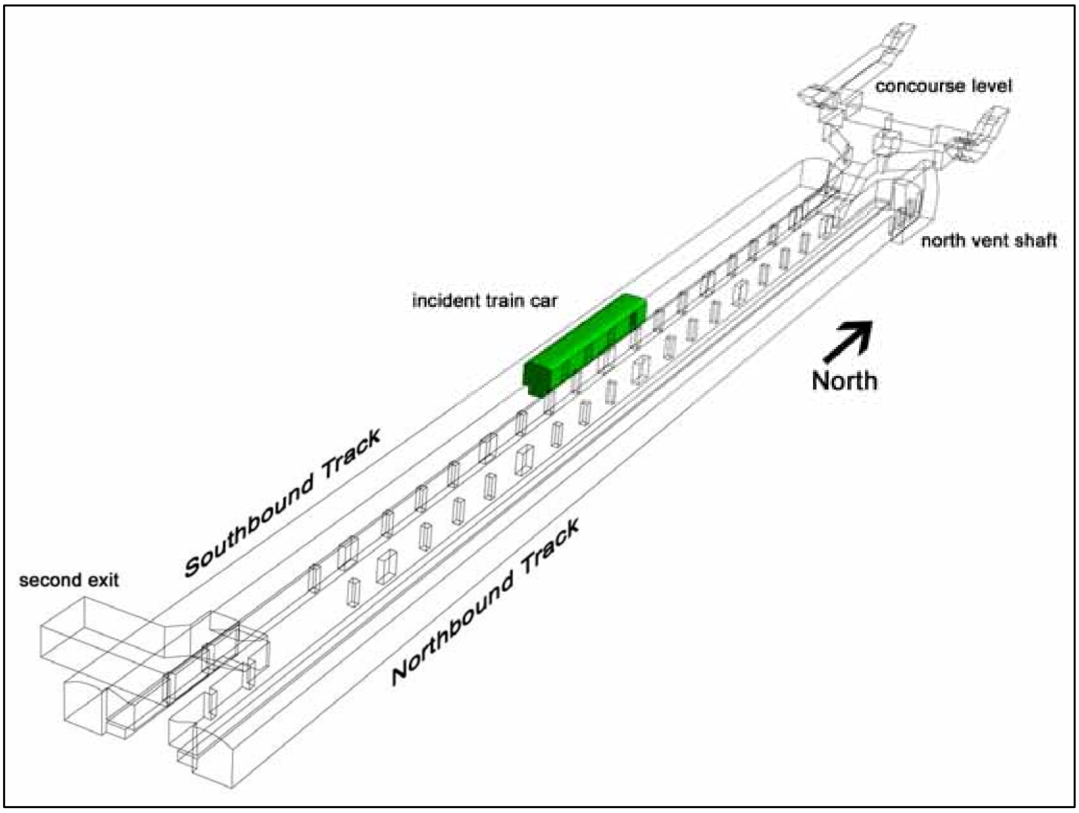

Figure 6: Incident Train Location

Figures 7 to 9 show typical visibility plots determined from the CFD simulations for the different ventilation modes.

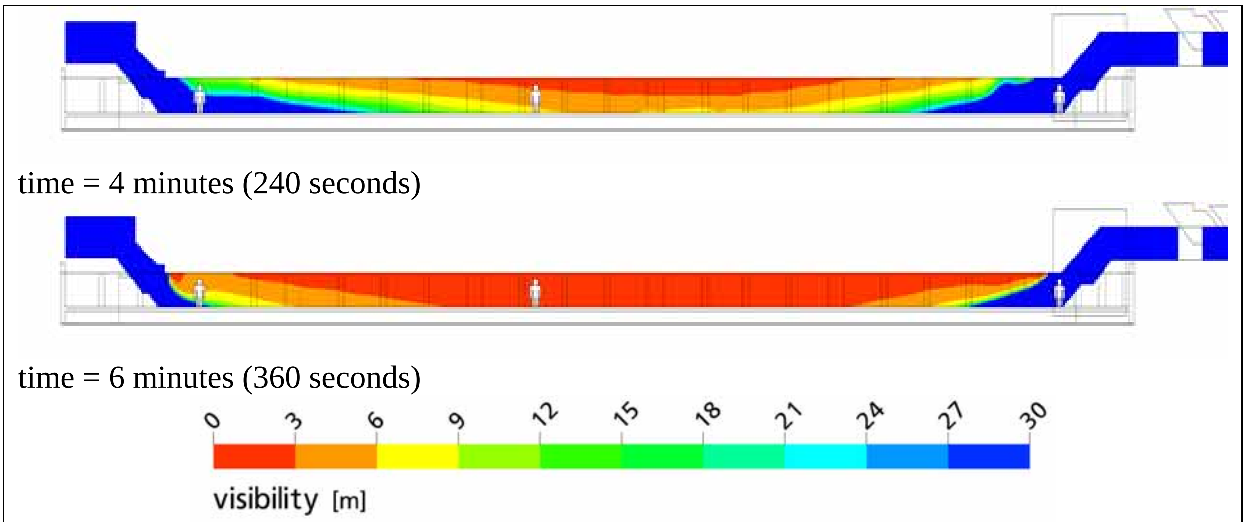

Figure 7: Visibility plots, centre of station, natural ventilation

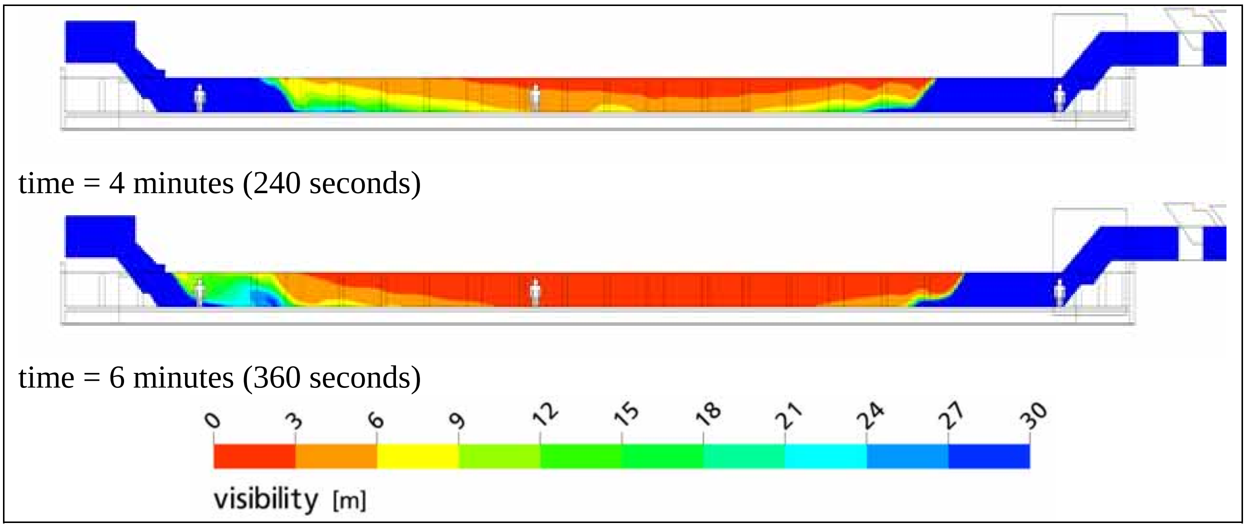

Figure 8: Visibility plots, centre of station, all-exhaust ventilation

`Visibility plots, centre of station, all-exhaust ventilation`

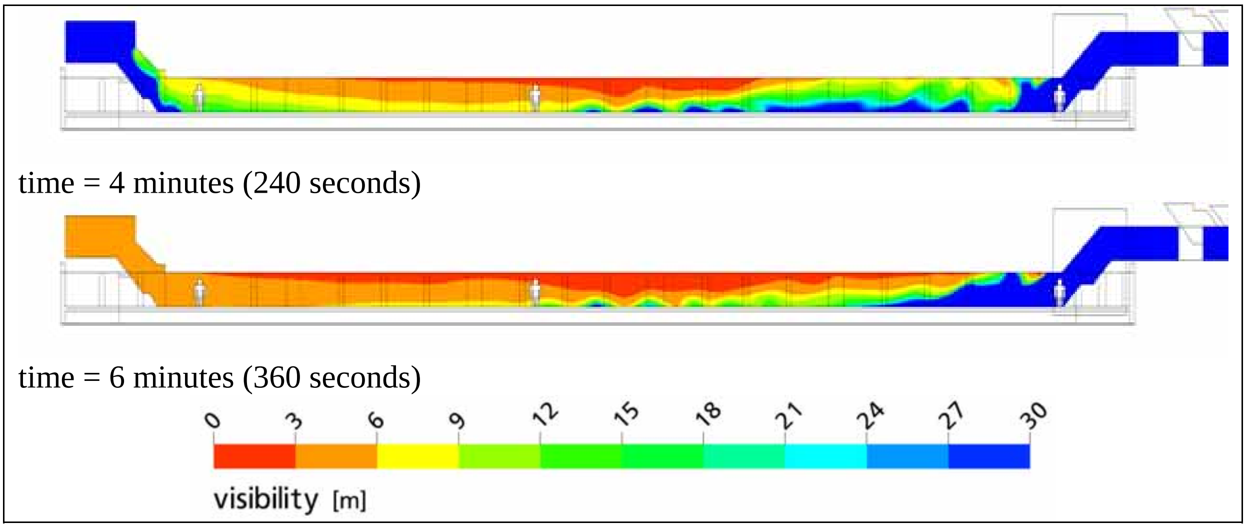

Figure 9: Visibility plots, centre of station, push pull ventilation

The analyses of the simulations determined that existing conditions and egress routes are improved when subway ventilation fans are operated. The most effective operating mode for controlling a centrally located fire incident at Museum Station would be to employ an all exhaust ventilation scheme.

CONCLUSIONS

A model has been developed to investigate effects of the subway ventilation schemes on a fire scenario at Museum Station. The fire scenario involved a fire incident located at the centre of a train on the southbound track. Simulations were performed to study the use of all exhaust and push pull ventilation schemes. A natural ventilation simulation with no mechanical ventilation was used to compare against the two ventilation schemes to understand the level of improvements which would be expected from the use of mechanical ventilation.

The critical locations of this model are platform level staircase interfaces, if the proposed ventilation scheme is capable of providing a smoke free environment then under NFPA 130 criteria, the staircase would be deemed a location of safety. Comparing Figures 8 and 9 clearly demonstrates that the all exhaust ventilation scheme induces greater mass flow through both staircases, keeping them clear of smoke, than the push pull ventilation scheme. This air movement helps prevent air/smoke from moving into the exit stairwells. The push pull ventilation scheme produced results which demonstrated that the second exit would become untenable after 5 minutes.

The results of the simulations show that an all exhaust ventilation scheme would be the best solution at Museum Station.

References

1) TTC Fire Ventilation Upgrade Project Technical Criteria Report, Third Draft, 18 August 2005
2) Subway Environment Simulation Computer Program, Version 4, User Manual, December 1997

NUMERICAL STUDIES ON DISPLACEMENT OF FIRE SMOKE IN A ROAD TUNNEL WITH A T-JUNCTION

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ABSTRACT

When a fire occurs in a road tunnel, one of the main risks for the people is the presence of fire smoke because of its toxicity, opacity and high temperature. Therefore, in order to ensure the safety of people inside tunnels, it is important to understand the effects of the various geometric and physical parameters on the flow of fire smoke. Herein we present a numerical study of the flow of fire-smoke in a particular geometric configuration, a junction connecting a lateral and a main tunnel branch. This type of junction is most often referred to as a T-junction and is of particular interest because it is very frequently encountered in city road tunnels.

Keywords: road tunnel, ventilation, smoke flow, fire simulation, T-junction, tunnel safety

1. INTRODUCTION

In the event of a fire in a road tunnel, two modes of ventilation are employed. The first one, the emergency ventilation, is used for as long as people are in the tunnel. Later, the second mode, the smoke evacuation ventilation, is turned on. The purpose of the emergency ventilation is to maintain as soon as possible a smoke-free area to allow rescue teams to act easily and to allow people to evacuate the tunnel safely. During the employment of the second mode, the fire smoke is pushed out to rehabilitate the tunnel while limiting the structure damages.

The present study concerns the emergency ventilation. During this phase, it is very important to keep the air breathable, with limited temperature, and as transparent as possible. Generally, during the first minutes of a fire in a tunnel the smoke is stratified due to buoyancy. However physical parameters such as tunnel geometry, natural ventilation and others can disturb and even prohibit stratification. For example, (Choi J. S. et al. 2005) shows the effect of transverse ventilation on the smoke propagation. Herein we investigate numerically the stratification of the flow of smoke during the early stages of a fire caused by a passenger car in the vicinity of a junction between the principal tunnel branch and a secondary lateral branch. This particular configuration is named T-junction according to, (Bassett M.D. et al 2001). Often the lateral branch is an on/off-ramp and thus is less wide than the principal branch. Three-dimensional simulations are obtained with the commercial CFD software FLUENT. Both temperature and velocity fields are computed. This analysis is aimed to provide useful information in the planning of escape procedures.

This paper is structured as follows. The section 2 describes the numerical model. Next, the section 3 presents the results and the discussion of the simulations without ventilation. Finally, the section 4 explains the study of the influence of the width of the lateral branch.

2. SIMULATION DATA

This section is divided in two parts. The first one introduces the geometry of the computational domain and the second the numerical model itself.

2.1. The geometry of the computational domain

2.1.1. Tunnel modelling

In this study, the tunnel is characterized by the connection of three branches as illustrated on figure 1. Each of them has a length of 100 m. The lateral branch is connected to the principal tunnel at an angle of 30°. The cross section is assumed to be a rectangle of 7 m x 5 m, unless otherwise noticed. The name of each branch is given in italic on figure 1.

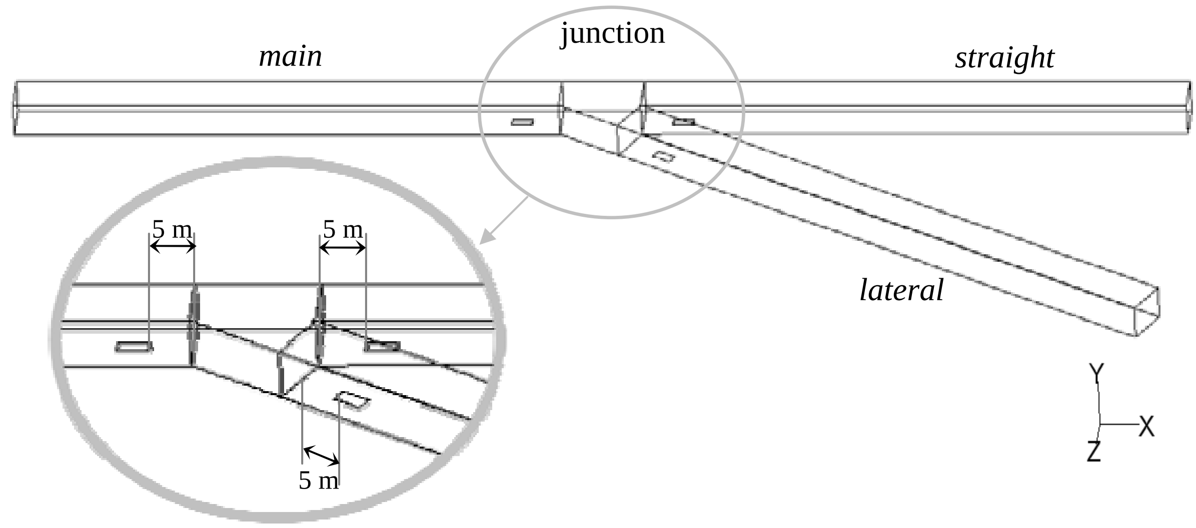


Figure 1: The geometry of the tunnel

2.1.2. Fire modelling

We suppose that the vehicle on fire is a passenger car of dimensions, 3.5 m x 1.6 m x 1.5 m. The fire source is placed at the middle axis in one of the branches according to the considered case. It is located at 5 m from the junction as indicated by a little rectangle on the tunnel floor of figure 1. Further, it is modelled by a heat release rate varying with the time following a quadratic law which is a generally accepted approximation for the early-stage evolution of the phenomenon. We also note that in this study we examine the early stages of the fire and, more specifically, the results of a burning time of 5 minutes. This corresponds, approximately, to a maximum value of heat release rate of 5 MW. Moreover, we do not take into account the chemical kinetics of the combustion process; instead, we assume that the smoke concentration is analogous to that of the temperature. It has been shown by (Yang G-S. et al. 2006) and (Bounagui A. et al. 2004) that this is a valid assumption in many cases of fires in tunnels.

2.2. Numerical model

3D CFD simulations are produced with the commercial software packaging FLUENT. The Reynolds-averages Navier Stokes equations are solved using a finite volume discretization and the turbulence is simulated by a k-ε model. The heat radiation is assumed to be emitted by a grey body and is introduced in the model by the radiative transfer equation solved for a finite number of discrete solid angles. The air in the tunnel is assumed to be an ideal gas. Its thermal conductivity, viscosity and constant-pressure specific heat, evolve with the temperature following a polynomial function. The simulations are made with a non-uniform grid using the grid generator GAMBIT. The mesh is composed of 347582 quadrilateral cells, denser in the regions of the junction and the exits.

Initially, in the tunnel, the air temperature is set at 15°C and the air has zero speed. At the exits of the domain, the variation of the pressure in the direction normal to the exit boundary is assumed to be zero. The temperature at the exterior surface of the walls is also set at 15°C. The tunnel walls are considered to have a thickness of two meters, with a roughness value of 0.005 m. They are supposed to be homogeneous in material and structure. Further, for the purpose of heat transfer calculations, the wall is assumed to be made of concrete.

3. FIELD ANALYSIS OF NUMERICAL SIMULATION

It is important to keep an area with fresh-air in the tunnel in order to help people to escape safely. That is why this study focuses on the first stage of the fire while the stratification exists. This section examines the temperature and the speed distribution of the flow resulted of numerical simulations. Three cases are considered according to the location of the fire in one branch of the junction.

3.1. The temperature distribution in the air

The smoke goes on both sides of the fire and at the junction the flux is again divided in two. Consequently, there is more smoke in the "fire branch" than in the others and the temperature is higher as depicted by the figure 2. In addition, in this fire branch, the height of "fresh air" decreases strongly with the distance from the fire and in the other branches the stratification is relatively well conserved.

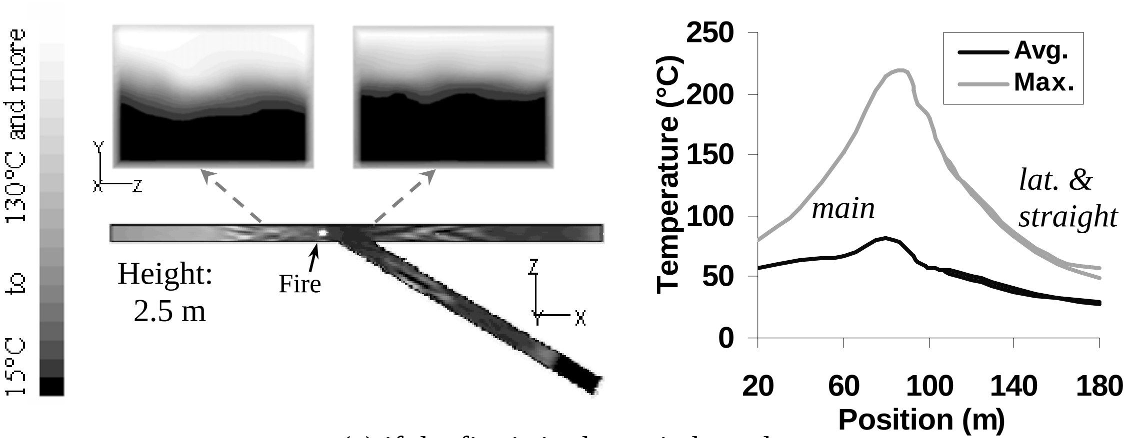
3.1.1. If the fire is in the main branch

The flow is not disturbed a lot at the junction and progresses nearly similarly in the two branches of the fork as illustrated on figure 2 (a.2). The division of the tunnel in two branches constitutes only an advantage by increasing the volume in which the hotter layer progresses. In the branches of the forks the temperature is lesser than in the main branch and the thickness of the hotter layer stays thinner on a more important length, see figure 2 (a.1).

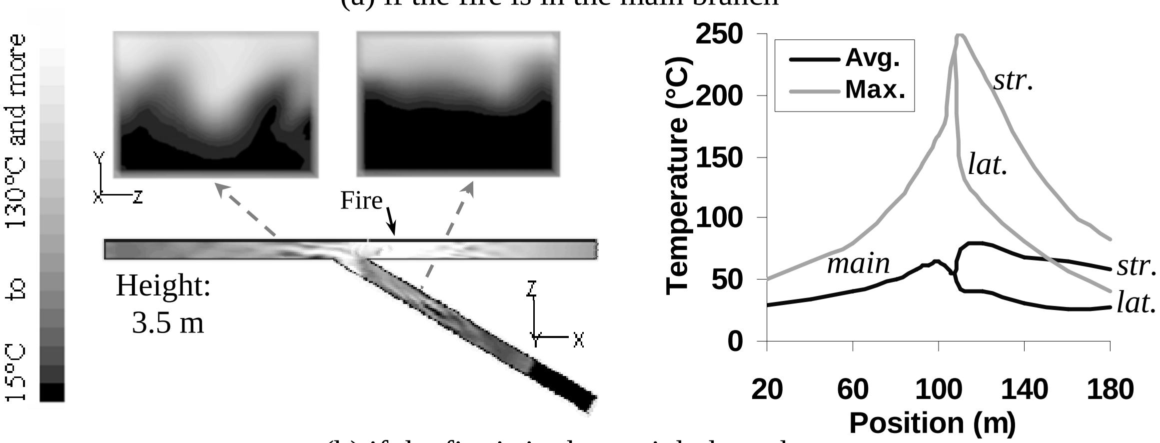
3.1.2. If the fire is in one branch of the fork

On figure 2 (b.2 and c.2), the temperature field is roughly the same if the fire is in the one or in the other branch of the fork. In the junction, the change of flow direction induces a perturbation of the stratification that is restored in each branch. Figure 2 (a.1 and c.1) puts in evidence that, in the branch of the fork that is not in fire, the temperature, the thickness of the hotter layers and the length on which the hot flow progresses, are lesser than in the main branch. That can be explained by the trajectory of the flow imposed by the walls (see section 3.2 The velocity distribution in the air).

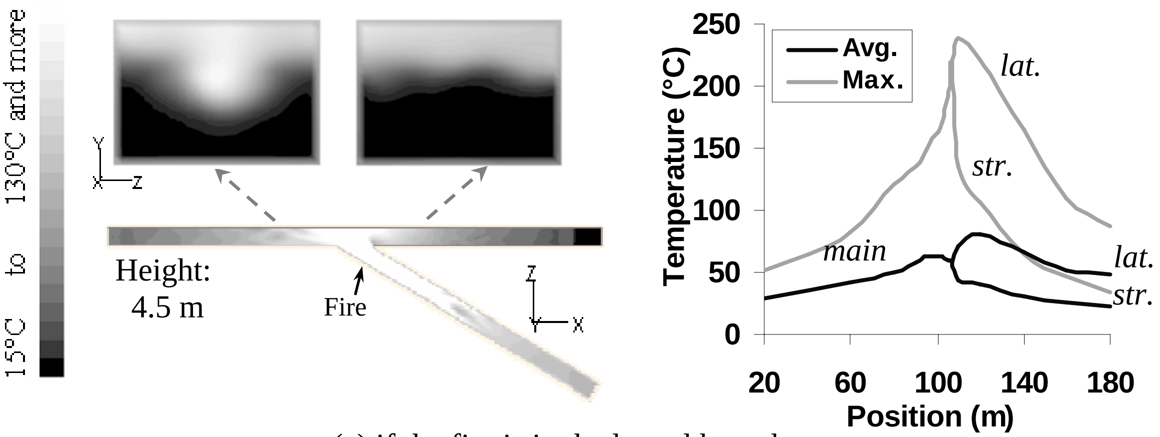
Usually, the smoke layer is roughly homogeneous on the width of the section except near the lateral walls where the layer is a bit thicker and more diluted. However, the smoke layer is perturbed by the junction on some meters; either it is higher in the centre of the section as observed on figure 2 (c.1) or it has a wavy lateral repartition as on figure 2 (b.1).



(a) if the fire is in the main branch



(b) if the fire is in the straight branch



(c) if the fire is in the lateral branch

Figure 2: The temperature in the air: 1) the field, 2) the maximum and the average values along the tunnel

3.2. The velocity distribution in the air

In the absence of natural or mechanically induced ventilation, air flow can be generated by natural convection only. Consequently, the displacement of the air is more important near the fire and near the ceiling of the tunnel. The average value is around 0.5 m/s in the branches, it can reach 1.5 m/s locally in the junction and up to 7 m/s near the fire.

Natural convection creates a circulation between the lower layers, going from outside in direction of the fire, and the hotter flow near the ceiling, going in direction of the exits. Moreover, there are some "recirculation" zones resulting from the geometry of the junction and from the change of the flow direction. As the direction of the flux varies with the height in the tunnel, these "recirculation" zones can be situated in different locations according to the layer considered.

For example, if the fire is located in the lateral branch, there are three recirculation zones as illustrated on figure 3. The first one in the centre of the junction (A) is due to the change of the flows direction. The second (B), in the lower layers, and the third (C), in the upper layers, depending on the flow direction, result from the deviation of the flow by the central wall of the junction.

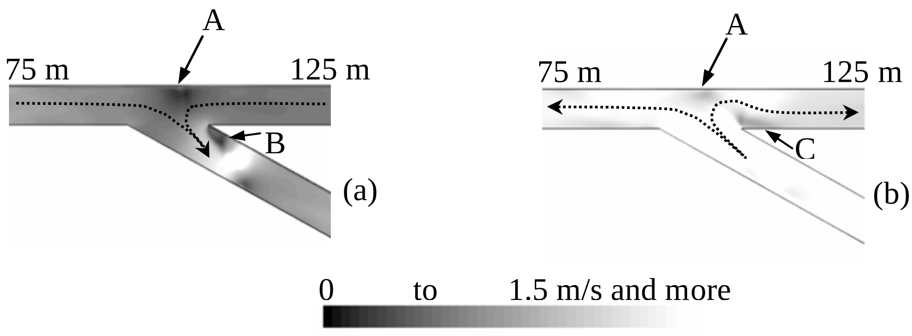


Figure 3: The velocity field in the air, when the fire is in the lateral branch

(a) for a lower layer, height = 1.5 m (b) for a upper layer, height = 4.5 m

3.3. Conclusion

If the fire occurs in the main branch, the junction emerges more as an advantage than as a disadvantage. The increase of volume constitutes the only phenomenon to take into account for determining the ventilation in this zone.

People must be encouraged to escape by the branch making the smallest angle with the fire branch because the geometry of the junction restricts the hot flow in this branch. For example, considering that the "fresh" air has a temperature inferior to 40°C, if the fire occurs in the lateral branch, the height of "fresh" air is still of 3 m at 20 m from the fire. However, if for some reasons, the people have to leave the tunnel by the other branch that is not in fire, it is better that they move on the side rather than on the middle of the section.

4. INFLUENCE OF THE WIDTH OF THE LATERAL BRANCH

The lateral branch of a T-junction is often an on/off-ramp with one lane and so one direction of traffic only. Therefore it is quite often less wide than the principal branch. In this section, the influence of the width of the lateral branch on the temperature and on the velocity distribution is studied for a tunnel without any ventilation.

Two widths of the lateral branch are considered: 5 m and 7 m. As the width of the lateral branch conditioned the length of the junction, this length is respectively of 10 m and 14 m as shown on figure 4. The same conditions and assumptions of simulation are used for the two configurations (cf. section 2). The only difference is the number of meshes: 298809 cells for the case of the width of 5 m.

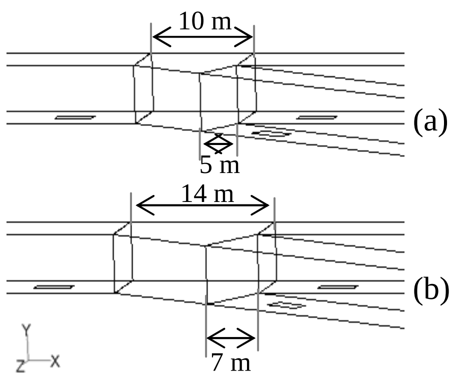


Figure 4: The junction zone of the tunnel, for the width of the lateral branch of (a) 5 m, (b) 7 m

4.1. The temperature distribution in the air

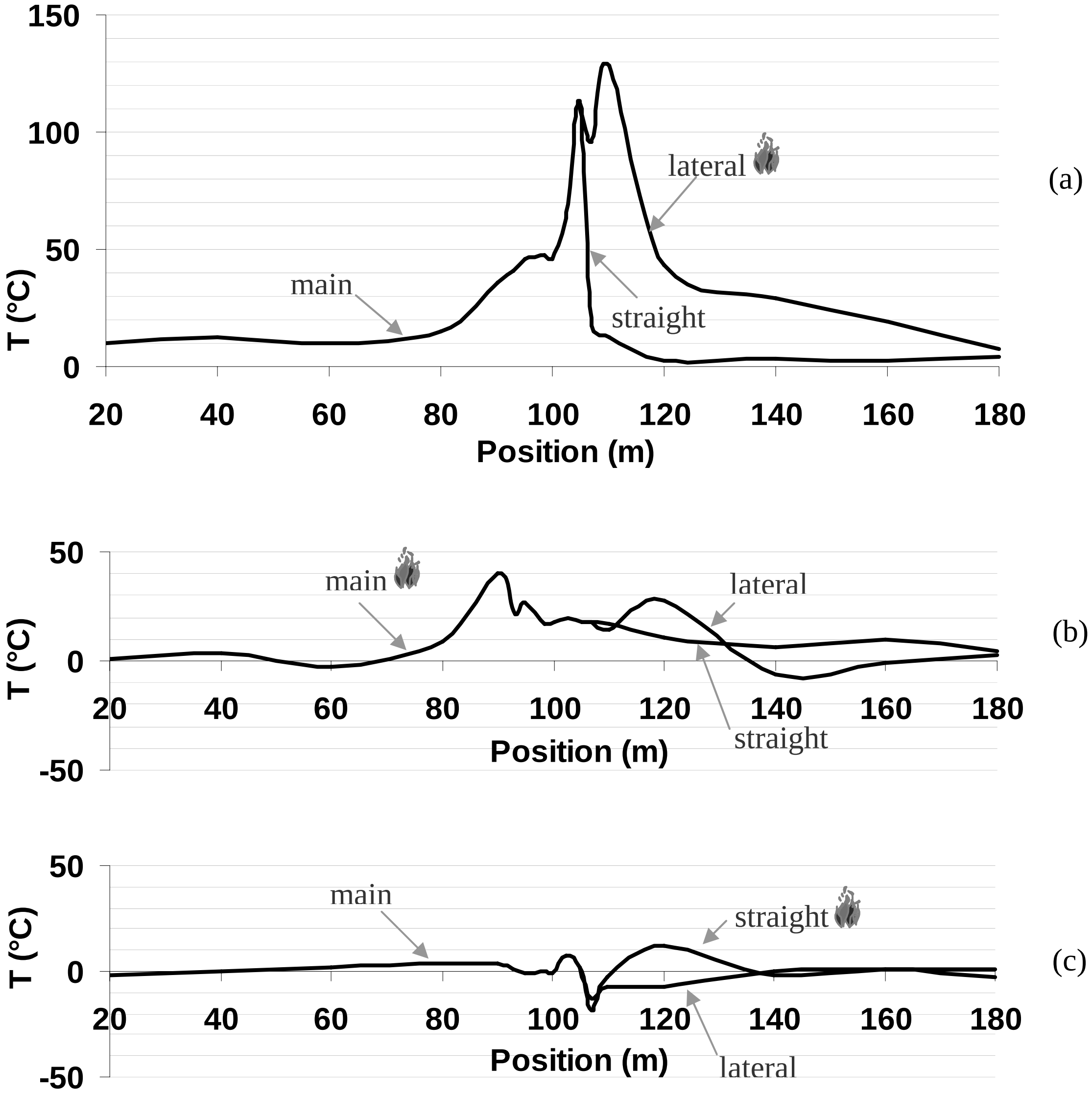


Figure 5: T_{max} (width of the lateral branch = 5 m) - T_{max} (width of the lateral branch = 7 m), when the fire is located
(a) in the lateral branch, (b) in the main branch, (c) in the straight branch

On figure 5, the temperature is influenced by the width of the lateral branch on approximately 20 m on either side from the junction centre and in the fire zone. However if the fire is situated in the straight branch, the influence seems not significant.

If the fire occurs in the lateral branch the maximum temperature decreases obviously with the width of the lateral branch and consequently the stratification is preserve on a more important length. However if the fire is located in one of the other branches, the influence in the lateral branch is not more important than these in the other branches.

4.2. The velocity distribution in the air

As in the case of the temperature distribution, figure 6 shows that the influence of the width of the lateral branch is particularly important in the vicinity of the junction and in the fire zone. Further, if the fire is situated in the lateral branch, it affects the smoke flow all along this branch.

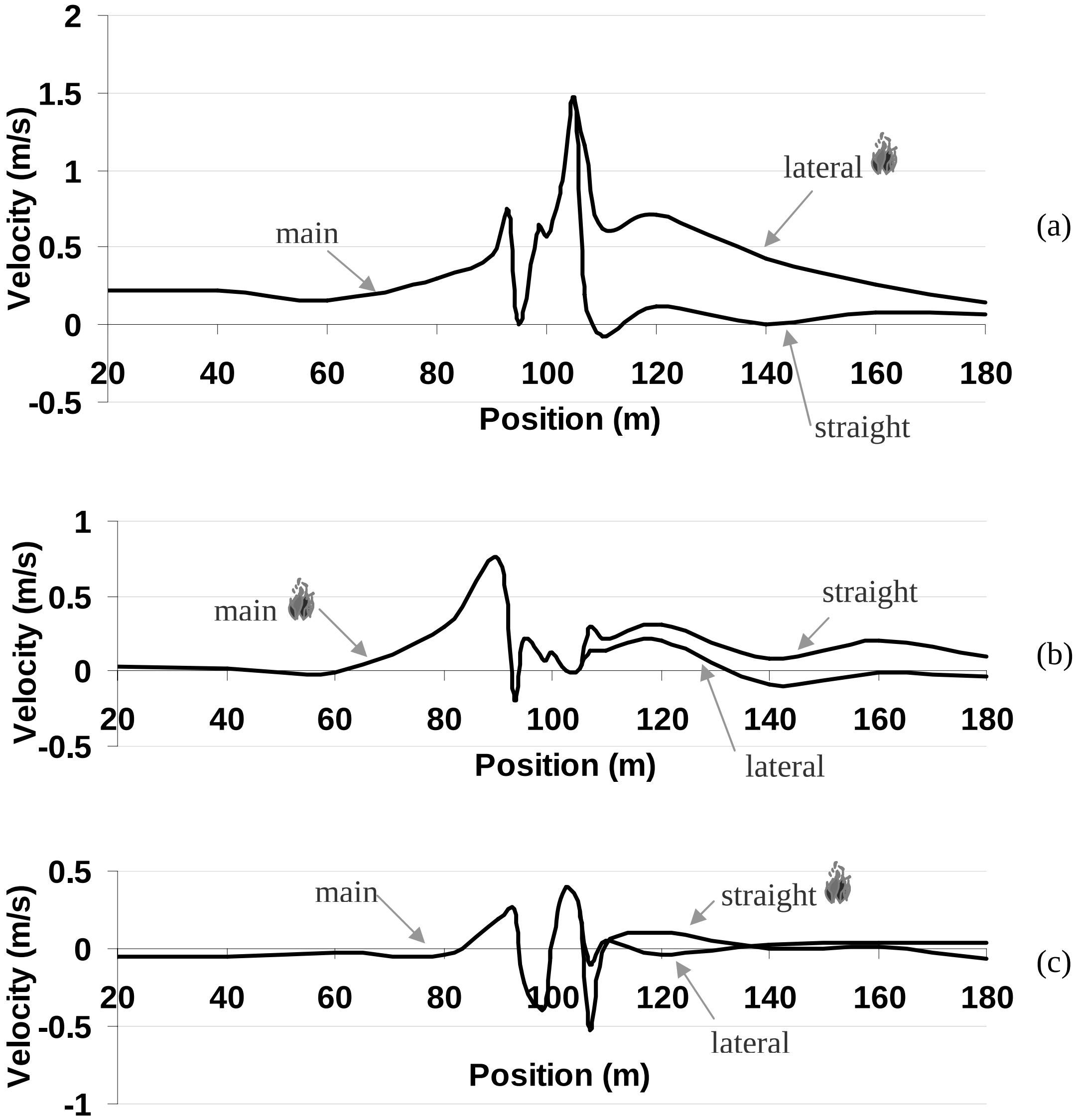


Figure 6: T_{max} (width of the lateral branch = 5 m) - T_{max} (width of the lateral branch = 7 m), when the fire is located
(a) in the lateral branch, (b) in the main branch, (c) in the straight branch

4.3. Conclusion

If the fire is located in the lateral branch, the influence is lesser in the straight branch because the sharp angle between this branch and the lateral branch limits the "smokes" progression. Moreover, it is obviously that the width of the lateral branch has an influence on the temperature and velocity field in this branch itself due to the increase in volume. The same phenomenon, the influence of the tunnel width, has been observed by (Lee S. R. et al. 2006).

In the junction, the temperature and the velocity are higher if the lateral branch is less wide because the length and the width of the junction are as well reduced. These effects are visible on a zone a little longer than the junction because of the heat transfers from the hotter junction. However, if the fire is in the straight branch, as the sharp angle of the fork reduces strongly the progress of the “smokes” in the lateral branch, it is not surprising that the narrow of the lateral branch has a very few impact in this case.

5. CONCLUSION

In the first part of this paper, we study the evolution of the temperature and the velocity fields in a tunnel comporting a junction between three branches. Three configurations are studied, each one depending on the location of the fire.

Our simulations predict that if the fire is in the main branch, the junction does not disturb a lot the flow and the behaviour is roughly the same in the two branches of the fork. In this case, the junction can be regarded as an advantage and considered like a widening for the choice of the ventilation mode.

If the fire is in one branch of the fork, the smoke flow is characterized by the presence of recirculation zones at different locations depending on the layer considered and the increase of the flow speed in the junction. It can be interesting to keep these recirculation zones and in addition the limitation of the progression of the flow in the fork branch not in fire. In this way, people can escape by the branch making the sharpest angle with the fire branch. However it is important to take into account the lateral disturbance of the smoke layer.

Finally, this paper studies the influence of the width of the lateral branch on the temperature and on the velocity in the junction according to the location of the fire. It emerges that the narrowing of the lateral branch has just the same effect than the reduction of the section in several parts of the tunnel: firstly in the junction with the surrounding effects and secondly in the lateral branch itself if there is it a fire. However, these considerations cannot take into account if the fire is in the straight branch because the results show that the influence is not significant in this case.

6. AKNOWLEDGEMENTS

We would like to thank Jacques E., from the Université catholique de Louvain in Belgium, for all his fruitful advices. This work is funded by the Transportation & Equipment Department of « La Région de Bruxelles-Capitale » and Sofico (Société wallonne de financement complémentaire des infrastructures).

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SMOKE STRATIFICATION STABILITY: PRESENTATION OF EXPERIMENTS

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ABSTRACT

EGSISTES is a project, partly founded by the French National Agency for Research (ANR). It is dedicated to the representation of the effects of dangerous phenomena such as fire, explosion or gas dispersion in underground transport systems. The development of physical models to quantify those effects requires experiments. In the particular case of fire, our attention will be care on smoke stratification stability. This publication is a presentation of the objectives and the experimental facilities retained to evaluate this stability and to analyse the influence of disturbances on it. As described in this paper, experiments are achieved on the one third scale INERIS fire gallery to respect criteria involved in physical process. This paper describes the objectives of the experimental campaign and gives the preliminary experimental plan.

Keywords: smoke stratification, experimental campaign

1. INTRODUCTION

The smoke stratification is the basic phenomena in several types of tunnel ventilation system. For memory, this is the case for semi-transversal and transversal ventilation system, even if the longitudinal flow is controlled or not. This concept of stratification has been extended to longitudinally ventilated tunnel in case of possible presence of blocked vehicles at each side of the fire.

Consequently, this phenomenon has been studied in terms of:

- favourable conditions to obtained the smoke stratification;
- stability as a function of various longitudinal flow rate.

However, only few works have been done considering the capacity to maintain this phenomenon in complex perturbed media such as real conditions of a fire ventilation mode in tunnel.

The aim of the experimental campaign briefly described in the current paper is to characterise the stratification stability in case of thermal or mechanical disturbances.

The current paper firstly presents the campaign framework and aims, and secondly the experimental device and a preliminary plan.

2. OBJECTIVES OF THE EXPERIMENTAL CAMPAIGN

2.1. Notion of stratification

The word “stratification” is often associated to several definitions depending on the studied field.

The **thermal stratification** is often considered as the main phenomenon. It is due the buoyancy effect produce by the heat released of the fire. This is mainly depending on the fire heat production and the various heat exchanges with the medium. This is the main driving phenomenon in case of fires smoke stratification.

The **chemical stratification** is firstly due to the transport phenomenon of combustion products. This aspect gives a large similarity with the driving phenomenon (buoyancy). However, the physical properties of the various chemical species imply a lost of stratification process due to chemical diffusion and sedimentation, also a possible re-enforcement of the stratification in case of light chemical species. This notion is particularly important for tunnel safety characterisation and more especially far from the fire where the thermal stratification can be considered as weak.

The **opacity stratification**, is associated to dust and soot propagation which are mainly responsible for the smoke optical density. The derived notion of visibility is a key element to characterise self-evacuation conditions. In terms of physical phenomena, the optical density mainly depends of the nature and the quantity of soot produced by the fire. It behaviour is somehow different from the heavy gas dispersion due to the nature of soot which is closer to particles than to a gas.

These three approaches of smoke stratification give an idea of the necessity to specify which type of stratification is suited for which purpose.

In addition a quantify definition of stratification is needed for each of these approaches.

2.2. Why an experimental campaign

The large experimental campaign of the Memorial tunnel (Massachusetts Highway Department and Federal Highway Administration, 1995) as well as the Eureka 499 project (European union, 1996) can be considered as starting point of major studies about fire behaviour in tunnels aiming at improving the tunnel fire safety levels.

Following these global approaches, some studies have targeted more specific phenomena as the smoke stratification. Tabarra (1997) studied the stratification stability using a 1/15th scale model and CFD approach. He works on the use of the Richardson number to characterise the smoke layer stability. Then, he looks at the effect of large panels on this layer.

More recently, Vauquelin and Megret (2002) have used an air/helium 1/20th scale model to analyse the behaviour of the low density gas layer. They characterise the effect of geometrical parameters on the critical velocity. Then, they work simultaneously on the downstream smoke layer stability and the upstream smoke layer propagation length.

In the same time, Demouge (2002) realised numerical development to modelled stratified flow. He has validated his results by comparing with the experimental results of Vauquelin and Megret (2002) and Ingason (1999).

More recently, Gaillot (2006) has used a 1/30th scale model to highlight the difference between the upstream and the downstream smoke layer thermal distribution using the parameters defined by Newman (1984). He shows the importance of heat loss by exchange between walls and smoke on the length of the upstream smoke layer.

Almost all these studies treat the stability of the smoke layer in academicals context. The effect of various perturbations, such as vehicles, tunnel portals or use of jet fans or injectors has not been fully studied.

2.3. Aims of the campaign

The principal aim of this experimental campaign his to characterise the stability of hot smoke layer in case of local perturbations. These perturbations are principally due to mechanical phenomena.

3. EXPERIMENTAL SET-UP

Before going any further in the experimental strategy description, it is important to consider the reasons why the described method was chosen. The experimental choice was done considering the objectives of the study to describe the stratification stability and effects of disturbance. This implies to reproduce with enough precision effects responsible of both stratification and loss of stratification. The first is linked to the buoyancy phenomena; the second is associated to the turbulence intensity. The first section of this chapter presents the scale effects and their influence on phenomena described above. Next, the experimental device retained is detailed. Finally, the preliminary experimental schedule is presented.

3.1. Scale effects

Two different kinds of experimental devices are available in INERIS. The first one is a cold tunnel model that enables achieving 1/20 scale experiment. The second one is a fire gallery with a scale ratio of approximately 1/3. To choose between those two possibilities, physical phenomena and associated quantities must be analysed. As described previously, physical phenomena responsible of stratification and its loss is respectively the buoyancy effects and turbulence. Both phenomena can be described through two non dimensional numbers. The first is the Reynolds number that represents the ratio between viscous forces and inertia:

$$Re = U\,d\,/\,\nu \tag{1}$$

This number is representative of the turbulence intensity. The more this number is high, the more the turbulence is important.

The second is the Froude number which represents the ratio between gravity effect and velocity force:

$$Fr = U / \sqrt{gd} \tag{2}$$

On one hand, the Froude number represents the stratification effect, its value must be strictly respected for these experiments. On the other hand, the Reynolds number represents the turbulence intensity, that is to say the physical phenomena responsible of the stratification loss. So, to put it in a nutshell, both numbers must be, as far as possible, conserved between real case and experimental apparatus. Because the scale effects, it is of course impossible and a compromise must be done.

It appears clearly that, to conserve the Froude number, equation (2), the ratio $U/\sqrt{d}$, must be kept constant. This implies, for a scale ratio of α, i.e. *d* is divided by α, the velocity must be divided by $\sqrt{\alpha}$. Consequently, the Reynolds number, equation (1), is divided by $\alpha\sqrt{\alpha}$.

Lets now consider the two experimental devices : the cold tunnel model and the gallery with their respective scale ratio of 20 and 3. This means that, to respect the Froude number in the cold tunnel model, the Reynolds number is divided by $20\sqrt{20}$, approximately 100. In the case of the gallery, it is divided by $3\sqrt{3}$, i.e. 5. Dividing the turbulence intensity by 100 or 5 is highly different. In the first case, the turbulence regime is altered, which is not the case in the second case. Considering this, it appears clearly that using the fire gallery enable to have a better respect of non dimensional numbers and consequently of the physical phenomena.

On top of that equilibrium respect, the gallery enables us to consider thermal effect, that is to say the thermal exchange between the smoke and the roof is taken into account. On the opposite, this cannot be done using the cold tunnel model.

3.2. Description of the experimental setup

The INERIS fire gallery is composed with a 50 m long and a 10 m² section horizontal tunnel and a 10 m height vertical chimney. This chimney is equipped with fans to control the air flow in the gallery and with an air cleaning system that enables to purify smokes before the atmosphere release.

In order to deal with both longitudinal and transversal ventilations, the gallery is equipped with a roof to divide the section in two parts, as schemed on **Figure 1**. The upper part is the smoke duct that enables smoke extraction through 3 dampers located along the gallery.

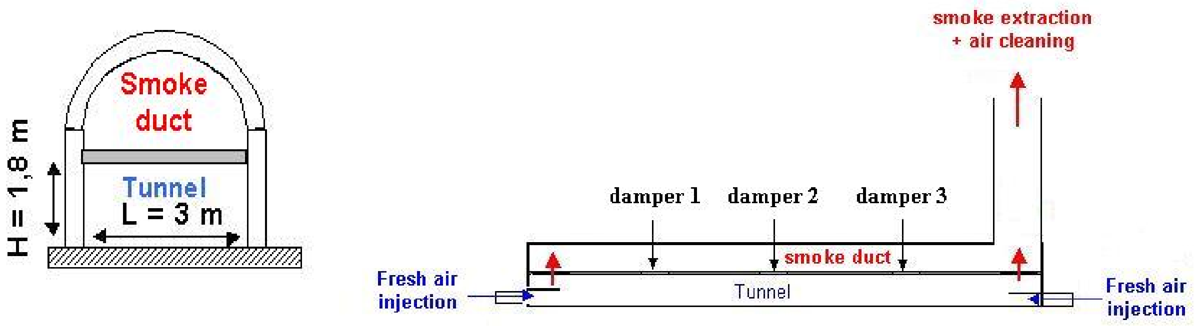

Figure 1 : Experimental fire gallery scheme**.**

To be representative of a real fire in a road tunnel, the heat release rate of the fire used will be up to 4 MW. Considering the 1/3 experimental scale, this corresponds approximately to a 12 MW fire, which corresponds to the fire of a small lorry. This fire will be experimentally generated using a heptanes pool fire. The fire heat release rate will be controlled by the pool surface and the duration by the heptanes feed thanks to a control pump.

It is important to remind that one of the aims of this project is to describe the stratification stability in tunnel. Of course phenomena occur far away from the fire and the gallery is only 50 m long, that corresponds to a 150 m long real tunnel. To study phenomena far from the fire, a deporting fire strategy is retained. This means that the fire is not located inside the gallery but outside. Smokes are then injected in the gallery with conditions in accordance with those predicted thanks to both experimental and numerical approaches.

3.3. Preliminary experimental strategy

As described in the first part of this paper, the aim of the experimental campaign is to study the disturbance effect on the smoke stratification in tunnels. Several kinds of disturbance can be generate in real configuration : jet fan, turbulence induced by blocked vehicles (congested tunnel), … However, it is extremely important, before going any further in the description of the disturbance effects, to be able to produce, transport and describe with a good precision the stratified smoke layer. Because of the length of gallery which is too short to represent distant effects in case of long tunnel, the stratified smoke layer must be translated while keeping its properties. Of course, respecting these properties required a high level in the stratification knowledge.

3.3.1. Smoke stratified layer characterisation

As described in chapter 2, stratification concerns not only the temperature but species and visibility too. So, before discussing the disturbance effect on stratification, the first part of the experimental schedule consists in quantifying the three aspects of stratification. To do this, all quantities must be measured along the height. On top of that, to quantify the ratio between stability and disturbance, it is also required to quantify the smoke layer displacement, which means to measure velocity along the tunnel, for different positions.

Smoke layer measured upstream and downstream the fire will be quantify in details to inject this smoke layer in the gallery in order to represent a longer gallery. This strategy will enable us to model the effect of obstacles or disturbance far from the fire. For this first characterisation part, the fire will be located inside the gallery as depicted on **Figure 2**. The schematised position corresponds to the configuration for downstream smoke layer study. The opposite will be done to study the upstream smoke layer and characterise its stability.

For those cases, the objective is to describe in details the smoke layer in both upstream and downstream directions without disturbance.

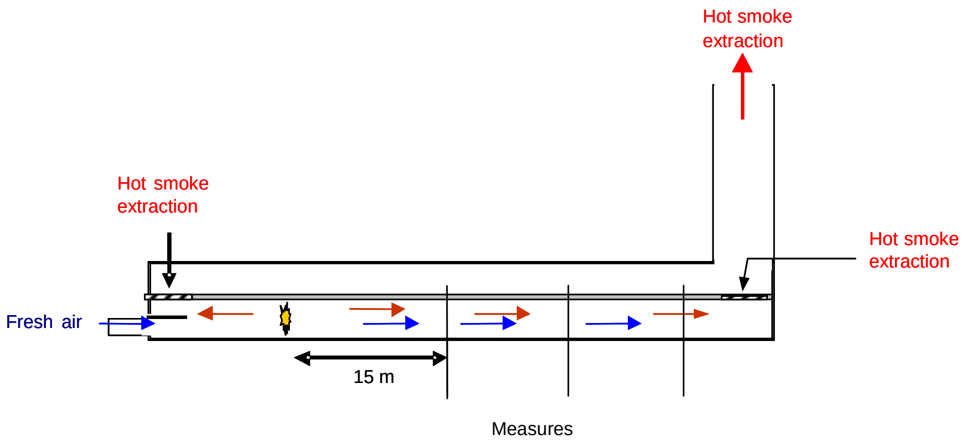

Figure 2 : Experimental set-up for smoke stratified layer characterisation.

3.3.2. Physical disturbance effects

Several kinds of physical disturbances can have an effect on the stability of the smoke layer and can induce the stratification loss. As mentioned earlier, two kinds of phenomena can affect the stratification: mechanical or thermal effects.

Firstly, mechanical effects occur because of vehicle displacement, shears due to vehicle stopped in case of congested tunnel or fan blowing close to the stratified smoke layer. All these effects are generating turbulence. Consequently, the turbulent intensity is increased and then induces turbulent mixing between fresh air and smoke. The consequence is the loss of the stratification.

This idea is illustrated through the congested tunnel example. In case of vehicle free tunnel, the section is 50 m² with 5 m height; the whole section is used to evacuate gases. In the congested configuration, the section is diminished by the vehicle height, approximately 2 m. due to the section reduction, the velocity is increased. Increasing the velocity means increasing the mean gradient, one of the main turbulent source term. On top of that, the roughness increases due to the vehicles shape and then generates turbulence.

Secondly, thermal effects are due to thermal exchanges with wall or roof, and the ambient air. These effects correspond to an energy sink term, which means a smoke temperature decrease. Considering that density ratio on the origin of stratification phenomena is based on the temperature gradient, diminishing the temperature gradient induces a decreasing of density gradient and consequently a stratification stability loss. Even if the project focuses on mechanical disturbances, the fire gallery used for experimentation enables to account for thermal exchanges, as discussed in the experimental devices description. To summarize and before describing with more details the preliminary experimental strategy, the case that will be reproduce are:

- Stopped vehicles effect on stratification through the turbulence generation;
- Fan effect.

As described in the previous paragraph, smoke layer disturbance will be studied far from the fire thanks to a smoke injection strategy. To study the vehicle influency, obstacles will be introduced in the gallery. Considering the most important risk situation, that is to say a congested tunnel, vehicles will be motionless. In case of non congested tunnel, people can evacuate safety driving the car to the outlet. In such case, stratification stability is not as crucial as in the congested one. In this congested case, people can not drive to the exit and of course the stratification stability has a great importance.

Figure 3 shows the experimental set-up that will be used to study the stopped vehicles influence on smoke layer stratification stability.

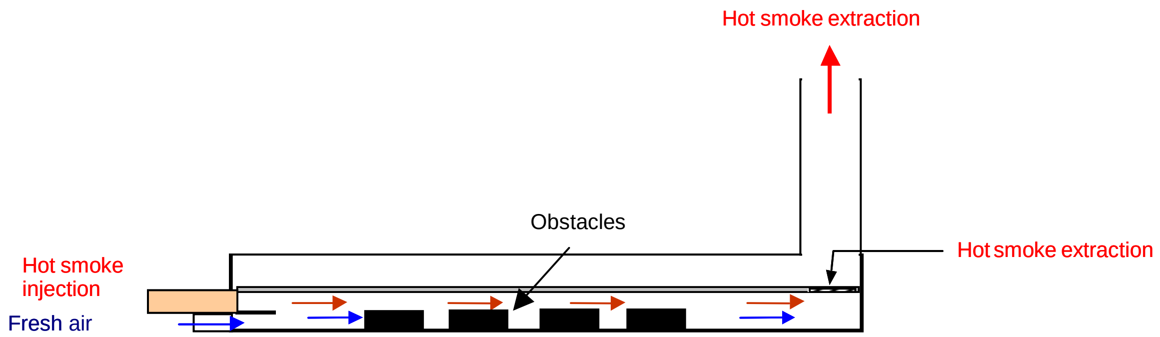

Figure 3 : Experimental set-up for congested vehicles disturbance effect.

The second disturbance effect modelled is jet fan working in front of the upstream smoke layer. In real tunnels, such situation may suddenly implies a lost of stratification upstream the fire where people are evacuating.

To study the physical phenomena occurring during such interactions, the gallery will be used with the smoke injection device and a simulated discontinuous velocity profile in the cross-section as presented at **Figure 4**. The velocity gradient importance will be studied as well as the intensity.

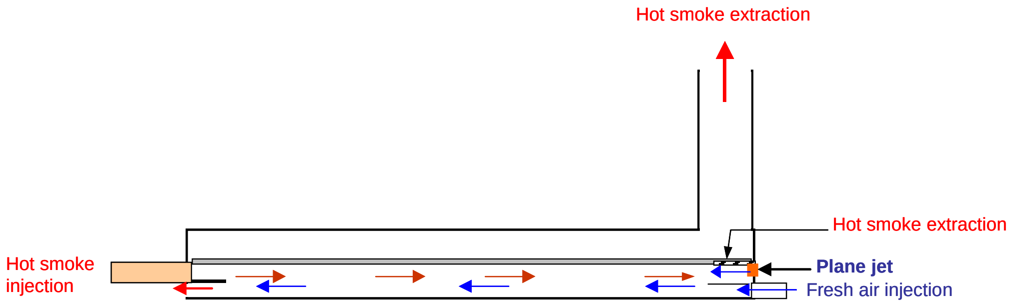

Figure 4 : Experimental set-up for studying interaction between fans and the smoke layer.

4. SYNTHESIS

As described in this paper, several phenomena can disturb the smoke stratification in case of fire inside a tunnel. The objectives of the experimental campaign detailed in this paper are, first, to be able to characterise accurately the smoke layer in the neighbourhood of the fire. Then, the study will deal with smoke behaviour far from the fire, mainly in case of disturbance such as blocked vehicles or fans.

To study those phenomena, experiments will be achieved on the INERIS fire gallery. The scale ratio of this device enables to keep dimensionless numbers representative to the main phenomena as the Froude and the Reynolds numbers. The first is strictly conserved by scaling, the second is kept in the same range, i.e. the turbulence regime is not modified.

Two series of experiments will be done. At first step, fire will be located inside the gallery to study in details the smoke layer in the neighbourhood of the fire in terms of temperature and visibility. Such approach will enable us to inject a smoke layer representing a layer far from the fire, in order to study physical phenomena that occur. Stability of the smoke layer in presence of blocked vehicles or activated fan will be particularly studied.

5. AKNOWLEDGEMENT

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PRIDICTING FIRE GROWTH AND SMOKE CONDITIONS IN TUNNELS AND METROS – AN ADVANCED FIRE MODEL

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ABSTRACT

The idea of predicting fire growth, fire heat release rates, and smoke conditions in tunnels and metros has lived for a long time in the minds of researchers and tunnel fire life safety practitioners. As technology evolves, many seek to develop and use new tools. This has been the motivation behind many experiments, both scaled, and full-size. But, to date, many have not solved the problem because they do not understand it, or they do not want to do what it takes to solve for it. Many claim that the problem is too complex and seek to over simplify the problem to the point that calculations have a large error margin.

This paper presents what the author considers to be the most advanced and only fire model available in the industry capable of predicting fire growth, fire spread, flashover (if attainable), peak heat release rate, steady-state fire heat release rate, and eventually fire decay, and its corresponding smoke products. This is achieved using Computational Fluid Dynamics performing close to reality geometry, full combustion, with radiation, thermo-physical properties, and fire performance data. The result is very robust and provides a visualization of how a fire generates smoke, and heat, and how the spread of them is through a three dimensional space.

Keywords: fire heat release rate, fire modelling, tunnel ventilation, fire life safety in tunnels

1. INTRODUCTION

In recent years, 2004 to be exact, Ingason and Lönnermark (2004) published a paper presenting an overview of the latest information available about Fire Heat Release Rate (FHRR) in tunnels, ranging from 6 to 300 MW. What the data shows is that the predicted FHRR varies all over the place. The paper does not identify uncertainty, nor how reliable the numbers are. Chiam (2005) provided a review of various methods used in the past to estimate FHRR not in a critical manner, but rather in a list manner. This review lists experiments made and FHRR adopted by some systems around the world, which vary very much. No insight as to why such variation on the estimate.

Sanchez (2008) discussed that in order to improve the accuracy of the predictions, numerically or experimentally, the physical models must be improved accounting for key physics in the fire phenomenon. In addition, the thermal physical properties, and fire characteristics of the materials that will potentially get involved in a fire must be known. Sanchez identified weaknesses in using the oxygen consumption method, which is considered the most accurate method to evaluate FHRR from experiments. Sanchez identified a miss conceptions made by many in the interpretation of $\dot{m}_{fuel}$ (kg/s), which many interpret as mass flow rate in stead of mass burning (reacting) rate (see Equation 1). After all, a fire is a chemical reaction; not a convective heat transfer problem alone. A proper way to model a fire is by accounting for air depletion (Equation 2).

Some approximate smoke from a fire assuming one gas phase (air), and smoke as a scalar. The assumption is that the presence of the smoke is in such a small concentration, and does not affect the thermo-fluid physical properties of the flow field. Such is the case of a smoke gas tracer. However, smoke from a fire is not negligible (large concentrations), and has a tremendous impact on the thermo-fluid physical properties of the flow field. In this case, smoke cannot be modelled as a scalar, but must be modelled as a multi-component fluid solving species transport equations.

$$\dot{Q}_{fire} = \dot{m}_{fuel-burning}\,\Delta H_c \neq \dot{m}_{fuel-flow}\, c_p\, \Delta T = \rho_{fuel}\, \mathrm{v}\, A\, c_p\, \Delta T = \dot{Q}_{convective} \qquad (1)$$

$$1\ kg_{fuel} + (AFR)kg_{air} \rightarrow (1+AFR)\ kg_{products} + heat \qquad (2)$$

Another miss conception made by engineers is that the fire is an stoichiometric reaction, with constant heat of combustion, ΔH_c. Sanchez illustrated that ΔH_c varies as a function of the equivalence ratio, ϕ, and temperature. The richer the combustion, and the higher the temperature of the reacting gases, the lower ΔH_c. Figure 1 illustrates such relation for gasoline at various ϕ and temperatures. The products of combustion also vary as a function of the equivalence ratio, ϕ, and temperature, as illustrated in Figures 2 and 3. The fact remains that we all know that incomplete combustion is present in all the uncontrolled fires we use as design fire scenarios. Therefore, it is quite possible that the experimental data reported may be exaggerated because the oxygen consumption method is based on stoichiometric conditions (complete combustion) and ΔH_c =13.1 MJ/kg of oxygen comsumed, which is valid only at a temperature of 298 K. (Janssens, M., (2002), Drysdale (1998))

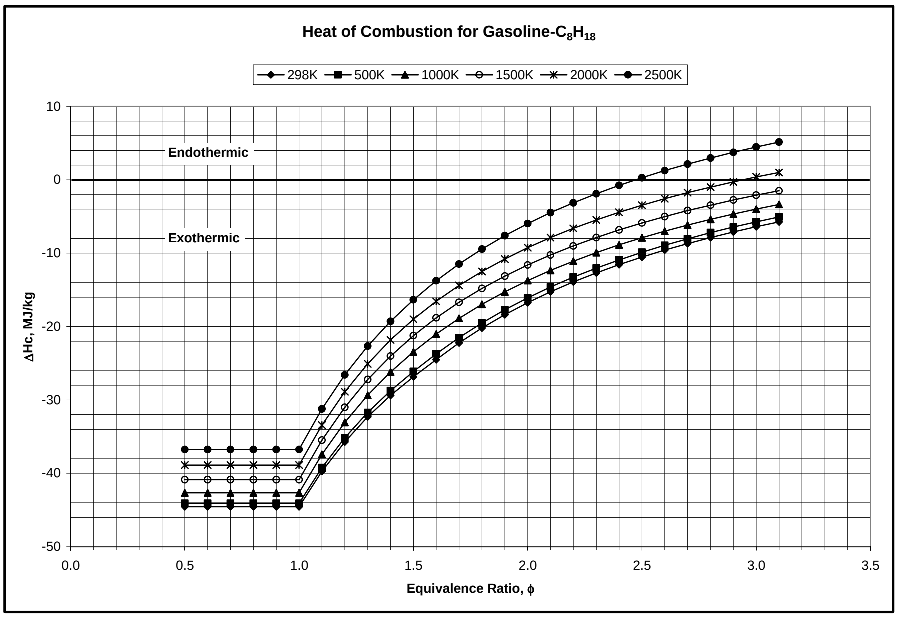

Figure 1: Heat of combustion for gasoline as a function of ϕ and temperature

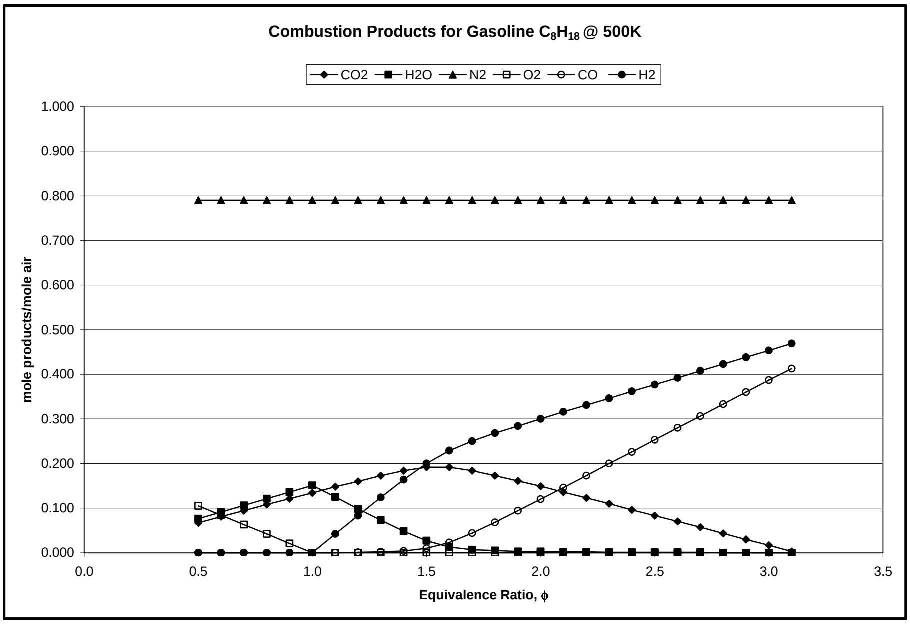

Figure 2: Combustion product for gasoline as a function of ϕ at T=500K

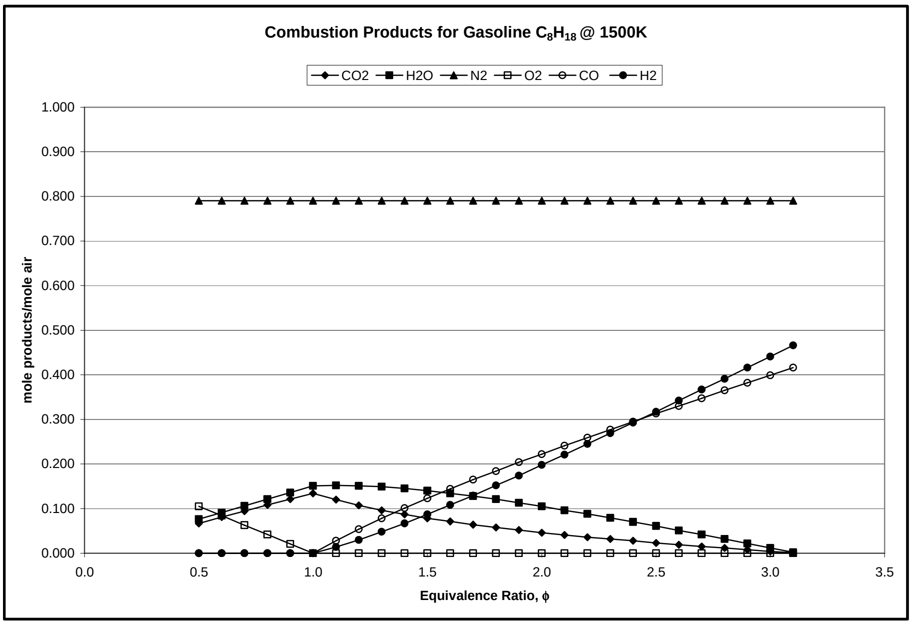

Figure 3: Combustion product for gasoline as a function of ϕ at T=1500K

2. FHRR MODEL

It needs to be understood that engineers rely on the models they create. Everything engineers do is an approximation to reality. These models depend not only on the mathematics used, but on the assumptions made. Sanchez (2006) provided an introduction of this advanced model using CFD.

In mathematics, we learn that as we decrease the size of the domain, our differential equations improve in accuracy. So is the case with time, as we decrease the time step, our accuracy also increases. But, let us not forget the properties required to solve the problem. From a fluid dynamics point of view, we need to know density, viscosity, thermal conductivity, and specific heat of the fluid. These properties are required to predict the mass and heat transfer in the fluid phase. From a fire point of view, we need to know density, thermal conductivity, specific heat, ignition temperature, and burning mass loss rate of the combustibles. It is interesting to note the dependence these properties have with temperature.

To date, many have studied fires and developed models that focus mainly on the gas phase after the reaction. They assume the FHRR in a form of a heat source which does not take into account the reacting mixture of fuel and air. Many postulate that with a heat release rate from a gas burner, the fire models predict well. However, I argue that this is not a fire model; it is merely a heat transfer model.

The chemical reaction, flame, products of combustion, ΔH_c (as a function of ϕ and temperature), radiation, pyrolysis, mass loss, and flammability limits are not modelled. Some claim that the objective of fire modelling is to simplify the problem. The question that comes to the attention is how much simplification this implies.

In order to develop a fire model, we must understand the physics we are trying to represent. Figure 4 depicts a general model for the process. The steps are as follows:

- Allocate combustible mass on the surfaces in a space representing very closely where fire is expected.
- Combustible surfaces are heated by some form of heat source.
- Account for incubation period, a function of thermal thickness of the materials, after which ignition takes place.
- Fuel is converted from solid to vapour through pyrolysis (Equation 3).
- Fuel and air mix (in all our fires, oxygen is provided by air).
- If fuel mixture is within flammability limits, and the gas temperature is above auto-ignition temperature (see Figure 5), a chemical reaction following Equations 4 takes place.
- Depending on the mixture ϕ, and temperature, ΔH_c (Figure 1), and products of vombustion are predicted (Figures 2, and 3).
- Depending on the localized $\dot{m}_{fuel-burning}$, ΔH_c, the FHRR is predicted (Equation 5).
- Radiation from the localized flame will radiate heat to the surfaces passing through the gas, or is absorbed by the soot and remain in the products of combustion. This will contribute to the fire spread and ignition of other surfaces away from the flame.

$$\dot{m}_{fuel-loss} \propto Ae^{(-E/RT)} \qquad (3)$$

$$Fuel + a(O_2+3.79N_2) \rightarrow bCO_2 + cCO + dH_2O + eO_2 + fH_2 + gN_2 + heat \qquad (4)$$

$$\dot{Q} = \dot{m}_{fuel-burning}\,\Delta H_c \qquad (5)$$

where:

$\dot{Q}$ = fire heat release rate (W)
$\dot{m}_{fuel-loss}$ = fuel mass loss rate (kg/s)
$\dot{m}_{fuel-burning}$ = fuel mass burning rate (kg/s)
ΔH_c = fuel heat of combustion (J/kg)
A = pre-exponential coefficient
-E = activation energy
R = universal gas constant
T = temperature (K)

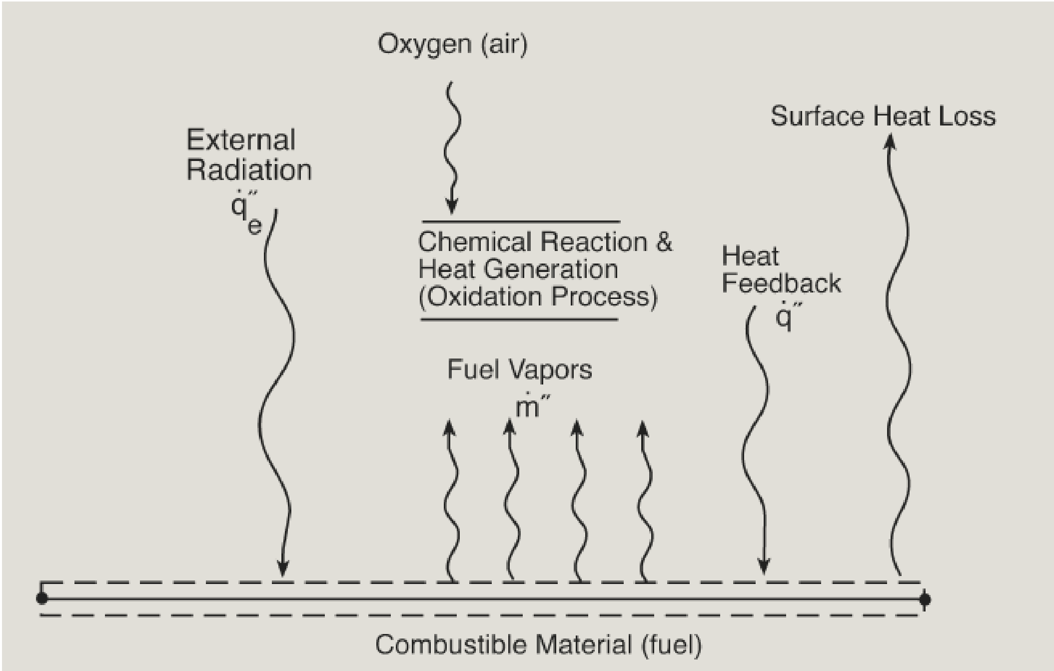

Figure 4: Physical process of a fire

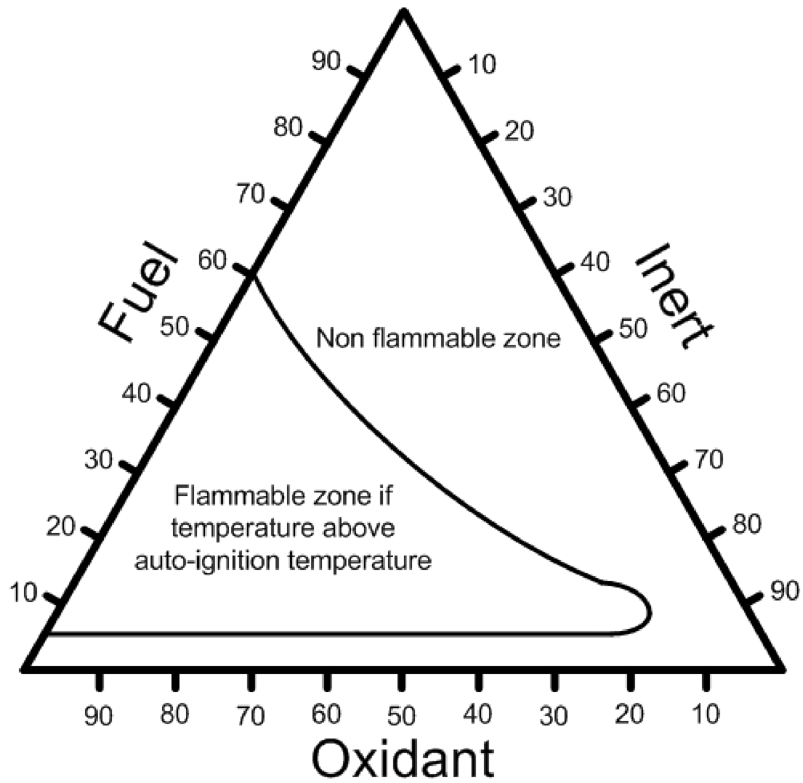

Figure 5: Generic vapor phase flammability diagram

3. FHRR PREDICTIONS

The predictions are achieved using a CFD computer software that allows for the detailed 3D geometry, and the modelling of the transport equations, among them:

- Conservation of mass (fuel burning rate as mass source)
- Conservation of momentum
- Conservation of energy with radiation (FHRR as heat source in flame zone)
- Turbulence
- Conservation of species (air and hot products)

To avoid repetition of these well-known conservation equations, the reader is encouraged to review the user's manual of the software used (FLUENT 2006).

The turbulence model used in this paper is based on the standard κ-ε, accounting for buoyancy effects, although other models are available, such as RNG κ-ε, Reynolds Stress Model, etc. The Discrete Ordinate radiation model was used.

Figure 6 illustrates a set of predictions made using this advanced fire model for a train in a tunnel, under natural ventilation, and on a 3% slope. The particular thermal and fire properties used are not important at this time. Let us focus on the information provided by this advanced fie model. The setup assuming a constant igniter in the form of a gas burner.

- The first thing to note is that there is a growth period, a flashover reaching a peak FHRR of 2.5 MW, a steady-state, then sharply decaying to the almost constant 700 kW heat release rate provided by the igniter. Let us not forget that ΔH_c, and products of combustion are calculated to follow the calculations illustrated in Figures 1, 2, and 3,

- The average cabin gas (air and hot products) temperature peaks at about 900 °C, and then drops to about 250°C.

- The fuel from the combustible surface burns through pyrolysis, burning near 1000 kg of mass. The model follows the flammability diagram (Figure 5), such that the fuel only burns if the concentrations of fuel and oxidizer are within the flammability limits, and the temperature is above auto-ignition temperature.

- The mass of air is shown to start at about 84 kg, and then drops as the temperature increases to 900°C, but as the temperature drops, the mass of air available inside the cabin increases to almost its original state. This is in agreement with the equation of state for gases.

- Figure 7 illustrates the surfaces that have ignited, as calculated by the CFD model. The ignition temperature was set to be 300°C (used for demonstration purposes in the sample model presented). Radiation, convection on the fluid side, and conduction in the solid side are modelled on the surfaces where there is combustible that has the potential to ignite and convert solid fuel into fuel vapour.

- Figure 8 illustrates how quickly the smoke generated from the fire spreads inside and outside the train.

4. MODEL VALIDATION

This model has been validated following ASTM E1355 from a physical-science (thermo-dynamics, heat transfer), and from a system setup point of view. The thermo-dynamics for the chemical reaction, species generation, and ΔH_c, were validated for gasoline, methane, and propane. There are extensive experimental and thermo-physical data for these three combustibles.

The system setup was validated monitoring temperature predictions made in room fire for a sofa burning and trash can fires. The heat release rate was not considered critical because the experiments are based on the oxygen consumption method, while the method presented in this paper accounts for variable ΔH_c.

5. CONCLUSIONS

The model presented in this paper represents the state-of-the-art, and the most advanced fire modeling approach in the industry today. There is no doubt that there is an art involved because the engineer has to compose a picture of the key physics in order to predict more realistically a fire and its effects.

The model accounts for fire physics not accounted in other models. This is achieved through the use of CFD, physical geometry, and reaction processes accounted for. It still relies on knowing thermo-physical, and fire performance data for the combustibles.

This advanced model can predict FHRR, smoke, and flame inside and outside a fire compartment – train car to station, vehicle car to road tunnel, etc. These effects have not been studied that extensively, although some claim so.

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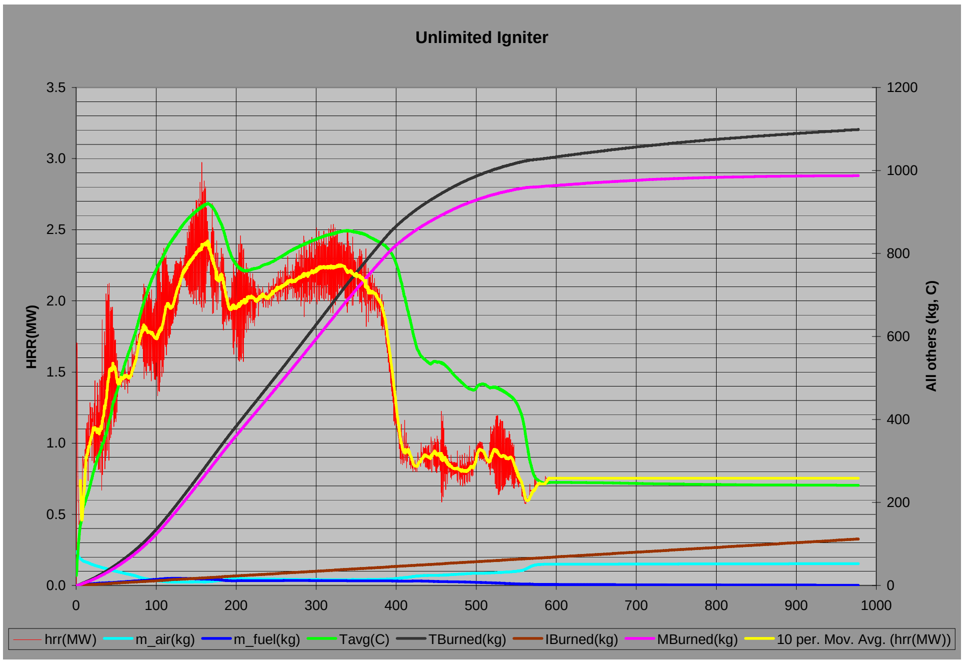

Figure 6: FHRR predictions in a train car in a tunnel

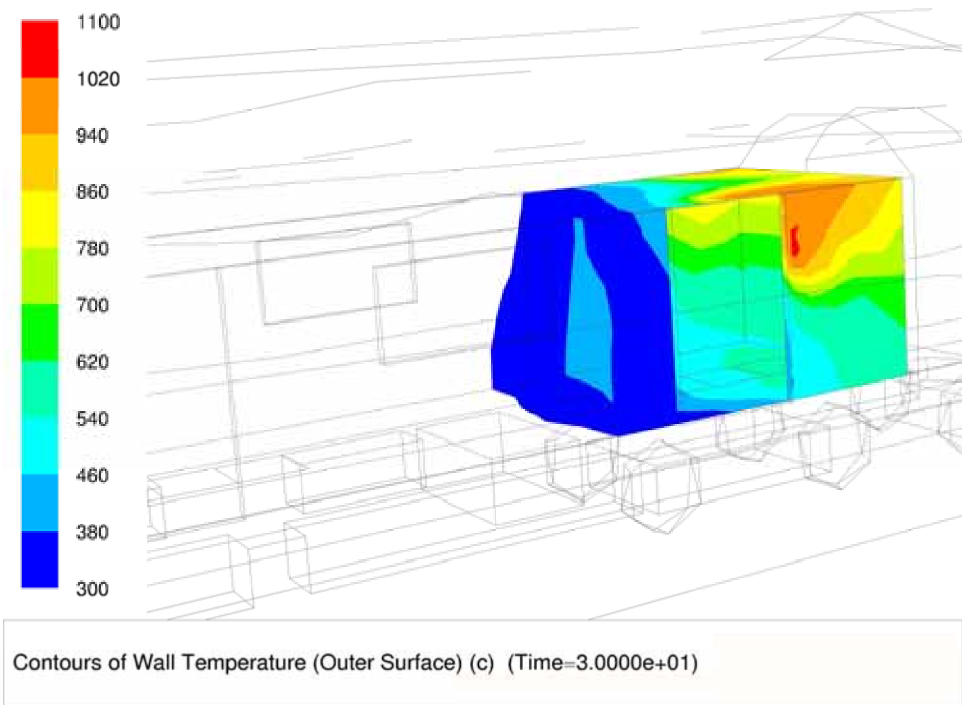

Figure 7: Inside train wall temperature above ignition temperature (set to be 300°C)

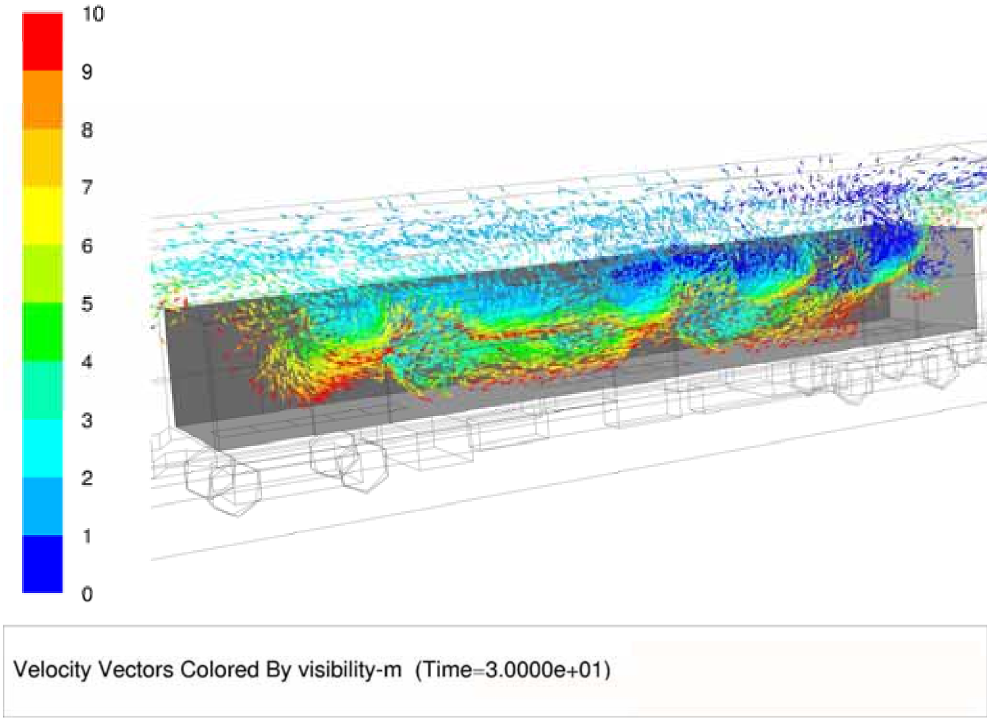

Figure 8: Smoke generated from train fire

VENTILATION CONTROL OF THE BLANKA TUNNEL: A MATHEMATICAL PROGRAMMING APPROACH

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ABSTRACT

The Blanka tunnel is a 5.7 km long highway tunnel under construction in Prague, Czech Republic. Because of its complicated topology and very strict environmental restrictions, the synthesis of ventilation control for normal conditions turns out to be fairly challenging.

The air flow is restricted to leave the tunnel through traffic portals – it has to be aspirated by ventilation centers and released by exhaust shafts and chimneys. To achieve this goal, control strategy was designed based on the mathematical programming principles. The designed controller, which is inspired by model-based predictive controllers (MPC) used in heavy industry, is energy optimal by definition, adapts to changes in operational conditions and requires significantly less design time than traditional approaches.

Keywords: ventilation control, city tunnels, model-based predictive control

1. INTRODUCTION

After its opening scheduled for 2011, the Blanka tunnel (see **Figure 1**) will form a part of the inner ring of Prague. Because of its complicated topology, strict operational demands and axial ventilation system, the ventilation control does not have a straightforward solution. After several attempts to use conditional control ("if-then-else" type), we decided to turn to modern control algorithms and to use model-based predictive control (MPC) to achieve the control objectives.

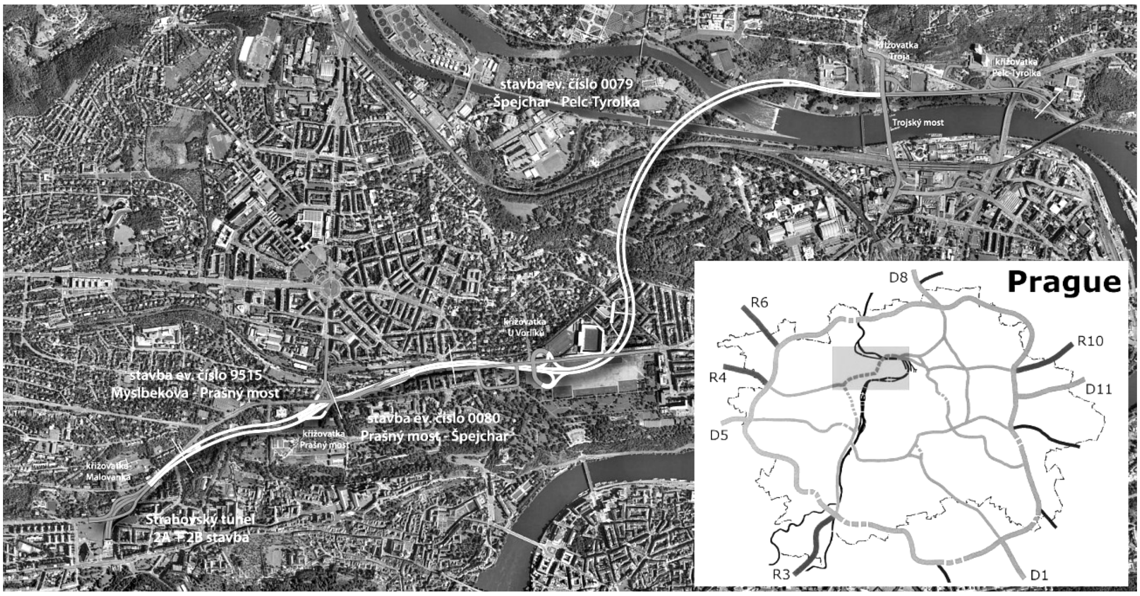

Figure 1: The Blanka tunnel in Prague

2. MPC CONTROL PRINCIPLES

The MPC control is an optimization strategy that minimizes an optimality criterion (cost function) over a finite time horizon. Its first use was in 1970's in oil industry and is widely used for optimal control of "slow" industrial processes today. The main advantages of the MPC control are:

- It handles multivariable control very naturally
- It can take actuator limitations into account
- It allows to define control constraints
- It is very intuitive to tune

For tunnels, the structure of the MPC controller is illustrated on **Figure 2**.

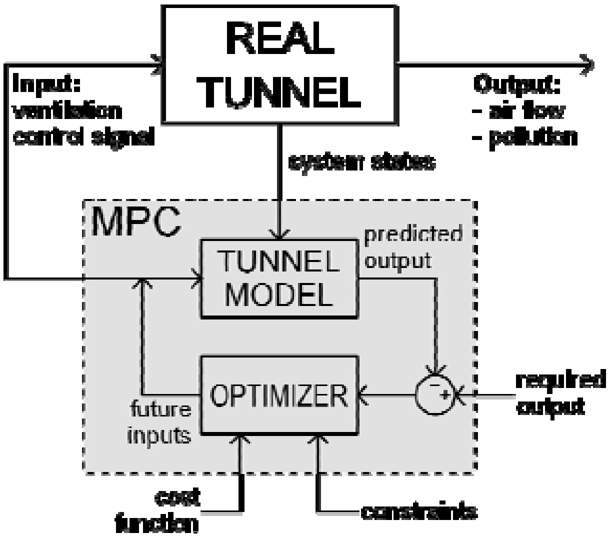

Figure 2: MPC controller block diagram

For the case of tunnel ventilation control, we use a linear model (which will be discussed further), the cost function has a quadratic form

$$F = x^T Q x + u^T R u \qquad (1)$$

wherein x denotes system states and u denotes system control signal. It is obvious that by means of matrices Q and R, we may directly influence the cost of system states and control signal.

The linear constraints have a form

$$Hx + Gu \leq 0 \qquad (2)$$

so we can impose physical constraints that exist in the system.

We have to point out that the MPC controller is not a classical, linear controller in the usual sense. It is rather an optimization procedure that optimizes the trajectory of the output signal, while trying to minimize the energy consumption of the system (through the cost function) and maintaining the physical or technological limitations of the system (through constraints).

3. TUNNEL CONTROL MODEL

The basic assumption for the control model is that the air flow has two major contributors – the air flow generated by ventilation system Q^f and the remaining air flow Q^*

$$Q = Q^f + Q^* \qquad (3)$$

Moreover, according to measurements from the Mrázovka tunnel (Pořízek, 2007), the air flow can be further expanded to

$$Q = \sum_{i=1}^{M} a_i f_i + Q^* \tag{4}$$

wherein f_i is the power input to the ventilation equipment in the i-th section of the tunnel and a is a suitable linearization coefficient, obtained by simulation or measurement.

The derivation of the simulation model was already presented in (Ferkl, 2007), with the resulting formula for the pollution level in a tunnel section being

$$p_i = \frac{k_i n_i s_i}{\sum_{j \in J_i} a_i f_j + Q^*} \tag{5}$$

wherein k is the exhaust production coefficient for a single vehicle, n is the number of vehicles and s is the length of the i-th tunnel section.

Referring to our previous results (Ferkl, 2007), the optimization process (which turns out to be an MPC controller) that aims to achieve the exhaust inside the tunnel to lie within given limits and the air flow to have the desired direction, is

$$\min_i \left\| \left\| \begin{matrix} \alpha_i f_i(t) \\ (f_i(t-1) - f_i(t)) \end{matrix} \right\|_{\ell 1} \right\|_{\ell 2} : \begin{cases} f_i \in \langle f_{low}, f_{high} \rangle \\ \sum_{m \in F_i^j} a_m f_m \in \langle Q_{i,low}^f, Q_{i,high}^f \rangle \\ Q_k \leq 0, k \in K \end{cases} \tag{6}$$

The cost function weights the power input to respective ventilation fans (first line) and minimizes the switching of the fans (second line) for enhancing the lifetime of the ventilation equipment. It minimizes the sum of cost functions for all tunnel sections (ℓ_1 norm) according to a quadratic criterion (ℓ_2 norm). Equation (6) is a representation of a mathematical program.

The constraints limit the power input f to the ventilation equipment (first line), imposes the exhaust limits through minimum required air flow Q (second line) and, if needed, requires a negative air flow for tunnel section in a set K (third line).

4. SIMULATIONS

To make the presentation of our results more comprehensive, we will only present the control for the northern tube of the Blanka tunnel only; however, the southern tube is similar to the northern one.

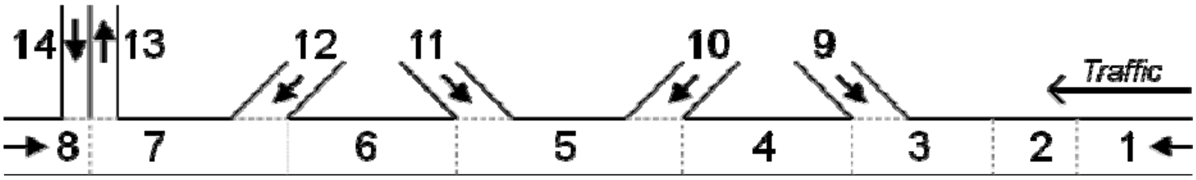

Figure 3: Control sections of the Blanka tunnel, as referred to in the text.

The geometry of the northern tube is shown in **Figure 3**. The tunnel is divided into control sections 1 to 14. Sections no. 13 and 14 represent a ventilation center. The figure also shows the preferred air flow directions for a "closed" mode of operation, wherein the only passage for the air to leave the tunnel is the ventilation center (i.e. section 13).

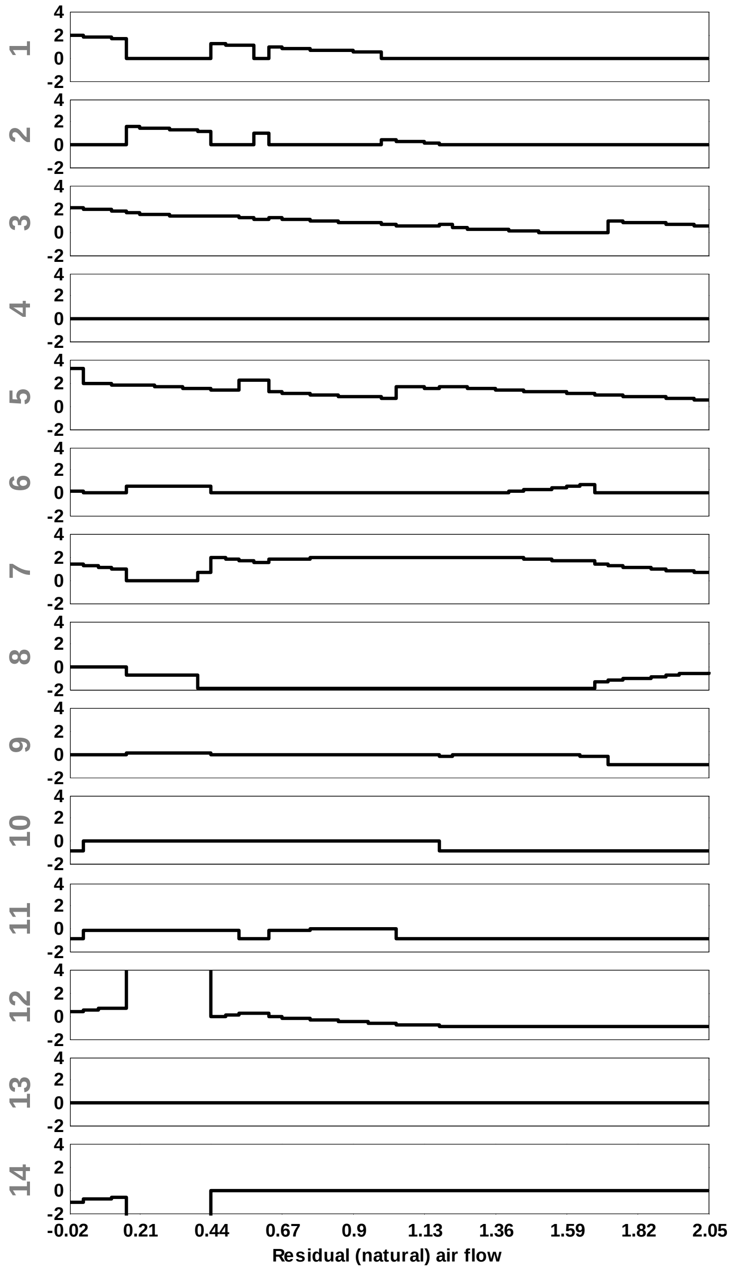

Figure 4: Simulation of MPC control for the Blanka tunnel.

In the following simulations, we use normalized power output equivalent to nominal power of an "average" jet fan installed inside the tunnel. Instead of using time characteristics, we show the results on static characteristics, wherein the power input to the ventilation equipment is the dependent variable and the value of the residual air flow (Q^* in Equation (3), which represents the measured air flow minus the air flow contributed by the ventilation system).

Figure 4 shows the result for the MPC controller without any preferences for the cost function (all power inputs are weighted equally). Unlike for linear controllers (such as PID controllers), the plots are not smooth. This is the result of the constraints – the controller distributes the power according to the capacities of the respective fans, in order to maintain the overall energy consumption minimal. This is something that is very difficult to achieve by purely linear controllers. Numerical difficulties may appear in some cases, as the air flow model is poorly conditioned in principle and the controller sometimes "hesitates", which ventilator to use. It may be seen from the figure that by combining sections 1 and 2 together, we could get a signal that is more "fancy" than the original two separate signals.

Figure 5 shows a comparison of three simulations with different cost functions. The performance of the controller is illustrated by the end-section of the tunnel (sections 7, 8, 12, 14), which is interesting for comparison – because the tunnel operates in a "closed" mode, the air flow in section 8 has to be reversed. In said simulations, the following conditions were set through the cost function:

1. Ventilation in all sections has the same cost.
2. Sections 9-12 (onramps) are penalized, i.e. their use has to be minimized.
3. Sections 9-12 are penalized, while the use of section 14 (the ventilation shaft) is preferred.

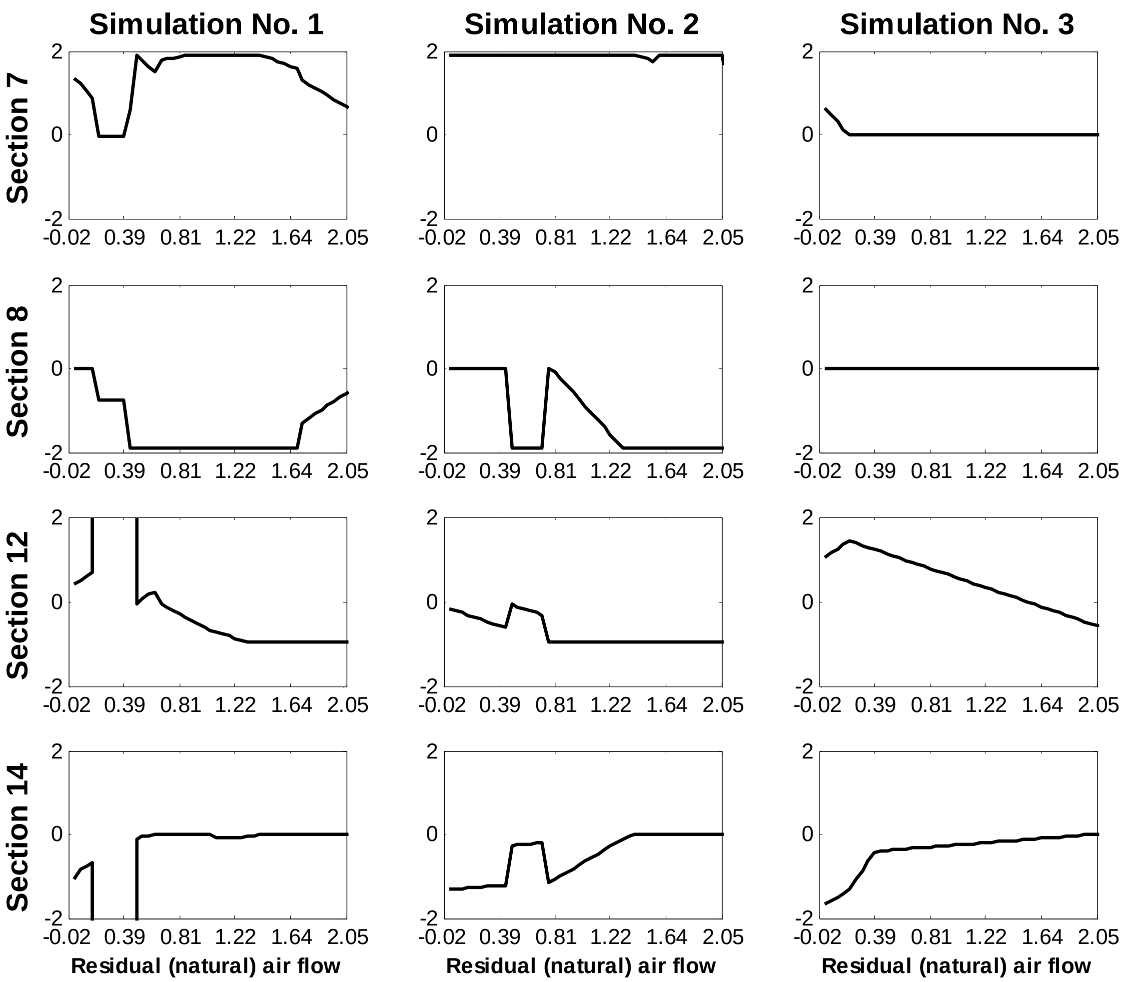

Figure 5: Comparison of controller tuned according to various cost functions.

The results show again a non-smooth behaviour, as the controller tries to balance the energy consumption. The first simulation is not quite desirable, as we can see that the controller counteracts by sections 12 and 14. Indeed, this is the controller with a uniform cost function. The second simulation is much better; we can see the effect of penalizing the onramp (section 12). The third simulation gives the best results, it even has quite smooth signal. The reason may be that preferring the ventilation shaft against other ventilators is natural, so it suits the controller the best.

5. CONCLUSIONS

We have shown an approach to ventilation control, which is based on MPC controller. This type of controller is widely used in industry, especially for large scale systems with multiple inputs and multiple outputs. This makes it an ideal tool for tunnel ventilation control, especially for city tunnels, where special requirements have to be met.

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INTEGRAL TESTS OF ELECTROMECHANICAL SYSTEMS IN MOTORWAY TUNNELS

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ABSTRACT

The reliability of the electromechanical systems on Switzerland's motorways and in motorway tunnels gets checked periodically on behalf of the Federal Road Agency ASTRA. The Local Road Agency (vif) of the canton of Lucerne developed a very innovative approach with a standardised test procedure for acceptance tests and annual re-tests. Based on a "system function matrix" the number of tests could be minimised and therefore the functional capability of the electromechanical systems – in combination with all integrated systems – could be tested very economically. An especially created database enables systematic and traceable checks of all safety-relevant systems.

Keywords: integration test, acceptance tests, re-tests of tunnel equipment, operational safety of motorways and tunnels, lifecycle of electromechanical systems

1. INTRODUCTION

Due to major accidents involving fires that have occurred in road tunnels over the last few years (Montblanc-, Tauern- and Gotthard Tunnel), the safety of all Swiss motorway tunnels longer than 600 meters were reviewed. Necessary measures for improvement were implemented immediately (signalisation, traffic management system, lighting, ventilation). Apart from the normal maintenance, the Federal Road Agency (ASTRA) has so far been investing some additional CHF 50 million per year.

As part of the project to increase tunnel safety presented here, the canton of Lucerne has commissioned a group of experts with the implementation of the following objectives:

- A systematic, traceable and economical testing method must be developed which allows periodic re-tests of the safety-relevant electromechanical systems on the motorways both during acceptance and operation phases.
- The system documentation must be checked as regards their completeness and correctness.
- The proper work of the systems must be checked in combination with all linked systems and under real operating conditions (as close as possible).
- The standard and alternative data communication path as well as the normal and "standard error conditions" (e.g. power failure) must be verified.
- Errors must be rectified
- Compilation of the project documentation with the support of:
  - Check lists
  - Test logs
  - Action plan
  - To-do lists
  - Final report

2. ASSUMPTIONS

It is assumed that all standard tests like factory tests of the equipment, data-point tests and commissioning were done properly, and all documents are complete and correct. Missing or not standardised documents of older systems were recreated as part of the project, or structured in a standard way.

3. DEVELOPMENT OF DOCUMENTS AND TOOLS

3.1. Detailed description of each tunnel

In the scope of the project the following documents were developed:

- General project and test documents:
  - Test specification sheet
  - “Function matrix” (overview of linked scenarios)
  - General test specifications (per system as basis for the check lists)
  - Address lists (control center, involved persons, third parties)
- Technical documents (for each tunnel):
  - Technical equipment
  - Emergency plan
  - Room arrangement and location of cubicles
  - Pipe and power line documentation
  - Longitudinal- and cross-sections
  - System documentation and manuals
  - Error messages and alarm lists

Test description:

- Test documents (for each tunnel):
  - Test flow chart with detailed timetable
  - Test requirements
  - Check and to-do lists
  - SCADA message logs
- Test reports for all tunnels:
  - Reference to basics
  - Timetable and test overview
  - List of detected failures (pending/rectified)

3.2. Test data base

Support by a software tool is a must, as the amount of results provided due to the traceability or surveillance can only be evaluated as required with the help of this tool. To this end, a database with the required recording screens and reports was developed.

The functional range of the software is:

- Table with all data points of the electromechanical systems in road tunnels of the canton of Lucerne (AKS code, name and technical detail information)
- Overview and definition of the general test specifications:
  - Preparation, implementation, final report
  - Assignment of the relevant systems (data points)
  - Qualification and number of staff required, tools required
  - Version management
- Overview and triggering of test requests:
  - Systems to be checked, test group formation
  - Link of the general test specifications to be applied
  - Resource planning
- Recording-tool
- Creating the final report or a pre-report
- To-do management

4. LIMITATION AND SCOPE OF THE TESTS

In addition to the safety-relevant systems of the tunnel, the drainage pumps, the structure (corrosion) as well as the emergency phones on the whole motorway network in the canton Lucerne were also tested.

Safety-relevant in accordance with the project scope are:

- Energy supply
- Emergency lighting
- Traffic management system
- Fire detection and fire alarm systems
- Emergency phones and fire extinguisher
- Break-in FM radio
- Passage lighting
- Ventilation
- Radio system
- Visibility
- Adaptation lighting

4.1. Tested operating modes

A “system function matrix” was defined for the integrated systems. The matrix shows the triggering element (column head), the responding element (line head) and the type of reaction as intersection of column and line. The scenarios generally represent the “normal operation mode”. The necessary tests are based of the intersections in the table. If the test run has been successfully completed, it is reasonable to assume that all involved elements work properly.

4.2. Non-tested operating modes

Preliminary studies have shown that scenarios beyond the “normal operating mode” of the systems are very difficult to test (technical and economical reasons). A sequence of events, even combined with a partial or complete system failure leads to a big number of possible combinations – that means a sharp rise of test-efforts.

Even the case of “normal operation mode” cannot be tested without any limitation. One example is so-called “tunnel red”. The traffic management system is not in the normal operation mode, because the test takes place in the tunnel and therefore a one-lane traffic management or a closed tunnel is necessary.

4.3. Test location

There are two groups of tests: First, tests which take place in the control centers, and second, tests which are carried out in the tunnel – during the latter the whole tunnel, or at least one lane has to be closed for the public traffic.

5. PROCEDURE

5.1. Preparation

The major work in the preparation period is to set the timetable as well as to provide information to all the participants (operating personnel, support personnel, experts and police). For instance, the police needs an advance period of approx. 2 months for their assignment and to prepare the traffic management.

5.2. Test phase

This period includes carrying out the tests based on flow charts and check lists as well as recording the results in a database. A general check of the documents, labelling and systems takes place.

5.3. Closing operations

Elimination of any existing defects with follow-up checks, data-management, devising of the final test report with to-do list and measures as well as check of the processes and check lists should be carried out. Adjustments for future tests are implemented, if required.

6. SCHEDULE

For the tests in the control center, a binding timetable is not necessary. The tests in the tunnel should be carried out at a time of maintenance work (costs, traffic management). This does, however, represent a problem/conflict of interests as regards the various objectives, test performance on one hand, and maintenance on the other side (light, ventilation etc.).

7. TRAFFIC MANAGEMENT SCENARIOS

The different scenarios are based on the traffic density, the type of tunnel and further risk assessments. For the tests in the tunnel, it should be blocked, but in special cases, it is sufficient to block just one lane. In rare cases the side-strip or other blocked areas can be used for the tests.

8. CONCLUSION / ADVANTAGES

Many tunnels in the Canton of Lucerne were designed in the 1970s. The tests showed that some of the electromechanical systems have reached the limit of their service life. It is increasingly important, that periodical tests take place and that an economical test method is available for this purpose. The advantages of the established procedures are: First, a low number of individual tests – even for highly integrated systems – are necessary, second, low efforts to add new tunnels or new tunnel-equipment to the test-procedure, and third, both, periodical as well as acceptance tests can be carried out in a proper way.

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AUTOMATIC INCIDENT DETECTION AND ALERTING IN TUNNELS

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ABSTRACT

A system for automatic incident detection and alerting in tunnels is presented. At the heart of the system is a multi-purpose detector, based on induction loops, which reliably detects incidents, whatever their origin, within seconds. As a result, valuable independent or assisted rescue time can be gained. This detector works in a hybrid fashion together with the video system of the tunnel control centre. In an alert case, the image of the tunnel section containing the incident is automatically switched to the alarm screen. The operating personnel are then able to precisely analyse the situation and initiate appropriate supporting measures. The process is tested and results presented.

Keywords: automatic incident detection, automatic alerting, multi-purpose detector

1. INTRODUCTION

It is impossible to avoid incidents occurring on the road network, this is true for tunnels as well. They are inherent to the system and occur unavoidably with known probability. Incidents can easily develop into minor accidents and extend right through to major catastrophes. The risk of this is particularly high in tunnels due to the design-inherent confined space. Unfortunately, history provides some examples.

Therefore, there is a requirement to accurately detect incidents at their onset from the point of view of the safety of the motorists in the tunnel. This permits timely initiation of counter-measures so that a severe or even uncontrollable accident situation cannot occur. If the incident situation is detected in the tunnel control centre within seconds, valuable time is gained to help motorists rescue themselves from an emergency situation. This time saving together with an appropriate incident location description also effectively supports the rescue efforts of the emergency services which have in the meantime been called to provide external support.

Modern-day tunnel control centres have a large number of screens which portray the traffic situation in the individual tunnel sections. Nevertheless, the operating personnel are not normally able to monitor all the screens at any time. If an incident occurs, this may cause a delay in reacting.

The following descriptions are concerned with the possibility of significantly reducing the workload of the operating personnel in the tunnel control centre by provision of reliable, automatic incident detection so that, should an incident occur, operator attention can be immediately drawn to the prevention of harmful accident consequences. Accordingly, the operating personnel are made aware of incidents in the traffic flow in tunnel sections in a targeted and automatic way using alarm screens. Visual analysis of the incident can start immediately and assistance and/or emergency measures appropriate to the situation can be initiated. Consequently, rescue time is gained and tunnel safety is decisively increased.

It is known that automatic digital image processing is operating at the limits of its capabilities in the ambient visual conditions that obtain in tunnels which, dependent on the set decision making thresholds may result in false alerts or missed alerts. These considerably lower the acceptance of such systems.

In the following, this situation is remedied by the presentation of a new, hybrid-type system. Automatic alert generation is achieved using a system with induction loop sensors, while manual analysis of the incident situation or incident cause is carried out by operators via the video alarm screens.

2. AUTOMATIC INCIDENT DETECTION PRINCIPLE

2.1. Requirements

A practical solution for automatic incident detection must fulfil a whole series of requirements. Thus the system should reliably generate an alert within 30 seconds for any incident that occurs. Missed alerts must not occur, they hinder preventative measures in the event of an incident and therefore favour development into an accident situation. False alerts must be reduced to a minimum to guarantee continued operator acceptance of the system.

From a system technology viewpoint, this means that the incident detection sensors must always work reliably independently of the constructional, traffic or any other ambient situation obtaining in the tunnel. They must be capable of automatically detecting any type of incident having an effect on motorist safety.

2.2. Incident causes

In a tunnel, there is a wide range of causes of the above named incidents. For example, the cause may be a stationary vehicle or one that is driving conspicuously slowly. This may breakdown, catch fire or become involved in an accident. However incidents may also be caused by shed loads or pedestrians on the carriageway. Visual impairments such as smoke, dust and snow flurries or blinding caused by reflections may also act as triggers, as can a smooth road surface caused by an oil spill or ice. Motorists driving against the traffic flow are a particularly dangerous incident cause. There are many other causes.

2.3. Multi-purpose detector

It would be very expensive, if not technically impossible to provide and operate a dedicated tunnel sensor for every different type of incident cause as well as to obtain an automatic alert from a combination of the sensors in a detector.

Therefore, a multipurpose sensor is suggested, which can detect any cause having an effect on the safety of motorists in the tunnel.

The principle behind this sensor is the awareness that, in all the above named incidents, there is a direct effect on the driving behaviour of the motorists in the vicinity of the cause of the incident. Thus for example, a vehicle which is following a damaged vehicle, will attempt not to become involved in an incident and will thus correspondingly reduce its speed, or even stop, or change lanes to avoid the danger situation. The following vehicles will also behave in a similar manner. Likewise, this applies to any other incident causes. The common factor to all these manoeuvres is that the vehicles affected will suffer an increase in travel time. These travel time increases are therefore a reliable indicator of an incident of any type. Moreover, they have the system advantage that generally they point to incidents as they develop, i.e. before they actually manifest themselves.

The multipurpose detector detects these travel time losses and immediately generates the alert. The operators are now able to analyse in detail the situation on alarm screens of the incident cause in the disturbed tunnel section and initiate appropriate assistance measures in plenty of time.

Based on knowledge of the vehicles currently located in the respective tunnel section, an indication of the possible fire load can be generated.

2.4. Principle of the multipurpose sensor

The multipurpose detector works with the induction loop sensor in the carriageway in accordance with the RABT (German directive for Equipping and Operating Road Tunnels). The advantage of this sensor is that it always works correctly and reliably independent of the ambient and/or traffic conditions. Impairments caused by a lack of visibility, covering or poor differentiation between objects as occur with optical sensors, do not exist.

The multipurpose sensor works in accordance with the MAVE® principle. This is based on a correlation measurement procedure, which is a development of the MAVE®-S method adapted for use in tunnels. MAVE®-S has been successfully used on the long-distance road network for many years to measure travel time and traffic density. The vehicle sequences at the entrance and exit of a particular tunnel measuring section are continuously, automatically measured using the induction loop sensor and compared with each other (correlation). The multipurpose sensor can automatically detect a "stationary vehicle” or “abnormally slow vehicle” as well as the number of vehicles in the measuring section from the result of the comparison. Moreover, motorists travelling against the traffic flow, local slow motorists as well as vehicle type (passenger car, heavy goods vehicle, etc.) are determined from local analysis.

2.5. Length of the tunnel sections and reaction time

The length of the tunnel sections can be selected according to measurement technology parameters within wide limits. Thus the system has, as described below, been successfully tested with section lengths between 300 and 1300 m.

Based on traffic safety requirements within the tunnel, the length of the section must not however be chosen to be too large, as the section length has a direct influence on the system reaction time. This arises from the fact that the most important measurement is the significant deviation of the actual travel time from the normal travel time. A measurement is significant, if the time for a vehicle to exit from a particular measuring section is significantly greater than its expected travel time. What “significant” means, in particular, can be parameterised.

The reaction time of the system to an incident is dependent on its location within the tunnel section. If the incident is close to the entrance to the tunnel section, then theoretically a minimum reaction time elapses near to the normal travel time, by contrast if it is at the end of the tunnel section, then this minimum reaction time reduces towards zero. In a practical implementation of the system, a parameterisable verification interval of a few seconds is added to the minimum reaction time. The purpose of this is to ensure triggering of an alert and avoid missed alerts. In this way, significant travel time deviations always lead to an alert, correspondingly missed alerts are avoided.

The specification of the RABT directive for installation of measuring sections with induction loops every 300 m gives a sufficiently good reaction time to incidents at any location within the tunnel section. The expected travel time over 300 m at a speed of 80 km/h is 13.5 s, at a speed of 60 km/h, 18 s. Taking into account a suitable verification interval, alerting to an incident can reliably take place within 30 s.

Independent of the above named approach, motorists driving the wrong way are immediately detected when they arrive at the measurement location and an alert triggered accordingly.

2.6. Award

The described multipurpose detector is a central component of the MAVE®-tun system, which automatically detects incidents in tunnels and generates alerts accordingly. This system was recommended by an international expert jury for the innovation award at the international transport fair, Intertraffic 2006, in Amsterdam.

3. RESULTS

3.1. Rennsteig tunnel, A71, Germany

Within the framework of a test installation in the above named Rennsteig tunnel, proof was generated on 26.08.2003 that the measurement procedure MAVE®-tun directly and reliably detected incident-threatening characteristics in the traffic flow within tunnel sections. In particular, a “stationary vehicle” within the traffic was detected as were also abnormal traffic conditions, e.g. caused by particularly slow vehicles, etc.

The tests and checking of the results was carried out by RWTH Aachen University. The results are were published in issue 925 of “Forschung Straßenbau und Straßenverkehrstechnik”, page 91. The procedure is described in the article under the identification SDS 1.

The tunnel section was in a tube with 2 lanes of traffic travelling in the same direction. It had a length of approx. 300m. 12 different scenarios were implemented with stationary and slow-travelling heavy goods vehicles and passenger cars in normal traffic conditions.

All incidents were correctly detected within a maximum of 17 s. There were no missed and no false alerts.

3.2. Elbe tunnel, A7, Germany

Within the framework of a test installation proof was generated between 31.03. – 07.04.07 in the above named Elbe tunnel, that the measurement procedure MAVE®-tun directly and reliably detected incident-threatening characteristics in the traffic flow within tunnel sections. In particular, stationary vehicles were detected as well as abnormal traffic conditions, e.g. caused by particularly slow vehicles, etc.

The test involved 2 sequential tunnel sections. One tunnel section was approx. 300 m long, the other approx. 600 m. The tunnel sections were in a tube with 2 lanes of traffic travelling in the same direction. No scenarios were implemented, rather the normal traffic flow was analysed using the test system and recorded for checking purposes in parallel with video recordings in the tunnel control centre.

Various incidents with stationary passenger cars and heavy goods vehicles occurred. The test phase and checking of the recordings and results was carried out by the tunnel operator. All incidents were correctly detected within a maximum of 30 s. There were no false or missed alerts.

3.3. Felbertauern tunnel, B108, Austria

The described procedure for incident detection in tunnels has been underway since January 2006 in a first expansion stage under controlled operation in the above named Felbertauern tunnel. The purpose is to continuously count the actual number of vehicles in the individual tunnel sections, differentiated between heavy goods vehicles and passenger cars, and to measure the travel time.

The tunnel comprises one tube, which is generally operated with opposing traffic flows. The installation encompasses the entire tunnel in both traffic directions. Each traffic direction comprises 5 measuring sections. Each section length is approx. 1300 m.

Testing is carried out by the operator. The number of vehicles and the travel speed are accurately measured.

In addition to the above named control installation, the capability of the described procedure for generating alerts in an incident case was tested in the Felbertauern tunnel. This took place mainly between 21.01 – 17.02.2008.

The test took place in a tunnel section of approx. 450 m length in both traffic directions.

The test procedure incorporated the normal traffic flow within the tunnel. In addition, the operator implemented scenarios with stationary and slowly moving vehicles as well as with vehicles driving against the traffic flow.

The operator checked the results with the help of his video system in the tunnel control centre. All incidents were correctly detected within a maximum of 30 s; vehicles driving against the traffic flow were detected immediately. No false or missed alerts were detected.

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DIMENSIONING OF A FRESH-AIR-IMPULSE-DAMPER

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ABSTRACT

The usage of big multileave dampers in tunnel ventilation systems for punktual extraction of smoke is in the meanwhile relatively popular respectively a requirement of the new safety regulations and standards. And furthermore the system has already shown his functionality and reliability in a couple of simulations, tests and also real fires.

One of the most important premesis for this system is to reduce the air-speed inside the traffic room as quick as possible to a minimum to ensure a complete and compact de-smoking of the traffic room.

To influence (slow down) the length speed of the air inside the tunnel is often realised with jet.fans at the portals. Other possibilities could be regulation via exhausting in neighbouring ventilation sections, air curtains in the traffic room or fixed nozzles in the fresh air channels to inject air (Saccardo ejectors).

In some cases it is an advantage to use an adjustable multileave damper instead of the saccardo ejectors to get more flexibility and options for the system. The system of the "Frischluftimpulsklappe" (Fresh-air-impulse-damper) is already investigated and tested amongst others by the Technical University of Graz.

Keywords: "Frischluftimpulsklappe" (Fresh-air-impulse-damper) Abbr. FLIK

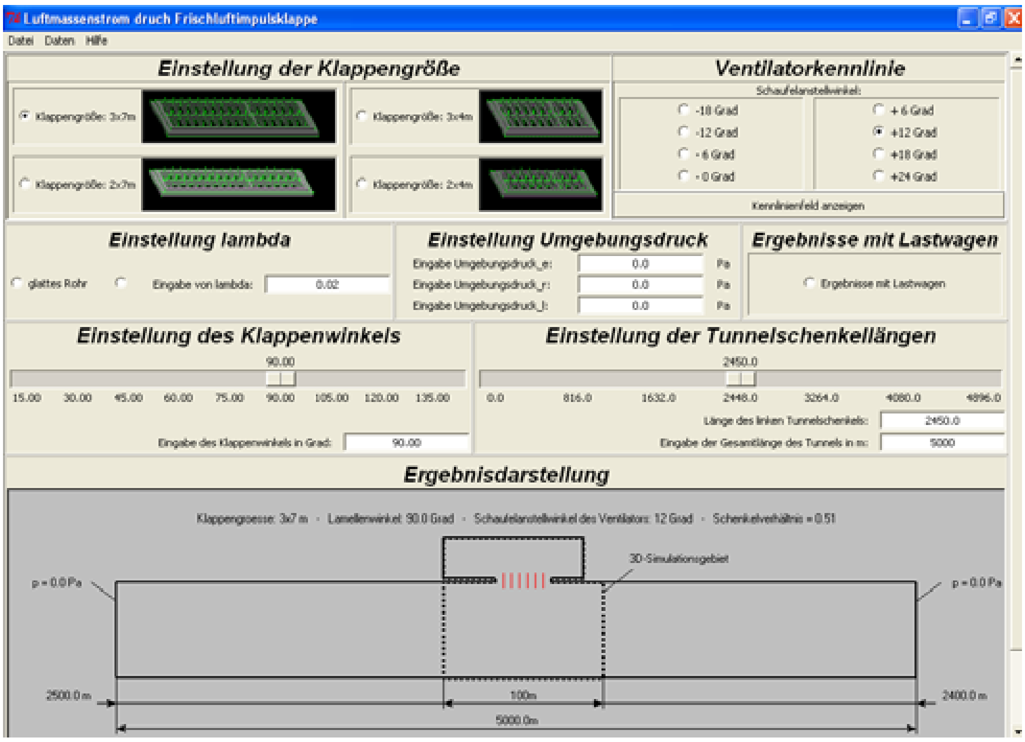


Figure 1: Working surface of the selection software

1. INTRODUCTION

Within the scope of a research assignment of the Technical University of Vienna the stream conditions influenced by a Fresh-air-impulse-damper FLIK were investigated.

Furthermore it was a target to develop a basis to assist dimensioning and the layout of a FLIK for different applications and projects. To receive a very variable description for different applications the calculation results were summarized in a small choice- and exposition software within that a multitude of variables are selectable.

2. CALCULATIONS AND SIMULATION

The calculation of the stream conditions are done in a combination of an 3D-Fluent simulation, showing a 100m long part of a Tunnel and some additional 1 dimensional calculations showing an additional left and right tunnel part beside the 3D simulation field.

Basis of the calculations is a real tunnel cross section including a fresh air and an exhaust channel. The FLIK model is of a realistic design, the frame is built into the tunnel ceiling, the blades are of a fish-tailed design to minimise pressure losses, also the needed frame splittings and stiffeners are considered. The damper dimensions are selected in 4 sizes between 2x4m and 3x7m. The blade angle varies from 15° to 140° in steps of 15°. The simulation considers a ventilation system with an axialfan with variable blades, the related characteristic diagram is included in the calculations.

The result of the calculations are the pressures, resistance coefficient trough the damper and between the limits of the 3D part, division of the volume flows and mass flows of the system. Figure 1 shows the calculation model and the description of the results of the calculations.

In addition to the 3D Simulation a 1D calculation is combined to the 100m field of the 3D model. This 1D calculation allows to various also the length of the complete tunnel (or ventilation part) and the position of the FLIK in the tunnel. Also the pressures at the portals and the coefficient of friction are selectable for the calculation and will be considered.

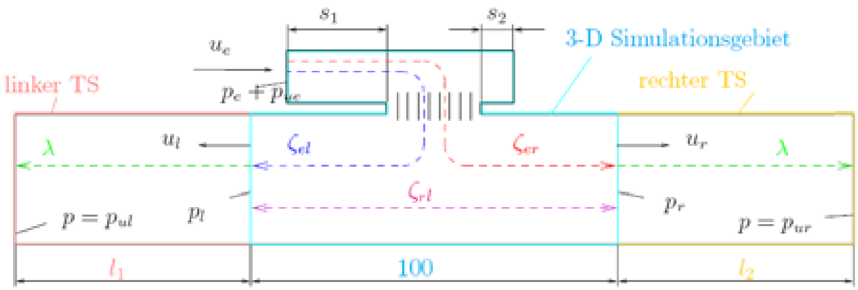
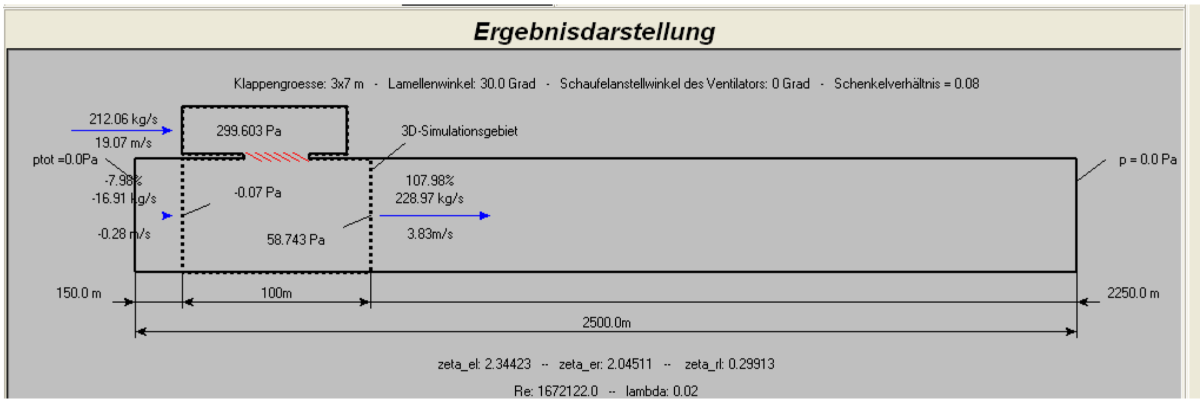


Figure 2: Description of the results

It is the prior intention of the simulations to get comparisons in the calculations related to different damper sizes and to find the optimal blade angle for an impulse effect.

Damper size 3x7m



Damper size 3x4m

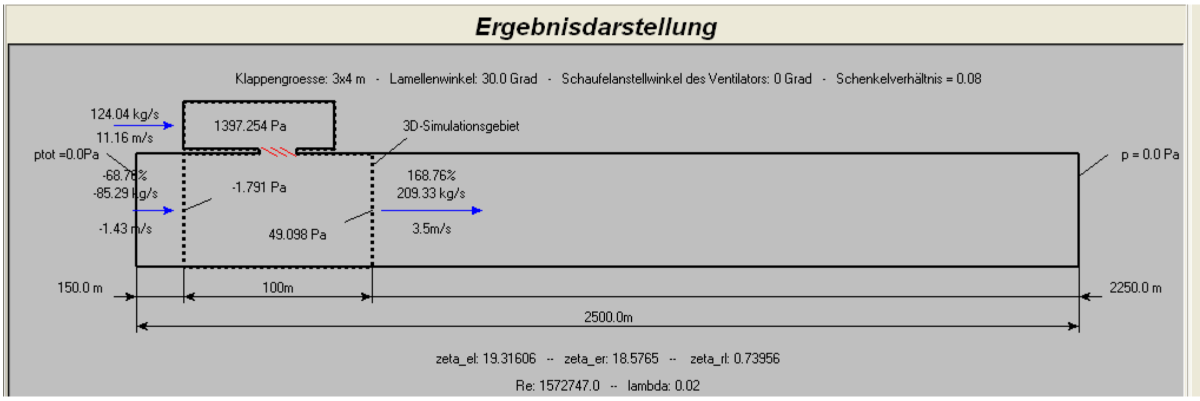
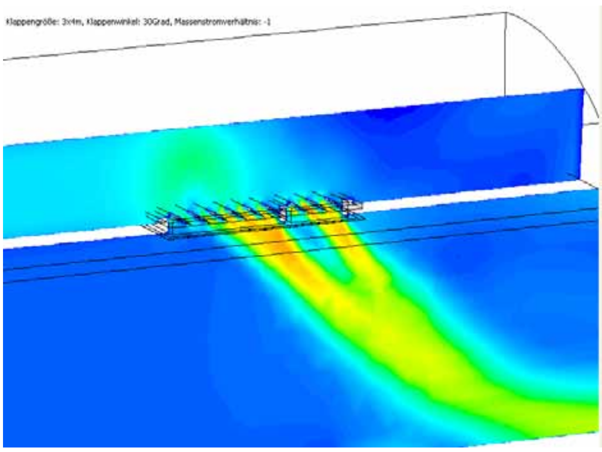


Figure 3: Shows the comparison of damper sizes of the FLIK.

The blades of the FLIK are designed to allows blade angles up to 140° for an inversion of the flow direction through the damper. This gives possibilities to act on the air velocity in the traffic room in two directions. The Simulation gives good results of this inversion of the flow and shows the possibility to create an impulse effect also in this case of inverse. See results in Figure 4 (showing a sample calculation)

Blade angle 30° Blade angle 140°



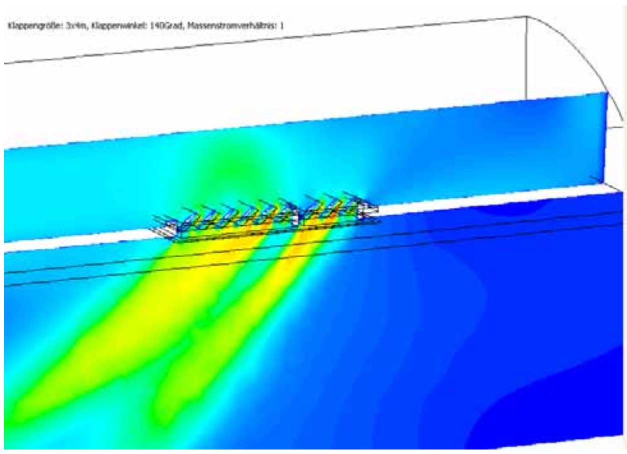


Figure 4: Inversion of Flowdirection

3. INFLUENCE OF TRUCKS

Up to this point the investigations have shown the influence of the air flow inside an empty tunnel without any disturbance. Therefore it was decided to continue the calculations with investigations on the influence of trucks in the area of the FLIK.

Different situations have been simulated. (Truck below the damper, beside the damper; with 5 m and also with 30 m distance to the damper in airflow direction). In addition these simulations are done with one truck in the line below the damper and with one truck on each line of the traffic room.

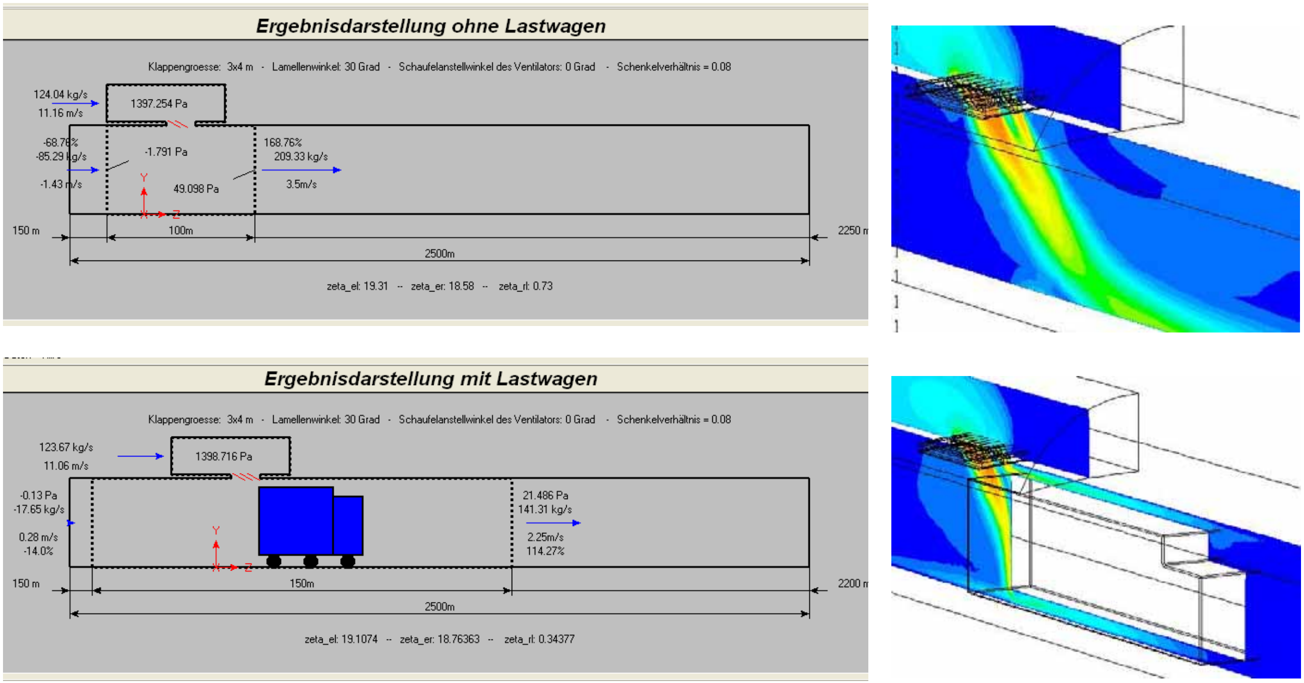


Figure 5: Comparison of results with and without a truck in the traffic room.

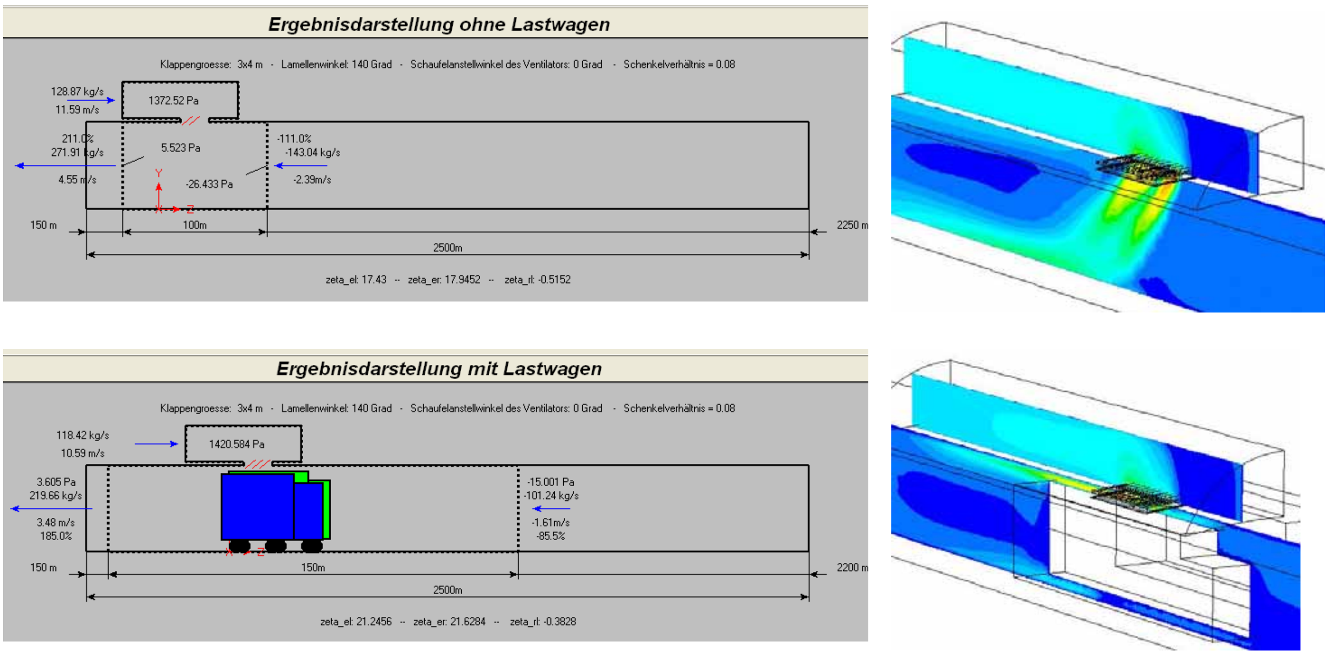


Figure 6: Comparison of results with and without a truck in the traffic room.

4. CONCLUSION

The first part of the investigation has proven, that the longitudinal air flow within the traffic section of the tunnel can be influenced by the means of fresh air fans in combination with the FLIK in the required extend and manner.

The second part of the investigation has been shown, that the negative influence of hindrances as trucks is by far not that big as expected. The designated effect of the FLIK to the air flow in the traffic room is reached also in the case of hindrances.

Finally it can be pointed out, that a FLIK could give positive properties for tunnel ventilation systems. In the design phase it could be worth to compare the effect of Saccardo ejectors with the effects of a FLIK.

Furthermore in some cases of tunnel refurbishment, the FLIK could even give an alternative to jet fans.

THE EFFECT OF A WATER MIST SYSTEM ON LARGE-SCALE TUNNEL FIRES

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ABSTRACT

This article describes the experience gathered through tests prior to the application of a Water Mist System in two tunnels in the Netherlands. After providing background information/a short introduction (1), the article describes the principles behind the RWS specifications (2), followed by the main points of the test results (3), the analysis of the risk of a BLEVE (4), the results of tenability tests (5) and the main conclusions (6).

1. INTRODUCTION

In 2003 it was agreed between the Minister of Transport, Public Works and Water Management and the regional and municipal authorities, that the safety policy for the tunnels located on the A73 motorway at Roermond and Swalmen would be implemented as follows:

- LPG tankers would be permitted;
- There would be no emergency lane;
- In addition to the more or less standard package of safety measures, a remote-control system using compressed-air foam (CAF) would be installed.

As a stationary CAF system had never been used in tunnels before, it was decided to run a pilot project. The objectives of the pilot project were to achieve prompt, sound and reliable use of the system, have it installed in time and within budget and to have a system ensuring high reliability.

The tender procedure took place in 2004. The year 2005 was dominated by extensive testing and necessary design modifications. The design was tested in Norway (November 2005 – December 2005). Two extreme scenarios were taken as the starting point: a solid fuel fire and a liquid fire, both of about 150 - 200 MW. The tests demonstrated that the solid fuel fire would be sufficiently controllable within a limited margin. The pool fire was extinguished extremely effectively.

The fire-fighting capability could therefore be characterized as good, but the complete system had not yet been fully developed. For example, the combined reliability of detection, operation and control had not yet been established in detail. In the meantime, however, the basic investment had risen to such an extent that it was well in excess of the financial resources budgeted for in advance. The increasing costs were caused in particular by a doubling of the costs for the integrated CAF system.

Taking all this into consideration, in August 2006 the Minister of Transport decided not to continue with the CAF pilot, and therefore not to go ahead with the integrated CAF system in the tunnels on the A73 motorway. The decision was based on the fact that the increase in safety did not outweigh the extra costs of using an integrated CAF system. However, the aid stations in the walls were built with CAF handlines.

Given the extremely short preparation time remaining, a conventional technology already used in a tunnel environment emerged as the most acceptable variant. The new chosen system was a Water Mist system. This is because this technology, unlike compressed-air foam, has a pipe system which is permanently filled with water, therefore reducing the time between activation and tackling the source of the fire. A Water Mist system, in contrast to the tested compressed-air foam system, can therefore be brought into operation before the fires have developed.

2. THE SPECIFICATIONS (RWS)

2.1. Schedule of Requirements

The use of Water Mist is based on a safety analysis in which all possible scenarios are considered, but without taking into account the risk of the scenarios occurring and the cost of controlling them. As a result, the design also takes into account ‘extreme scenarios’ (risk of occurrence < 10^{-6} per annum). The scenarios considered were those involving a pool fire, a solid fuel fire, a lorry and car fire and a thermally-caused explosion (BLEVE).
The tests were designed to investigate the effectiveness of Water Mist against (potential) big fires, i.e. fires of 200 MW, corresponding to ‘fully developed’ fires involving a lorry with approx. 100 m³ of burning pallets or a burning diesel oil pool of 100 m². Under normal conditions, an active fire-fighting system should prevent large solid-fuel fires from developing. In the case of large pool fires, the requirement is different: these fires can grow very quickly to their maximum size. The fire-fighting system should be able to reduce these large pool fires to a manageable size.

As mentioned in the introduction, Water Mist is part of an active fire-fighting system:
detection, operation and control. Under normal circumstances, the active system should preferably prevent such large fires, especially in the case of solid fires which develop slowly.

The objectives of the Water Mist system are:

- To reduce and control solid fires to prevent fatalities, fire flashover, hot BLEVE and damage to the construction.
- To extinguish liquid fires to prevent fatalities, damage of the construction, fire flashover and hot BLEVE.
- There is also the requirement that self-rescue should not be negatively influenced and the fire source should remain accessible by the fire brigade.

This leads to the following functional requirements:

- The Water Mist system has to reduce a solid fire (potential 200 MW) to achieve the following conditions within a maximum of 1 minute after the external command ‘large fire’ has been issued:
    - at a distance of 30 m up-stream of the fire, the heat flux shall not be greater than 3 kW/m², at a maximum ambient temperature of 50 ºC;
    - at a distance of 20 m up-stream of the fire, the heat flux shall not be greater than 5 kW/m², at a maximum ambient temperature of 50 ºC;
    - at a distance of a minimum of 5 m down-stream of the fire, the heat flux shall not be greater than 12.5 kW/m², at a maximum ambient temperature of 280 ºC.
- The Water Mist system has to control a solid fire for at least 50 minutes.
- The Water Mist system has to extinguish a liquid fire (potential 200 MW) within a maximum of 1 minute after the external command ‘large fire’ has been issued.

The external command 'large fire' is achieved via a linear temperature detection of about 150°C, representing a fire of 25 MW.

2.2. Test Objectives

The general objective of the large-scale fire tests is:

- To verify the Water Mist system regarding the Schedule of Requirements (verification).
  The system is considered as part of an active fire fighting system. The abovementioned detection values and realistic values of the time between activation and tackling the source of the fire of 30 seconds are taken into account.
- To investigate the maximum fire size that can still be controlled by the system (performance).
  In investigating the limits of the system, the contribution of AFFA (Aqueous Film Forming Additive) is also taken into account.

The installation and performance of the system in the Runehamar test tunnel has to be representative of the system in the A73 tunnels.

2.3. Test program

The test program followed is as follows*:*

1. 50 MW solid fire, 480 pallets, 80% wood, 20% plastic, Water Mist with AFFA (verification)
2. 200 MW liquid fire, diesel oil pool of 100 m², Water Mist with AFFA (verification)
3. 200 MW liquid fire, diesel oil pool of 100 m², Water Mist without AFFA (performance)
4. 200 MW liquid fire, diesel oil pool of 100 m², Water Mist with biodegradable AFFA (performance)
5. 200 MW solid fire, 720 pallets, 80% wood, 20% plastic, Water Mist without AFFA (performance)

3. PERFORMANCE OF THE WATER MIST SYSTEM

3.1. The test location

For large-scale fire tests the Runehamar Test Tunnel in Norway was used. The Runehamar Test Tunnel is an abandoned road tunnel of approximately 1,500 m in length with a cross-section size of approximately 43 m² and is cut into solid rock. At the location of the fire source, the tunnel structure was protected by means of a fire-resistant insulation lining. The test tunnel was equipped with a longitudinal ventilation system to facilitate wind speeds of at least approximately 2.5 m/s under any circumstances.

3.2. The layout of the Water Mist system

The nozzle lines were installed underneath the intermediate ceiling at an approximate height of 4.5 metres above the tunnel ground surface. The nozzle lines covered a length of 75 m of the tunnel, divided into 3 sections of 25 m each. Each section comprised 3 nozzle lines: one mounted in the middle of the tunnel underneath the tunnel ceiling, and one on each side underneath the tunnel ceiling at a distance of approximately 3 metres. The spray nozzles were integrated into the nozzle lines and are spaced at a distance of 2 m.

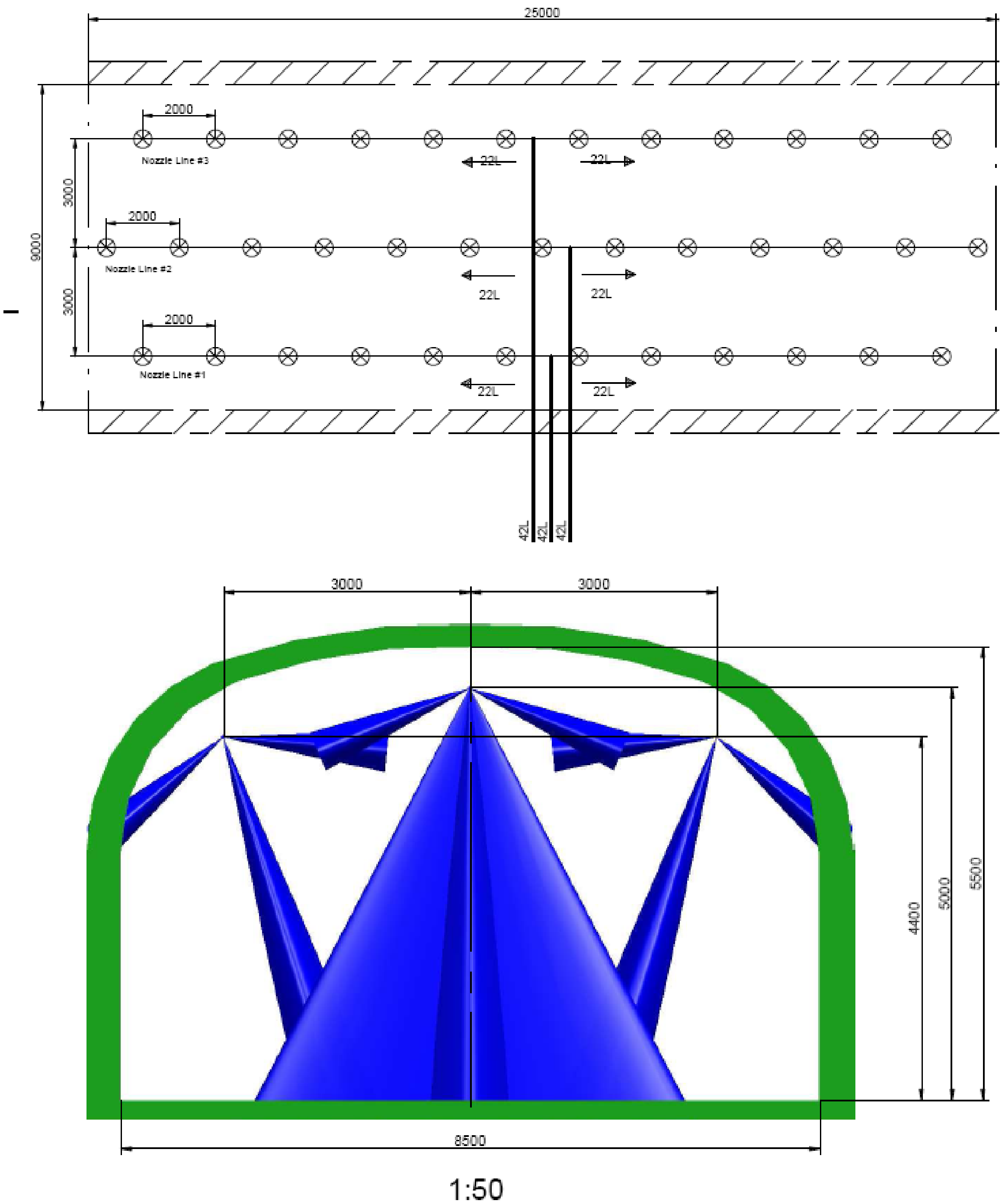


Figure 1: Plan view of one section and cross section: the Spray Nozzles and Nozzle Lines in the test tunnel

The water pump unit provided 3,000 l/min of water at a pressure of 50 bar. The system was equipped with an AFFF unit to enable a mixture of 1 - 3% AFFF and biodegradable foam to be added to the water supply.

3.3. The test results

After calibration testing of the Water Mist System, two verification tests and three performance tests were performed in accordance with the test program. In order to verify the performance of the Water Mist System against the schedule of requirements, temperatures, heat fluxes and fire sizes were measured.

3.3.1. Temperature measurements

Temperatures were measured in several locations and at various distances from the fire source. In the graphs below, the temperatures above the fire load and at a distance of 5 m downstream of the fire load are shown by way of reference.

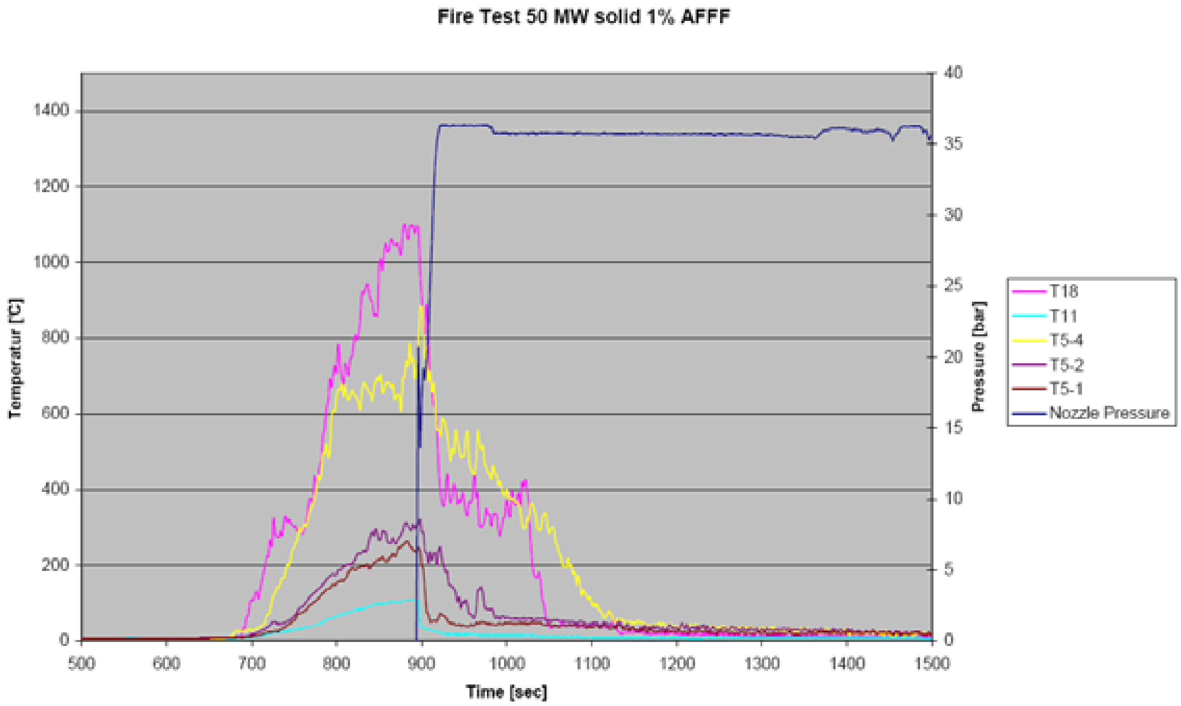


Figure 2: Temperature measurements - 50 MW solid fire test

The temperature graph for the 50 MW solid fire test (verification) shows a rather quick development of the fire up to 1,100°C, mainly due to the increased ventilation speed of 5 m/s before ignition. After activation of the water mist system, the temperatures above the fire load T18, T11 and at a distance of 5 m downstream of the fire load T5 decrease immediately and are brought down to acceptable temperature levels within 100 seconds.

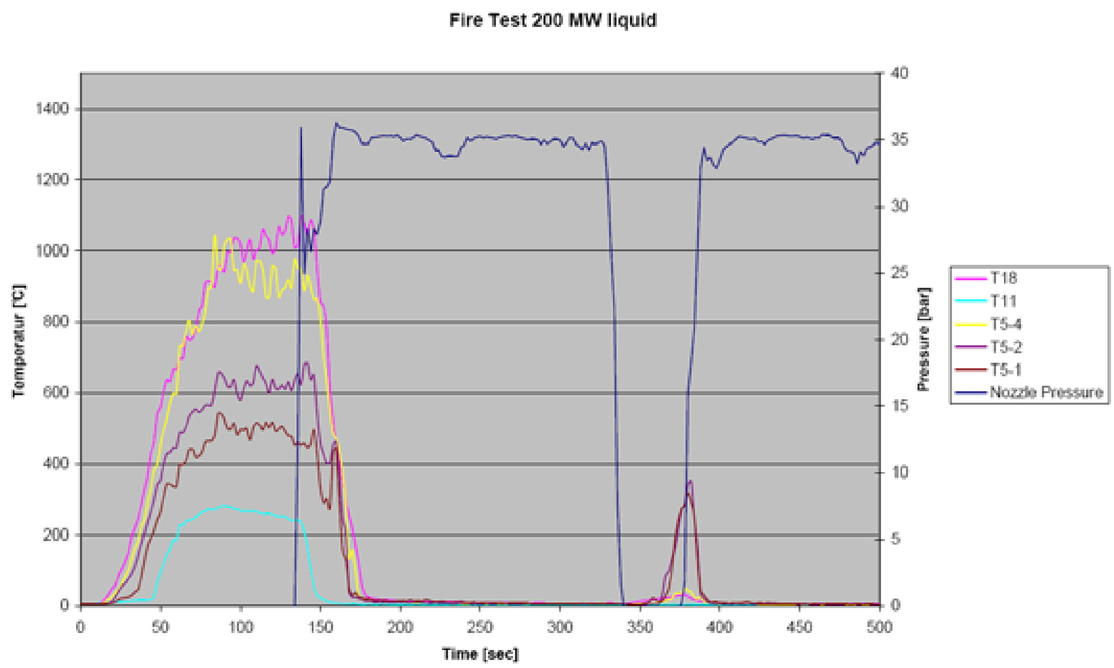


Figure 3: Temperature measurements - 200 MW liquid fire test

The temperature graph for the 200 MW liquid fire test (verification) shows an even quicker development of the fire up to 1,100°C. After activation of the water mist system, the temperatures above the fire load T18, T11 and at a distance of 5 m downstream of the fire load T5 decrease within 50 seconds until the fire is extinguished.
The peak, reached at a time of 350 seconds, demonstrates that there is still some fuel remaining and it is possible for the pool to be re-ignited.

3.3.2. Conclusions

The measured temperatures are within the limits as set forth in the schedule of requirements. In both directions relative to the fire load, namely upstream as well as downstream, the temperatures after one minute are well below the required 50°C upstream, and well below the required 280°C downstream respectively.

4. RISK OF A BLEVE

4.1. Introduction

In July 2007, the Rijkswaterstaat, the department within the Ministry of Public Works of The Netherlands that is also responsible for tunnel safety, decided that full-scale tests on the effectiveness of a Water Mist extinguishing system should also serve as a unique opportunity to obtain experimental data on the risk of a BLEVE in the area immediately downwind of the fire, and also to perform measurements on the tenability conditions within the first few hundred metres downwind of the fire.
Accordingly, Efectis, in combination with TNO, were asked to submit designs of suitable measurement methods and to carry out the necessary measurements during the fire tests.
In December 2007 and January 2008, five tests were carried out using both solid fire loads and fire pools. The largest solid fire load consisted of 720 pallets, configured to represent a loaded heavy goods vehicle. The fire pool consisted of diesel fuel and had a surface area of 100 m^2. The fire loads were designed to be similar to the ones used in the previous tests for the Rijkswaterstaat in 2005, and (in the case of the solid fire load) to one of the UPTUN tests in 2003.
This section focuses exclusively on the risk of a BLEVE. It does not deal with the effectiveness of the extinguishing system. It provides an overview of the data collected as well as some preliminary conclusions.
First the background common to the BLEVE tests is given, such as the general test objectives, the test location, geometry, the location of fire load and the location of the Water Mist system.
Then the BLEVE measurements are described in terms of the predictive model used, the required experimental data, the measurement system and the experimental results that were obtained.
In due time, an extensive analysis and more detailed evaluation will follow. Our particular thanks go to NBL and the Statens Vegvesen for their active contribution to the success of these tests.

4.2. The BLEVE tests

4.2.1. Principle

The principle of the BLEVE test was to actually measure the thermal behaviour of a water-filled LPG tank near the fire and to predict the risk of a BLEVE from such thermal behaviour. The use of a full-size LPG tank as a test object would ensure that the flow of air and water mist around the tank, the absorption of radiation, the condensation of water vapour on the outer surface, and even the run-off of water from the surface, should conform as closely as possible to actual real conditions.

The measurements were targeted to predict the risk of a BLEVE for a reference tank filled with LPG up to 10% of its maximum capacity. According to an extensive simulation study, this fill percentage will give the highest risk of a BLEVE. The test tank was filled with water up to 5% of its volume to achieve the same thermal capacity as the LPG.

The test tank was equipped with extensive instrumentation to measure wall temperatures, internal and external air temperatures as well as heat fluxes from the environment through the tank wall and into the water.

4.2.2. Assessment method

A simple model was developed to assess and give an indication of the risk of a BLEVE based on the measurements. The model was derived from the models developed for a simulation study. It predicts the rise in the actual stress in the shell (wall) of the reference tank and determines the drop in the maximum stress that the shell can withstand. As long as the actual stress remains well below the maximum stress, the risk of a BLEVE due to tank rupture is considered negligible.

The maximum stress that the tank shell can withstand is calculated from the temperatures measured on the external surface of the tank and the steel properties of the tank wall.

The actual stress in the tank shell is calculated from the tank diameter, the thickness of the shell and the pressure inside the tank. The pressure is calculated from the temperature of the LPG in the tank. In order to calculate this temperature, the heat flow into the LPG liquid is needed. Most of the heat penetrates directly through the ‘belly’ of the tank into the LPG liquid and is measured via heat flux meters in the test (where the LPG is replaced by water). Another non-negligible flow of heat towards the LPG liquid is radiated from the ‘non-wetted’ tank wall. This heat flow is calculated from the temperatures measured on the internal surface of the tank wall.

4.2.3. The test-tank

The measurement configuration consisted of an LPG tank, filled with water up to 5% of its volume.

Figure 4: The test tank in the tunnel and the access door that was cut in the end wall.

For practical reasons, the test-tank (length 6 m, diameter 2.5 m) was smaller than the reference tank (length 12.0 m, diameter 2.0 m). The smaller diameter of the test tank corresponds well with the fact that the test tunnel had a somewhat smaller cross-section than the reference tunnel. The shorter length of the test tank would cause a quicker rise in temperature and thus a higher probability of a BLEVE. The wall thickness was 8.8 mm, compared with 10 mm for the reference tank. This would lead to somewhat higher wall temperatures and is an acceptable conservative approach.

4.2.4. Instrumentation

Heat flux sensors (measuring the amount of heat entering the tank from the surroundings) were installed in holes drilled in the lower tank wall. The receiving surface of the sensors was carefully mounted exactly flush with the outer tank wall, as illustrated in Figure 5.

Figure 5: Mounting of the heat flux sensors in the tank wall - external and internal views

Thermocouples were mounted to measure the internal and external wall temperatures of the tank and the air temperatures 0.10 m from the tank wall. All data links and also the cooling water supply were connected at the rear side of the tank.

Figure 6 shows a schematic of the positions of the heat flux meters and thermocouples. The distance between the sections was approximately 1.2 m. A total of 13 heat flux meters and 65 thermocouples were installed.

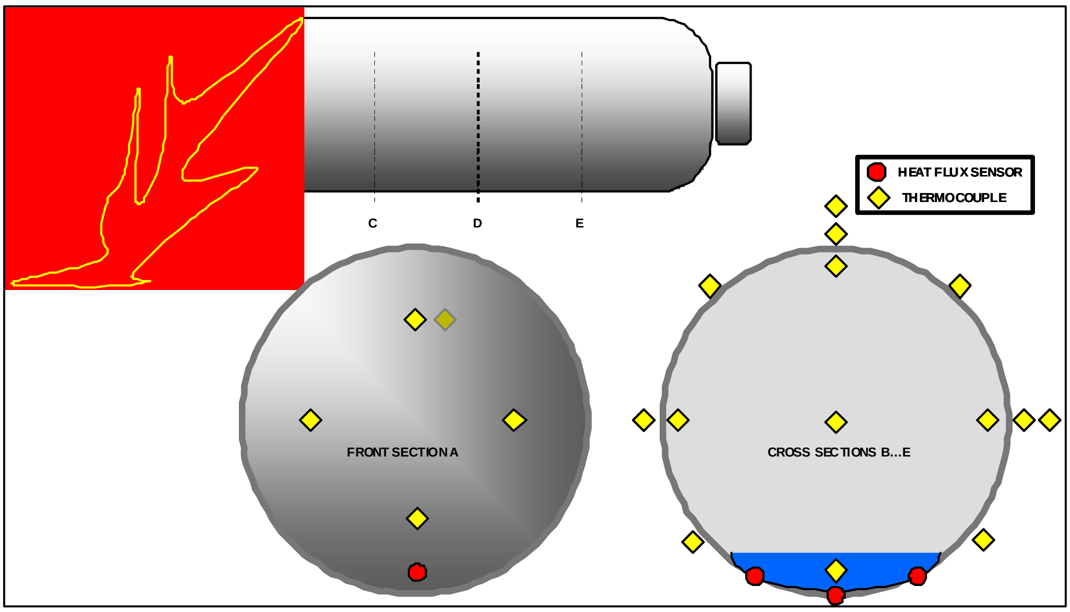


Figure 6: Positions of the heat flux meters and thermocouples

4.3. Results of BLEVE tests and discussion

The following abbreviations are used in the legends of the graphs:
VerTest1: 50 MW solid fire, Water Mist with AFFF (verification)
VerTest2: 200 MW liquid fire, Water Mist with AFFF (verification)
PerTest1: 200 MW liquid fire, Water Mist without AFFF (performance)
PerTest2: 200 MW liquid fire, Water Mist with biodegradable AFFF (performance)
PerTest3: 200 MW solid fire, Water Mist with AFFF (performance)

4.3.1. Temperature measurements around the tank

The temperatures measured near the external surface of the tank (0.10 m from the tank shell) are shown in Figure 7. The graph left shows the average of the 12 air temperatures measured over a period of 900 s after ignition of the fire. The sharp decrease in the air temperature was caused by switching on the water mist system. In the pool fire tests (VerTest2 and PerTest1 & 2), the fire was extinguished or significantly lowered within 60 s by the water mist, resulting in a temperature drop below 40ºC. In the solid fire tests (VerTest1 and PerTest3), the fire was only controlled by the system. In PerTest3, seeking the limits of the system, the mean air temperature remained around 400ºC (after an initial drop to 220ºC) and the maximum air temperature around 600ºC (after an initial drop to 400ºC).

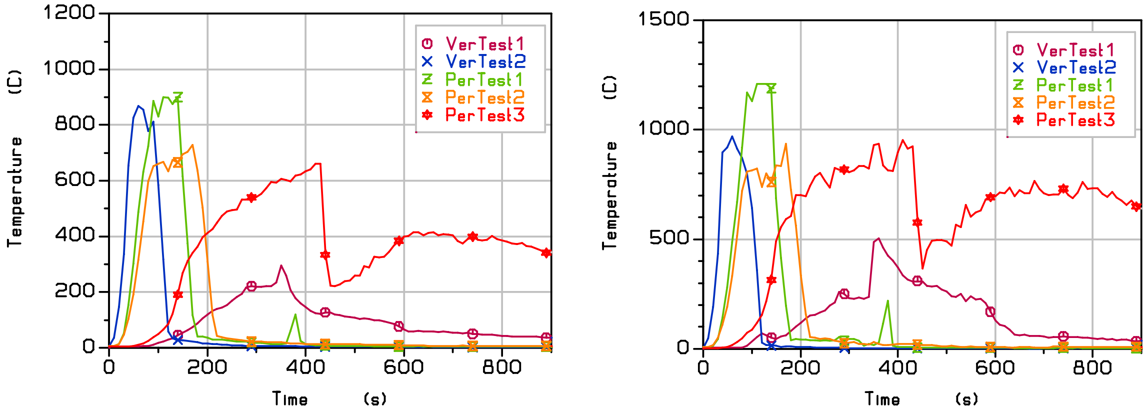


Figure 7: Mean temperature (left) and maximum temperature (right) of the air around the test tank

The position of the maximum temperature depends on the fire source as explained below.

First, in the pool fire tests, the (left) side of the tank facing the middle of the tunnel was exposed to higher temperatures than the other (right) side. This was partly caused by the symmetric position of the pool in the tunnel in contrast to the non-symmetric position (in the right lane) of the tank and also partly by the non-parallel position of the tank with respect to the tunnel walls. In the solid fire tests, the thermal exposure of the tank sides was more symmetrical, due to the fact that both the tank and fire source were positioned in the right lane.

Second, in the pool fire tests, the lower and middle parts of the tank were exposed to the highest temperatures. In the solid fire tests, on the other hand, the highest exposure occurred on top of the tank. This can be explained by the higher position of the solid fuel in contrast to the pool.

Finally, in the pool fire tests, exposure to the highest temperatures was more towards the back end of the tank (Sections D and E), whereas in the solid fire tests this maximum was more towards the front (Sections A and B). This difference is most probably caused by the distance between the base of the fire and the tank. With the pool fire, the minimum distance is attained almost immediately due to the fire spreading quickly over the total fuel surface. With the solid fire, the distance is larger because the fire spread more slowly from the rear of the pallet pile (where the fire was ignited) to the front (facing the tank) of the pile.

Clearly, in all tests except “VerTest1”, a significant part of the tank was immersed in flames. In the case of the pool fires, the flames were lower and more to the left side of the tank. With the solid fires, the flames were higher and more symmetrical, surrounding the top part of the tank. The reason for this difference is the position and height of the fire source with respect to the tank position.

4.3.2. Temperatures measurements of the tank wall

The maximum temperature of the tank wall is shown in Figure 8 for each test, but now for a period of 1,800 s. The maximum wall temperatures were in the same area as the maximum air temperatures around the tank. Clearly the wall temperatures follow the surrounding air temperatures, but with a time delay caused by the thermal inertia of the wall. The highest temperature (about 600ºC) occurred in the solid fire test “PerTest3”, where the fire was only controlled by the water mist system to a certain extent.

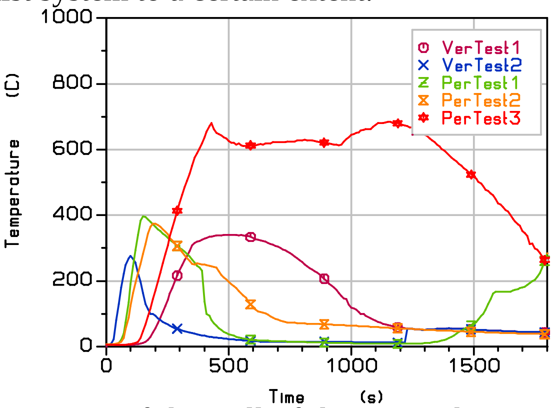


Figure 8: Maximum temperature of the wall of the test tank. Note: the increase in temperature in PerTest 1 is caused by the after-burning of the fuel and is not part of the official test.

4.3.3. Heat flux measurements

Heat fluxes measured from the tunnel environment in the ‘belly’ of the tank in contact with the water in the tank are shown in Figure 9. The figure shows the weighted mean value of all 13 heat flux meters. The highest heat fluxes occurred in the pool fire tests, where the tank was heated more from below than in the solid fire tests. The high peak in ‘PerTest1’ is probably due to the somewhat higher ventilation velocity during that test. The heat fluxes due to the solid fires are much lower, because of the higher position of the flames, as already explained in Section 4.3.1. Even in “PerTest3”, the mean heat flux remains below 20 kW/m^2.

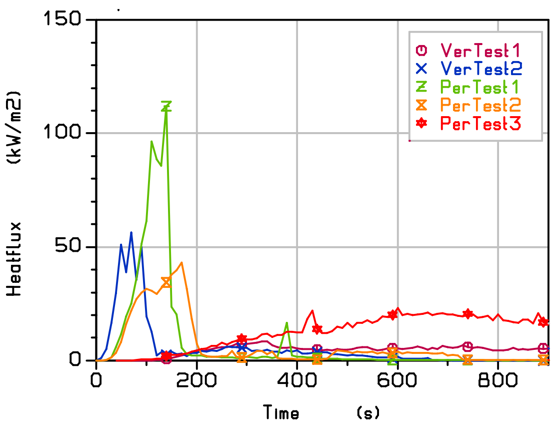


Figure 9: Mean heat flux in the ‘wet’ part of the test tank

4.3.4. Assessment of the risk of a BLEVE

Figure 10 shows the (LPG vapour) pressure that would occur in the reference LPG tank, calculated from the measured heat fluxes and tank wall temperatures. The rise in tensile stress in the tank wall due to the highest pressure (in "PerTest3") is shown in Figure 11 under the label TS-LPG. The same figure shows the drop in the maximum stress that the tank wall can withstand.

Clearly the only critical situation occurs in "PerTest3", where a sharp decrease in the maximum allowable stress occurs due to the high tank wall temperature. The critical situation begins after about the 400 s point and remains until about the 1,300 s point. The pressure rise due to the heating up of the LPG is less important.

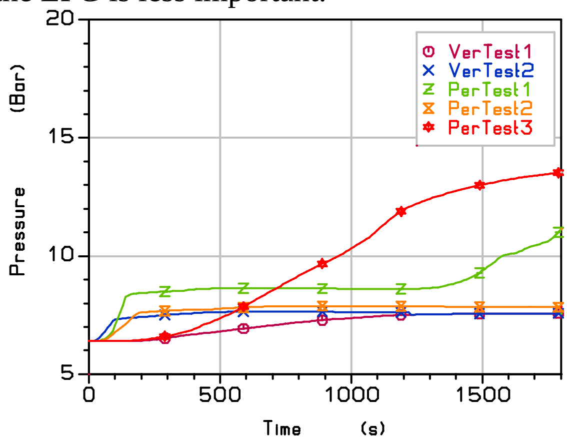


Figure 10: Pressure of LPG in the reference tank calculated from measured heat fluxes and wall temperatures of the test tank.

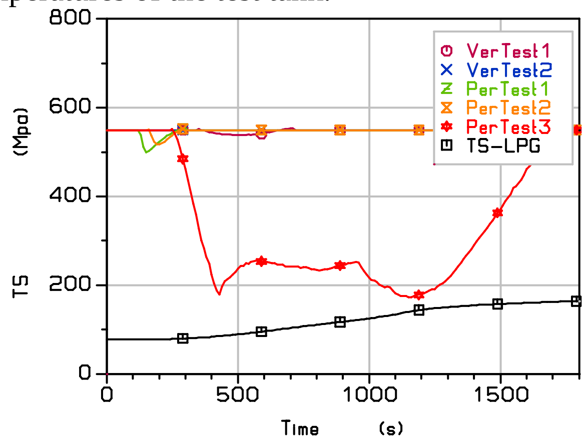


Figure 11: Maximum stress that the wall can withstand for each test versus the actual stress (label TS-LPG) in PerTest3. Note: the actual stress in the other tests is lower than in "PerTest3".

4.3.5. Conclusion

Only in "PerTest3", a test with a solid fire seeking the limits of the water mist system, did a serious risk of a BLEVE occur. This situation was created by waiting extremely long (ca. 7 minutes after ignition) before activation of the Water Mist System. In all other tests, the fire was extinguished or controlled quickly enough to prevent the heating up of the tank wall above a critical temperature of about 600ºC. Quick detection and extinguishment of the fire is of particular importance in the case of a pool fire, due to the fast rise in the temperature around the tank to about 1,000ºC.

The effect of the pressure increase of the LPG due to the heating up of the LPG is less important.

5. TENABILITY TESTS

This section focuses exclusively on the tenability conditions. It does not deal with the effectiveness of the extinguishing system. It provides an overview of the data collected as well as some preliminary conclusions. The tenability measurements are described in terms of the required experimental data, the measurement system and the experimental results that were obtained. In due time, an extensive analysis and more detailed evaluation will follow.

5.1. Aim

Tenability tests were designed to measure conditions between 20 m and 300 m downwind from the fire. When closer to the fire than 20 m, conditions are almost certainly life-threatening, while further away than 300 m, there may be sufficient opportunity and time for evacuation.

During previous large-scale tests such as the tests in the Runehamar tunnel in 2003 and 2005, temperature data were collected at greater distances (about 1 km downstream) as part of the data to measure the rate of heat release. At such distances, cooling has already caused a loss of stratification, and conditions are likely to be very different from those closer to the fire.

5.2. Parameters

The parameters demonstrating the greatest influence on the chances of surviving a fire are the thermal effects, due to the heat transfer to the human body, and the toxic effects of combustion products, in combination with the duration of exposure.
The heat transfer of the environment to the human body is governed by the convection of hot air and by radiation from flames or hot smoke. Heat transfer by evaporation or condensation can also be important, and for this mechanism the relative humidity plays a role. Ideally, in order to predict this heat transfer accurately, separate measurements of each parameter would be required.
The main toxic effects can be expected from gases like carbon monoxide, hydrogen cyanide and hydrogen chloride. In the tests described here, the fire loads consisted almost exclusively of carbohydrates (cellulose) and hydrocarbons (diesel, plastics). Carbon monoxide was the main toxic gas produced in these tests, and the CO concentration in the local atmosphere is regarded as the decisive criterion.
The duration of exposure to the thermal and toxic effects is determined by the time it takes to reach a safe location, and this time, in turn, is strongly influenced by local visibility.
It was decided to install sensors at a relevant height (between 0.6 m and 2.0 m), and at a range of distances from the fire: 20 m, 40 m, 100 m and 300 m downwind from the fire.

5.3. Layout of the system

In Figure 12, the downwind tunnel length of 350 metres is divided into three sections to fit on the page. The location of the test fires and the direction of the ventilation are shown.

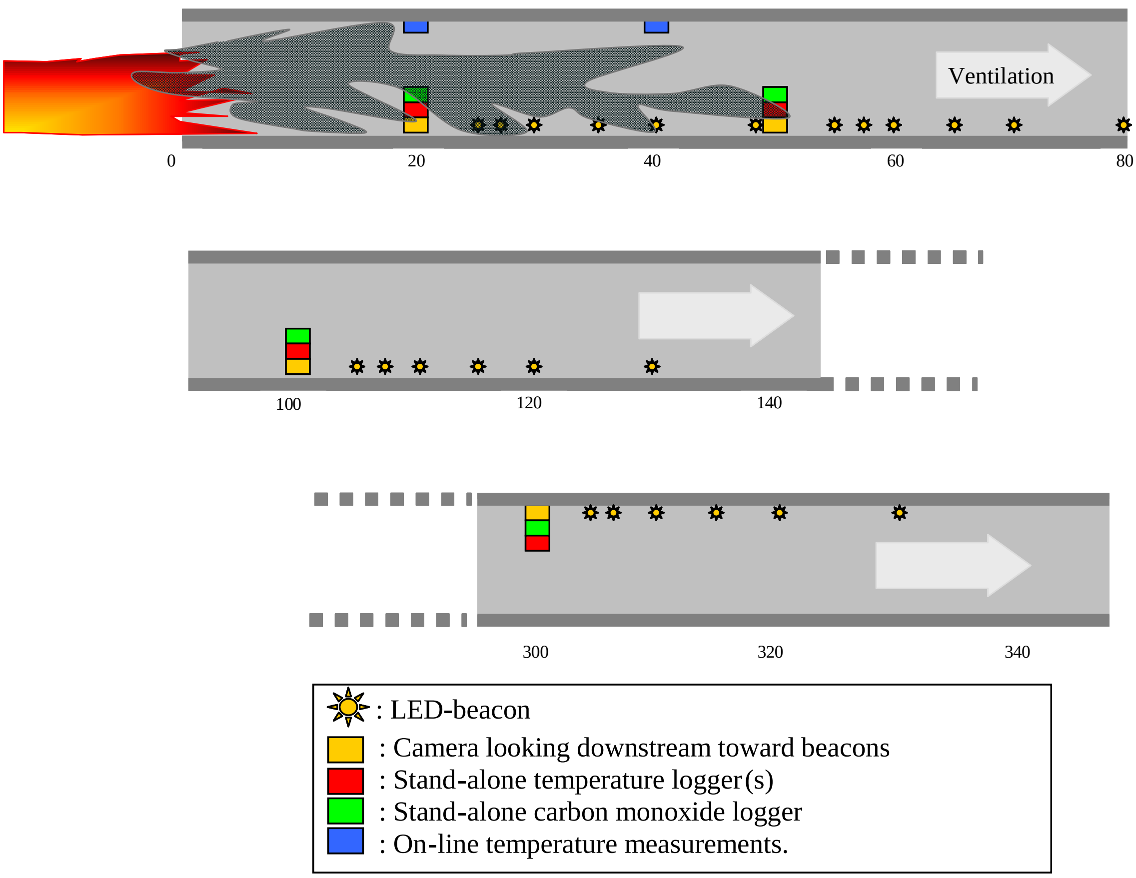


Figure 12: The physical layout and position of the cameras and sensors used to measure tenability. Each camera looks at six beacons, set at distances of 5, 7, 10, 15, 20 and 30 m.

The design of the sensors and cameras and their protection was based on the fact that conditions downwind during the actual fire test would be very severe. High temperatures, a very high moisture content, condensation of steam and sudden cooling by the water mist system had to be dealt with.

5.4. Results

The measurements yielded valuable data during all five tests. Some illustrations of the test results are given below.

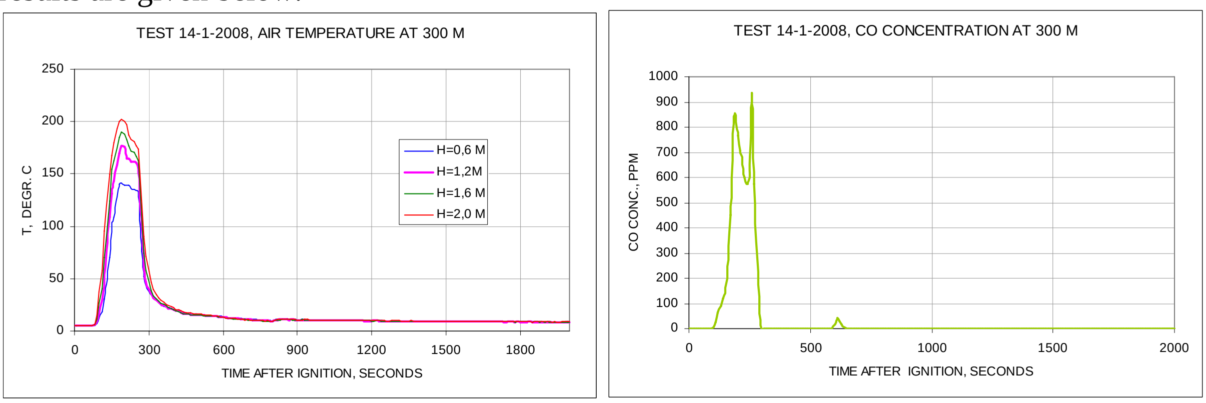
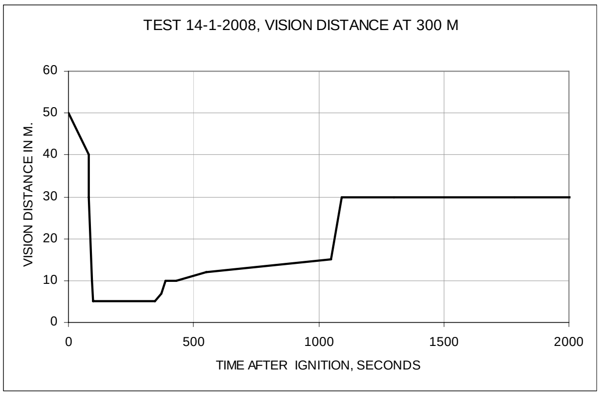


Figure 13: This sample shows the data recorded during performance test 2, at 300 m



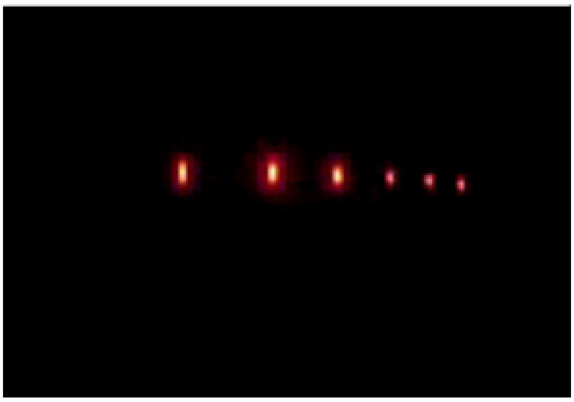


Figure 14:
The video stills illustrate the vision distances and are extracted from the images of six LED beacons.

This image shows all six LED beacons at distances of 5 m (on the left) to 30 m (on the right). This image shows (by way of example) the situation before ignition of a fire.

This image shows just 3 beacons, so the vision distance is 10 m. This image shows (by way of example) the situation a few minutes after ignition of a fire.

5.5. Analysis

The large amount of information in the data collected requires, initially at least, fairly basic criteria to make a first assessment of the tenability conditions.
For temperatures, we have assumed the following safety limits in our initial evaluation:
Up to 50°C is tenable indefinitely (hereinafter characterized as Green).
50 to 75°C is tenable for 5 minutes (hereinafter characterized as Amber).
Above 75°C is immediately life-threatening (hereinafter characterized as Red).
The fact that high relative humidity worsens the effect of high temperatures has not yet been taken into account, due to the lack of reliable humidity data. In setting the above temperature limits, a relatively high humidity is assumed corresponding to the activation of a sprinkler or water mist system.

For carbon monoxide concentration, the following values are used:

Up to 250 ppm is tenable indefinitely (Green).
Up to 500 ppm is tenable for 5 minutes (Amber).
Above 500 ppm is life-threatening (Red).

Furthermore, the following rules are applied:

Amber during more than 5 minutes = Red.

Amber + Amber = Red (the combined physiological effect can be life-threatening).

Amber + poor visibility (vision distance < 10 m) = Red. (The effect of extra exertion and stress can be life-threatening).

The analysis was carried out using the following procedure:

From the data collected and the criteria given above, it was determined when and for how long each "Red" situation lasted in each test and for each measurement location.

The results of this analysis are shown below in the form of graphs.

Each graph shows four bars, representing the 4 positions and their distance from the fire. The vertical axis shows the time elapsed since ignition. The colour of the bar at that time indicates whether or not the condition at that time is tenable. The term LTC in the graphs stands for: Life-Threatening Condition.

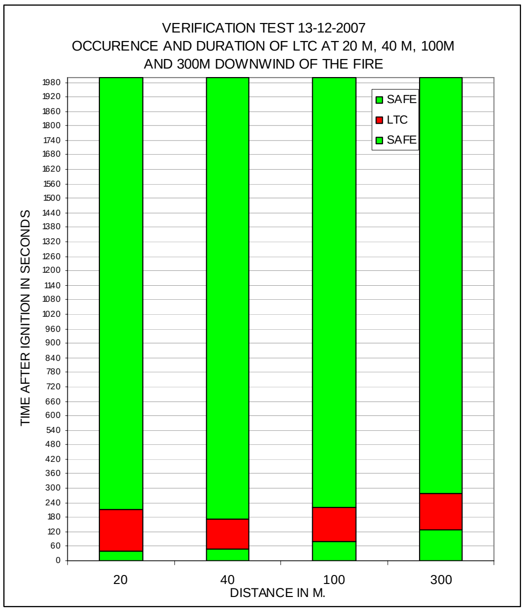


Figure 15: Small pallet fire, 50 MW

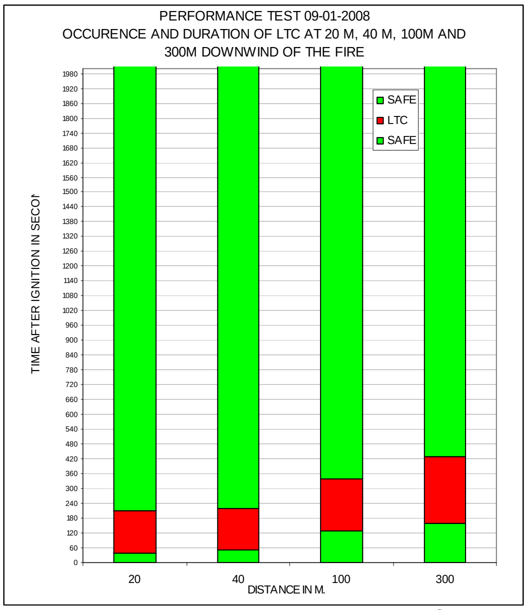


Figure 16: Pool fire, 100 m^2

5.6. Preliminary conclusions on tenability

In the case of an open pool fire of 100 m^2 and with rapid activation of the WMS within around 80 seconds, conditions downwind will be life-threatening for about 5 minutes or less. In the case of a pallet fire of about 50 MW, conditions downwind will be life-threatening for about 3 minutes or less.

It should be emphasized that these conclusions refer only to the actual test conditions in terms of tunnel geometry, ventilation, ignition method and start time of the WMS.

6. CONCLUSIONS

On the basis of the available data, the following tentative conclusions can be made:

- A Water Mist system is a very effective and efficient fixed fire-fighting system.
- A Water Mist system can extinguish or control a 200 MW liquid fire (especially when an AFFF is added) fast enough to prevent a BLEVE.
- A Water Mist system can reduce and control a 50 MW solid fire. There is no risk of a BLEVE.
- In the case of the 200 MW solid fire, the limits of the water mist system were approached, by waiting about 7 minutes after ignition before starting the Water Mist System. Serious risk of a BLEVE occurred in between 400 and 1300 seconds after ignition.
- Quick detection and extinguishment of the fire are essential to reduce the life-threatening conditions downwind and to prevent a BLEVE.

More comprehensive analyses and conclusions will be published later.

HI-FOG DEMONSTRATION AT TST, SAN PEDRO DE ANES FEBRUARY 15 AND 16, 2006

Dipl. Ing. Uwe Klinkhardt.[1]
[1]Marioff GmbH

ABSTRACT

During December 2005 – February 2006 Marioff Corporation Oy conducted an extensive set of over 40 full-scale fire tests in the San Pedro test tunnel. Official parts of the test series were witnessed by the following third party organizations: CEMIM (concentrating mainly in ventilation issues) / Spain, AFITI-LICOF / Spain, Hughes Associates Inc / USA and SP (Swedish Testing and Research Institute) /Sweden.

Three different HI-FOG configurations were evaluated:

- a deluge-type water mist system consisting of open spray heads only,
- a hybrid system consisting of both open spray heads and automatic, thermally activated water mist nozzles, and
- a water mist sprinkler system consisting of automatic, thermally activated nozzles only.

In all configurations the water flux density at the fire location was about the same (i.e. the suppression and control efficiency is the same), whereas the water flux density outside the exact location varied. All three systems were divided in zones of 32 m length.

A considerable safety factor was involved in all the tests. A real HI-FOG System for tunnel would be dimensioned for three full zones for a certain minimum pressure. Most of the tests, however, were run with only one zone open at the minimum pressure, as compared to three zones at the minimum pressure or one zone at a considerably higher pressure.

Different fire scenarios were tested, ranging from passenger vehicles fire up to catastrophic truck-type fires involving wood and plastic. It is worth nothing that plain pool fires represent real tunnel fires, which – to the most part – involve solid, Class A materials and have a potential to an ultra fast fire growth practically without an upper limit for heat release rate.

The primary result of the testing was:

1) *without* the HI-FOG system the fire would have been out-of-control just within a few minutes after it had properly ignited
2) *with* the HI-FOG system the temperatures in the tunnel were instantaneously and dramatically dropped down to non-damaging levels,
3) the fire was immediately under control and got suppressed during the discharge, and
4) the fire spread was stopped within the ignited vehicle or from jumping from vehicles to vehicle

All official tests are described and evaluated in detail by the third-party organizations in separate test reports.

1. DEMONSTRATION TESTS

1.1. Demonstration test 150206

Two demonstration test were conducted on Feb 15 and 16, 2006, the other one simulating a fire involving passenger vehicles, the one simulating a lorry. In the fire test, the HI-FOG deluge-type water mist system was applied. In the second test the HI-FOG hybrid-type water mist system was demonstrated.

For safety reasons, the demonstrations were run with relatively short preburn times and a full discharge time of 20 min. For comparison, corresponding temperature results of official tests with longer preburn and discharge times are included in the description on the following pages.

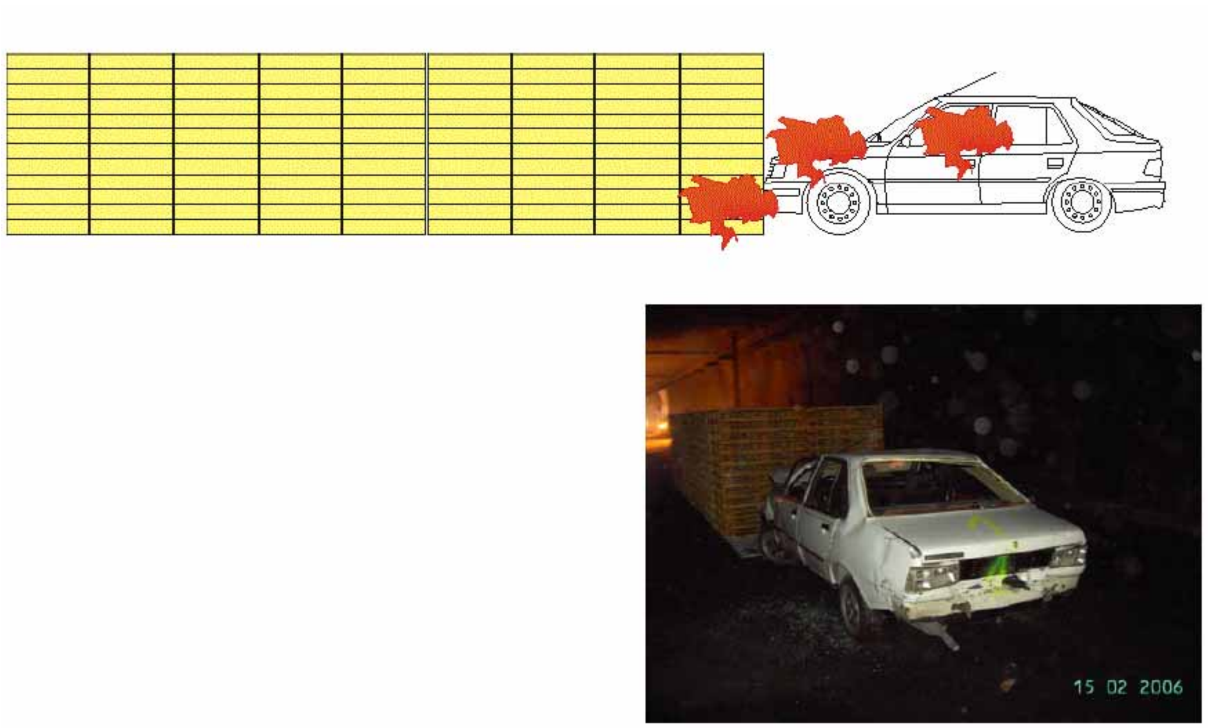


Figure 1+2: Fuel package (real car + 2 x 12 x 9 pallets on the floor level + target cars)

Figure 3+4: Freeburn demo test 150206 – abt 2 min 30 s
official test 230106 – 5 min 11 s
official test 240106 – 7 min 11 s

Ceiling temperature along the tunnel

(red curve – above ignition, orange curves – downstream, blue curves – upstream)

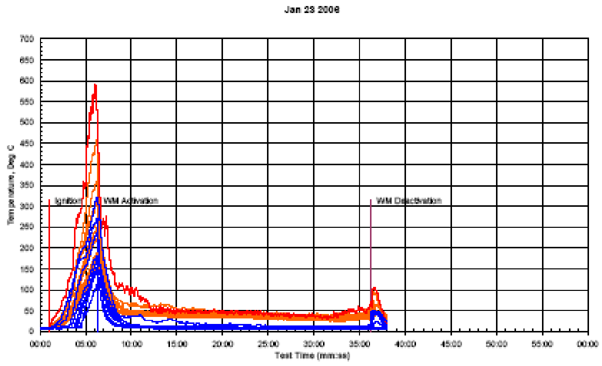


Figure 5: Official test 230106

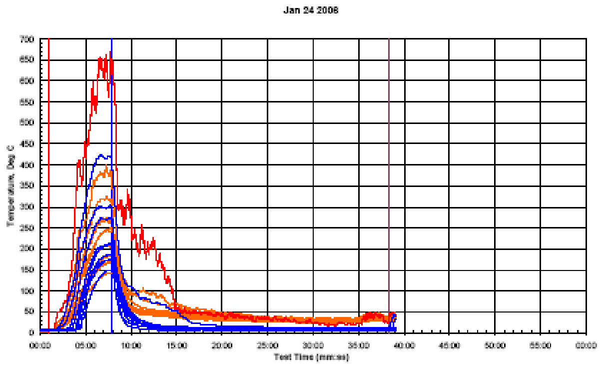


Figure 6: Official test 240106

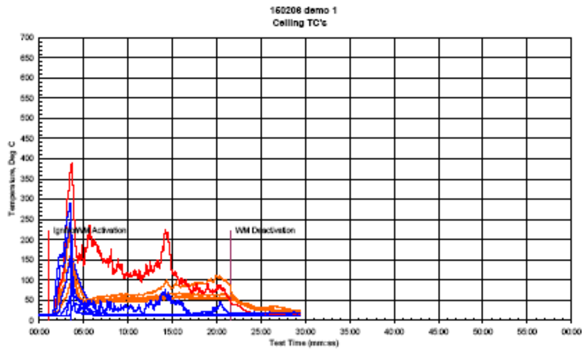


Figure 7: Official test 150206

- The effect of different preburn times is seen in the ceiling temperature before activating the HI-FOG system: the longer the preburn time, the higher the ceiling temperature
- The trend after activating the HI-FOG system is clear: there is an abrupt drop in temperatures immediately after HI-FOG activation. Just above the fire it takes longer to stabilize the temperatures to lower values.
- The differences in the curve of different test just reflect that full scale fire tests are never totally repeatable, but the overall performance is the same.

Temperatures within a cross section downstream from ignition

(red curves – ceiling level, green curves – 1,5 m level, blue curves – 0,5 m level)

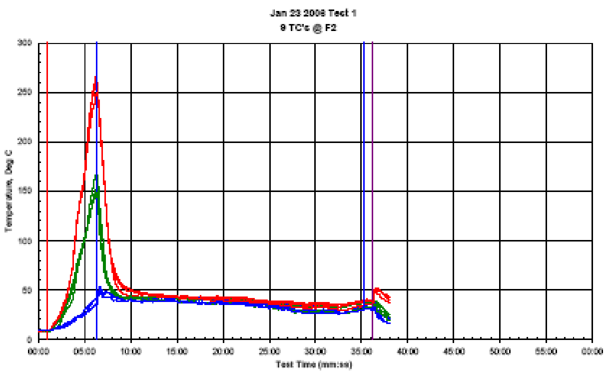


Figure 8: Official test 230106

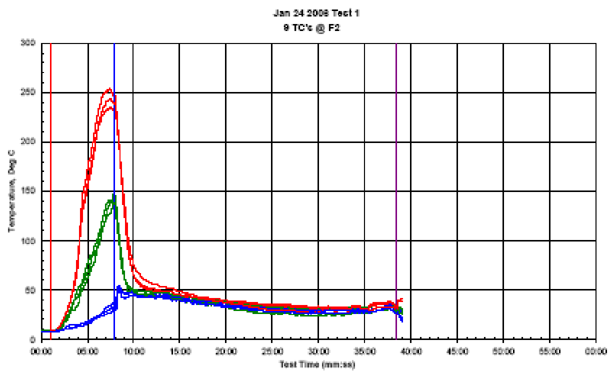


Figure 9: Official test 240106

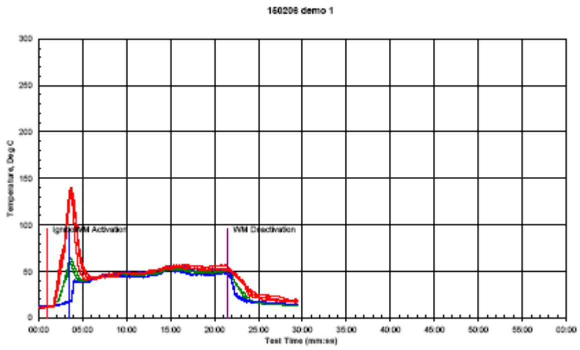


Figure 10: Official test 150206

Note:

The fire location was different in the January tests, the measurement cross section was 35 m downstream from ignition, whereas in the demonstration test the cross section was only 23 m from ignition

- The effect preburn times is seen especially in the ceiling and 1,5 m level temperatures before activating the HI-FOG system: the longer the preburn time, the higher the temperatures.
- The trend after activating the HI-FOG system is clear: there is an abrupt drop in temperatures immediately after HI-FOG activation.
- The differences in the curve of different test just reflect that full scale fire tests are never totally repeatable, but the overall performance is the same.

1.1.1. Damage:

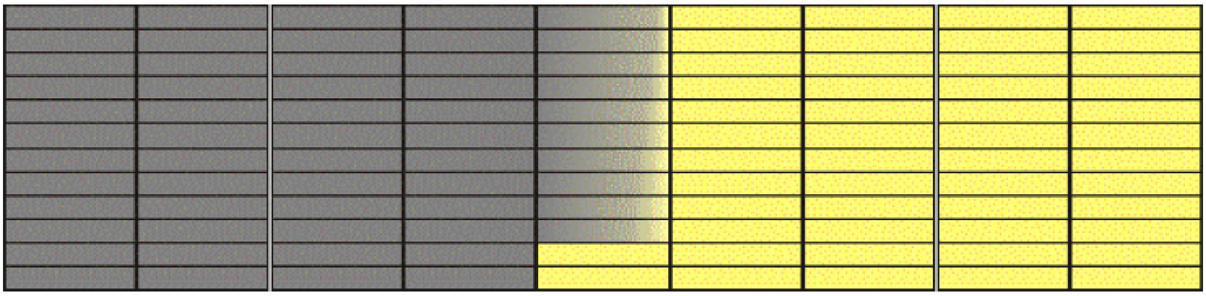


Figure 11: 4-5 / 9 stacks damaged, target cars intact

Figure 12: Not damaged stacks

Figure 13: Not damaged stacks

Figure 14: Intact target car

1.1.2. Demonstration test 160206

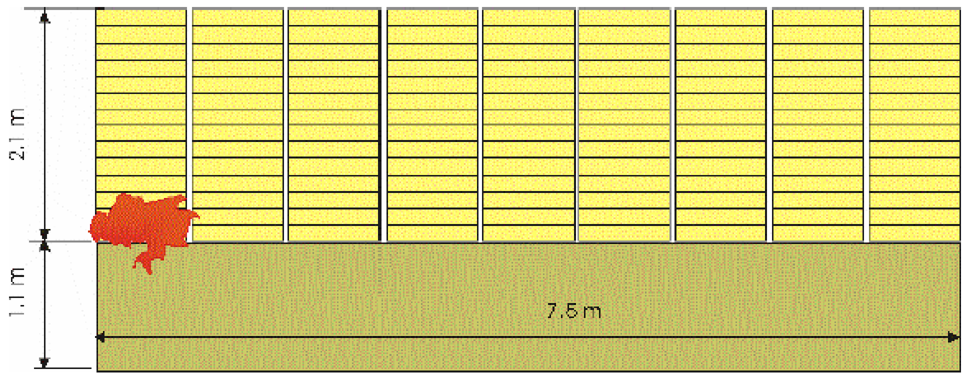


Figure 15+16: 2 x 14 x 9 pallets on a 1,1 m high stand

Figure 17+18: Freeburn demo test 160206 – < 4 min
official test 020206 – 5 min 40 s

Ceiling temperature just above the fire

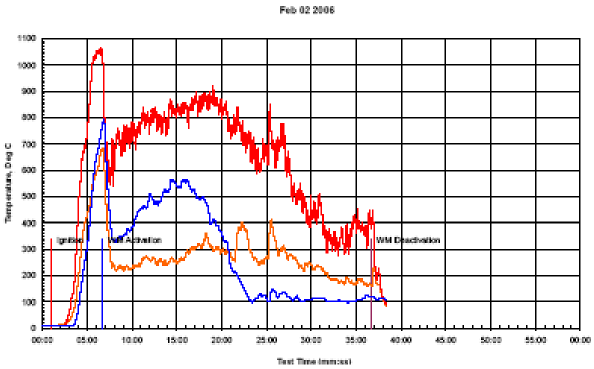


Figure 19: Official test 020206

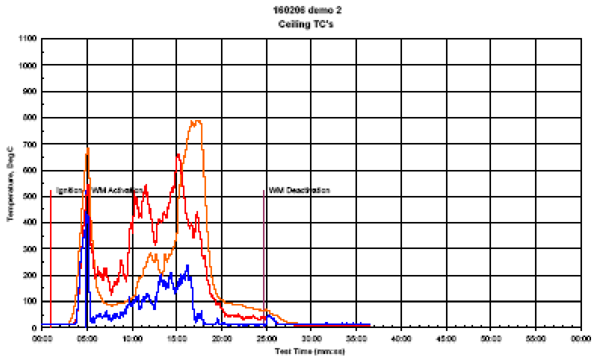


Figure 20: Demo test 160206

Ceiling temperature further away from the fire
(orange curves – downstream, blue curves – upstream).

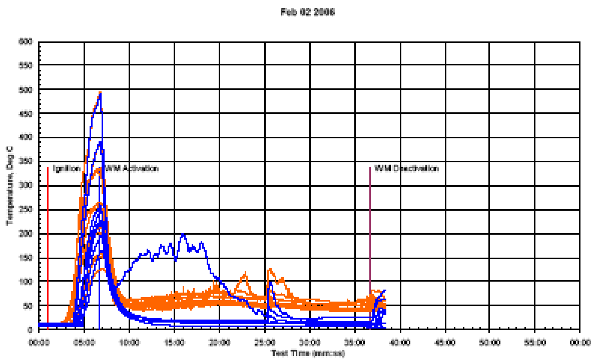


Figure 21: Official test 020206

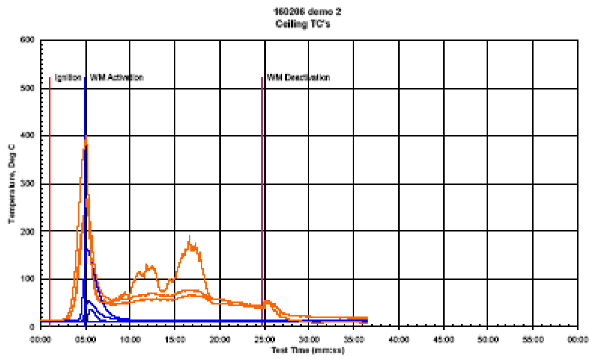


Figure 22: Demo test 160206

- The fire is very severe with the open wood pallet configuration: plenty of air is available everywhere within the pallets and the pile is constructed mostly of hidden, burning surfaces.

  The effect of different preburn times is seen in the ceiling temperatures both before activating the HI-FOG system and during the discharge: the longer the preburn time the higher the ceiling temperatures and the more severe is the fire. Just 2 min more of free burning increases the severity of the fire considerably and requires more time for getting it suppressed.

- The trend after activating the HI-FOG system is clear: there is an abrupt drop in temperatures immediately after HI-FOG activation. Just above the fire it takes longer to stabilize the temperatures to lower values.
- The differences in the curve of different test just reflect that full scale fire tests are never totally repeatable, but the overall performance is the same.

The demonstration test 160206 showed how unexpected things can occur during a large fire: at around 10 min after HI-FOG activation, the fire seemed to increase in strength till it abruptly was reduced again. The behaviour is likely to related to collapsing of piles, first exposing large surfaces of burning material and then fully collapsing and suppressing the fire.
(The cracking sounds heard during the test were related to a plugged assembly body made of brass that finally ruptured after surviving tens on tests – in real installation the assembly bodies are made of stainless steel and, of course, are not repeatedly exposed to open flames.)

Temperatures within a cross section downstream from ignition
(red curves – ceiling level, green curves – 1,5 m level, blue curves – 0,5 m level)

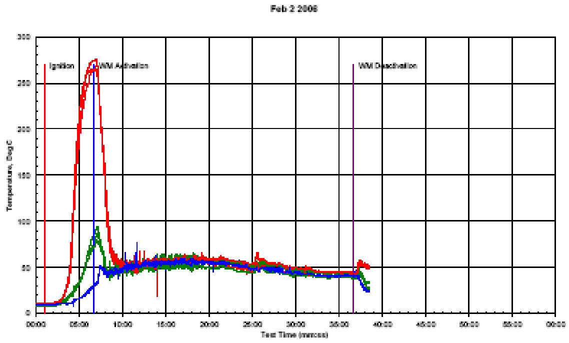


Figure 23: Official test 020206

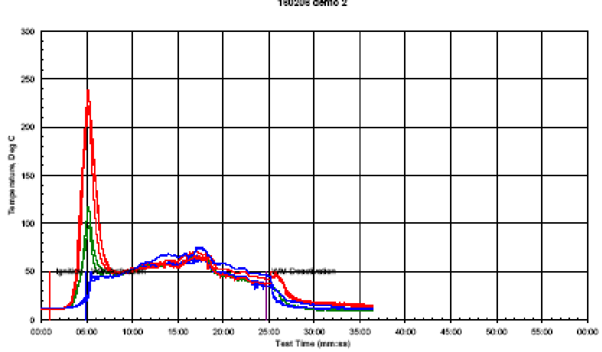


Figure 24: Demo test 160206

Note:

The fire location was different in the test 020206, the measurement cross section was 35 m downstream from ignition, whereas in the demonstration test the cross section was only 23 m from ignition

- The trend after activating the HI-FOG system is clear: there is an abrupt drop in temperatures immediately after HI-FOG activation.

1.1.3. Damage

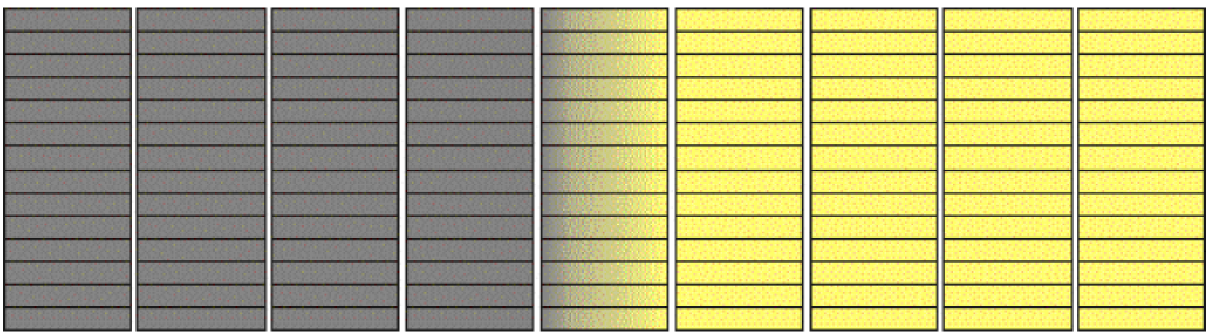


Figure 25: 4-5 / 9 stacks damaged

(The grey part is destroyed and/or damaged by the fire. Yellow means without fire damage.)

1.2. Summary

The demonstrations described above were tested successfully for the employment in the M30 Tunnel in Madrid and were the base for the planning and interpretation of the high pressure water mist system.

The HI-FOG system makes a decisive difference in the first 10 to 15 minutes of a tunnel fire. the most critical time in the fight to save lives and minimize material damage. The micro-droplets of HI-FOG water mist have a dramatic heat blocking and cooling effect immediately upon activation: in seconds, the temperature of the air surrounding the fire drops to 50°C. The HI-FOG micro-droplets rapidly absorb heat, particularly by evaporation, giving very effective cooling. By curbing the development of the fire´s heat intensity, they also greatly reduce the amount of smoke.

HI-FOG uses substantially less water than conventional sprinkler system: saving related to water supply, storage and drainage can be expected. The system´s high-grade stainless steel components will substantially outlast the equivalent components of a conventional sprinkler system. Savings can be expected here. Furthermore, the performance and cooling capabilities of HI-FOG may allow associated equipment to be operated at cost saving temperatures – every little bit helps in the long run.

HI-FOG is the world´s most tested and approved water mist fire protection system for tunnels. At the specification stage, HI-FOG is similar to a conventional sprinkler system when it comes to dimensioning – sizing zones and deciding on the number of zones that can be activated simultaneously. It does not introduce unwanted complexity into the equation. There is one significant difference. With HI-FOG, the dimensioned water flow rate is much less.

Zone size is decided according to the maximum vehicle length allowed, the expected fire load, the accuracy of the fire detection system, the ventilation technique and the safety margins associated with each of these parameters.

THE HAZARDS OF TRYING TO IMPROVE THE SAFETY OF TUNNELS

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ABSTRACT

In recent years a number of countries have updated their requirements for safety related equipment and facilities in road tunnels and, in 2004, the EU Directive set down minimum safety requirements for all tunnels on the Trans European Road Network. Manufacturers are also responding to this quest to improve tunnel safety by developing and marketing ever more products and systems and tunnel owners are equipping their tunnels with this latest technology.

But are all these safety-related products really improving the situation compared to the systems and equipment which have been used for decades? Are these products actually introducing hazards into the tunnel that increase the risks to tunnel users?

This paper will identify some of the many hazards which are introduced when safety facilities – both old and new – are installed in tunnels, attempt to identify why such massive investments are being made and question whether or not it is the best approach to improve tunnel safety.

Keywords: road tunnel, equipment, safety, hazards

1. INTRODUCTION

The majority of the safety-related facilities and equipment commonly installed in tunnels is concerned with reducing the consequences of fires. The EU Directive (Directive 2004/54/EC) and the design guidelines in many countries are requiring that yet more resources be invested, principally to mitigate the consequences of the fire incident even though it rarely occurs. Little or no investment is being required for either reducing the number of incidents or reducing the consequences of "normal" traffic incidents. This is despite the fact that both the number of casualties and the incident costs are significantly higher for accidents in a tunnel than they are for fires (Day 2003).

The inclusion of all these safety-related facilities and equipment brings with it additional hazards for the tunnel users. Contrary to the belief of some suppliers, equipment for improving safety actually introduces more hazards into the tunnel as is demonstrated below. Some of those hazards are identified for both old and new safety facilities; the approaches used to mitigate the hazards introduced by the "old" systems and facilities are described and those introduced by some of the latest systems and facilities are highlighted.

2. SYSTEMS

2.1. Fire Hydrant System

A pipe network leading from a reservoir to hydrants outlets distributed throughout the tunnel is one of the traditional systems that have been installed in many tunnels. Even this simple system introduces hazards into the tunnel but the associated risks have been minimised. The hydrant outlets are located in niches in the tunnel walls both to prevent them being a hazard to errant vehicles and prevent errant vehicles being a hazard to the hydrant system.

A mechanical failure in the system pipework could result in flooding but the risks from this hazard have been mitigated by sizing the tunnel's normal drainage system to be capable of receiving any water released.

2.2. Fixed Fire Suppression

Deluge systems have been installed for many years in a number of road tunnels in Japan with the specific aim of protecting the structure. All road tunnels in Australia have deluge systems that are activated manually by the tunnel operator. In Europe and the USA very few tunnels have fixed fire suppression systems but that situation is changing. Systems are going to be installed in a number of tunnels including the A86 tunnel in Paris which is nearing completion, the second Tyne Tunnel currently being designed and the Dartford Tunnel when it is refurbished. The latter two tunnels are submerged tunnels and the need to protect the facility by protecting the structure is obvious. It is unclear when these systems will be discharged – immediately the fire is detected or, like in Japanese tunnels, after some delay period to allow time for people to escape from the fire zone.

Although a fixed fire suppression system in a tunnel reduces the risks resulting from a fire by reducing the consequences it does also introduce additional hazards to the tunnel users. The obvious hazard is the loss of visibility when the system is discharged, particularly with systems based on water mist technology. To mitigate this hazard the Japanese delay the discharge of their systems until some time after the fire is detected in order to allow those trapped in the tunnel to make good their escape.

Another hazard is a false discharge due to either a system fault or a mechanical or material failure of one or other of the components of the system as a result of the aggressive atmosphere known to be present in road tunnels. Such a discharge did occur during May 2005 in the 335 m long tunnel near Boston in the USA (**Figure 1**) and, although there were no casualties in that instance, it could easily have resulted in an accident and, possibly, fatalities.

Figure 1: A malfunctioning fire suppression system drenched the tunnel under City Square in Charlestown in May 2005

(The photo seems to indicate that it was not so simple to turn off the water to the sprinkler system!)

2.3. Ventilation Systems

2.3.1. Longitudinal ventilation systems

The principle hazard associated with longitudinal ventilation systems is the security of the jet fans themselves. Failure of their mountings or the unit itself could result in the whole or parts of the fan falling onto the carriageway. To this end many countries now demand that the fixings for all equipment hung in the tunnel are manufactured from a stainless steel with a high molybdenum content, an alloy that has been shown to be resistant to corrosion in the aggressive environment found in a road tunnel.

Once a fire is detected in a tunnel the jet fans are switched on to control the smoke spreading. In a tunnel with uni-directional traffic all of the smoke will be blown to one side of the fire and those trapped in the tunnel upstream of the fire will be protected from it. In a tunnel with bi-directional traffic the jet fans will be used to stop any longitudinal flow to minimise the heat loss from the smoke and promote stratification so maximising the time before it cools and descends. In both cases the operation sequences are short and simple. Multiple jet fans provide a degree of redundancy to ensure that the smoke can be controlled provided, of course, that the electrical power to the fans and control equipment remains intact.

2.3.2. Smoke extraction systems

In many European countries emergency ventilation systems are required exhausting smoke from the tunnel near the fire into an exhaust duct through remotely controlled mechanical dampers. Assuming that the dampers are supported by the exhaust duct and are not hung from it, the hazards directly associated with such systems are the same as with a longitudinal system, i.e. the jet fans that are needed to ensure that fresh air is drawn in from both tunnel portals irrespective of the fire's location in the tunnel and the prevailing meteorological conditions.

The goal of these new systems is to minimise the smoke spread along the tunnel, reduce the length of the tunnel which is affected by smoke and, as a result, limit the number of people likely to be affected by it. While not questioning the effectiveness of these systems it has to be recognised that this depends on a number of other systems all functioning correctly:

- Rapid detection of a fire by the fire detection system or alternative measures
- Rapid detection of the fire's location by the fire detection system or by the operator correctly choosing the location based on CCTV images
- Opening of the correct exhaust dampers
- Starting and correct functioning of the exhaust fans
- Detection of the speed of the air coming from each portal
- Correct functioning of the jet fans to control the air speed coming from each portal

If any one of these systems fails to operate or operates incorrectly, the smoke extraction either will not happen, or will be from the wrong location or may not be all of the smoke. Any of these events would significantly increase the numbers of people who would be affected by the smoke hazard.

A similar situation would exist if the smoke extraction system failed during operation because of the inevitable changes in the flow and pressure drop along the exhaust duct. If the fans operating point is close to the stall boundary, these changes may be sufficient for it to go into stall. If the fan has variable pitch blades it is possible to avoid this situation and move the operating point away from the stall boundary by reducing the blade angle. However, if the fan is of the fixed blade, variable speed type powered through frequency converters it is not possible to move the operating point away from the boundary and the fan will have to be stopped. This situation with fixed pitch fans can only be avoided by ensuring that the operating point is well away from the stall boundary so that when the temperature in the duct rises and the pressure drop along the duct increases the operating point does not approach the stall boundary.

Even if the smoke extraction system and the jet fans function perfectly, the effectiveness of the system is dependent on the rapid detection and location of the fire. Failure to achieve this means that the smoke will have propagated well outside the exhaust zone and spread over a considerable length of the tunnel before the exhaust starts functioning, after which the spread of the smoke will be gradually reduced.

2.4. Tunnel closing

The hazard of drivers passing traffic and lane signals at stop as they are approaching tunnels is well known and measures such as physical barriers are being adopted. The EU Directive requires that provisions be made to stop vehicles entering a tunnel and at intervals through long tunnels in order to keep them as far away as possible from the hazards associated with an incident. Barriers can either drop down or swing across the carriageway (Figure 2).

Figure 2: “Drop down” and “Swing across” barriers

However each type of barrier introduces the hazard of vehicles colliding with them either as they are being closed or once they are closed – presumably by vehicles driven by the same people who “don’t see” the traffic signals!

There is an alternative approach that eliminates that collision hazard. It has been developed for the portals of the Sydney Harbour Tunnel to stop vehicles entering if there is an incident in the tunnel but also to stop over-height vehicles from trying to enter the tunnel. The “Softstop” system developed by Laservision (www.laservision.com.au) projects a laser generated image on to a water screen (Figure 3).

Figure 3: The “Softstop” system being used at the portal of Sydney Harbour Tunnel

The hazard then associated with this system is the water but any associated risks are easily mitigated using the tunnel’s drainage system.

3. FACILITIES

3.1. Emergency exits

The provision of an escape way through an opening in a tunnel wall is recognised as a hazard to errant vehicles impacting on the corner and the opening is often designed to minimise the consequences of such an incident. Sometimes the door is made flush with the wall; sometimes the “upstream” corner is shaped to deflect the vehicle.

In the past it was thought that just the presence of the emergency exit could be distraction to drivers and hence a hazard. As a result the exits were "hidden" with just a small discrete notice indicating their presence (**Figure 4**). The problem with that concept was clearly demonstrated in a number of the recent fires – when drivers needed to use them to escape from a fire they did not know the exits were there and, unfortunately, some of them perished. Nowadays the approach is completely different; the emergency exits are being well lit and clearly marked and they are almost impossible not to notice so at least people know they are there (**Figure 5**).

Figure 4: Typical sign that was used to indicate an emergency exit

Figure 5: Modern emergency exits are more noticeable!

In some countries the local regulations demand that the doors in the emergency exit have to be fitted with crash furniture and open in the direction of escape, just as when escaping from a building. In those countries this means that each emergency exit door has to be two doors, one opening in each direction. This configuration introduces another potential hazard of people fleeing through the emergency exit and "running" into the opposite tube into the path of vehicles still moving in there. The obvious solution to this hazard is to put a barrier on the kerb in front of the exits to "deflect" people. Unfortunately this mitigation measure introduces another hazard – drivers veering away from the barriers on the kerb as they pass them potentially resulting in an accident.

In most countries the "fleeing into moving traffic" hazard is not an issue because the doors from the tunnel only open into the cross connection and they are not fitted with crash furniture, just a normal handle. This means that those escaping from one tunnel reach a place of relative safety – the cross connection – through a door opening in the escaping direction but to go on to the opposite tube they have to pull the door towards them. This simple measure effectively mitigates the hazard especially when it is combined with a very visible notice on the inside of the door warning of possible moving traffic.

3.2. Internal finish/décor and lighting

Over a decade ago the potential impact on safety of the interior design of a tunnel on the drivers' perception, orientation, boredom and distraction was identified and some recommendations were made (Carmody, J. 1995). Questions concerning the internal décor of tunnels also formed part of the Austrian studies (Eberl G. 2002) but apart from these two papers there has been little attempt to really understand the effect of internal décor on safety.

Notwithstanding the lack of published information the potential hazard of the internal décor is recognised and some novel approaches have been adopted to prevent drivers becoming bored in long tunnels such as the lighting effects used in the Laerdal Tunnel in Norway and the Zhongnan and Xuefeng Mountain Tunnels in China (**Figure 6**).

Figure 6: Internal décor in Zhongnan (left) and Xuefeng Mountain Tunnels

It will be interesting to learn if these radical approaches have the desired effect or will they actually be a hazard and result in drivers being distracted and accidents occurring.

The Södra Länken Tunnels in Stockholm also have a novel way of informing drivers of the tunnel alignment and approaching junctions with white panelling suspended from the roof of the tunnel. Again, will this innovation reduce incidents or will it be a hazard?

3.3. Structural Fire Protection

The impact of a large fire on a tunnel's structure and fittings can be devastating as seen in the Channel Tunnel. In many tunnels the only hazard is physical damage to the tunnel resulting in parts of it falling be it a bare rock tunnel or one lined with concrete that spalls. The fire does not destroy the tunnel and it can relatively quickly be repaired. However structural damage to tunnels such as submerged tube tunnels could result in the complete loss of the facility.

Several manufacturers are promoting the use of materials to protect the structure of the tunnel from the effects of the fire using one of two fundamentally different concepts – modifying the reaction of the concrete to the effects of the heat from the fire or protecting the concrete by stopping the heat reaching it. The first incorporates polypropylene fibres in the concrete lining which has been shown to significantly reduce or eliminate spalling. The second approach is to protect the structure by applying materials to stop heat passing to the structure.

So what are the hazards associated with these two approaches? Adding polypropylene fibres to the concrete has very little impact on the conditions in the tunnel. They do not reduce the amount of heat passing into the tunnel structure and the temperatures in the tunnel falls quite rapidly with distance from the fire purely because of the heat losses to the walls. However, preventing heat from entering the structure means that it stays within the tunnel and the temperatures there will be significantly higher for greater distances from the fire. The higher temperatures will increase the extent of damage to fixtures and fittings within the tunnel and may pose an increased risk to anybody in the tunnel because of the higher temperatures there. In a very large fire there may even be sufficient heat retained within the air/smoke in the tunnel to enable the fire to "jump" considerable distances along the tunnel even if vehicles are separated by tens or hundreds on metres. Heat protection for small sensitive parts of the tunnel's structure is totally understandable but the consequential hazards of applying it to the whole structure must be carefully considered before such an approach is adopted.

Polypropylene fibres will pose no additional hazard to tunnel users during normal tunnel operations because the fibres are an integral part of the concrete structure. Measures to protect the tunnel structure from heat could potentially become detached from the tunnel surface or its support structure which would be hazard to motorists as it could result in accidents and, possibly, casualties.

4. DISCUSSION

Although the number of fatalities in road tunnel fires is relatively low there is still the drive to improve it still further. Manufacturers are developing more sophisticated systems each with the aim of reducing the consequences of fire incidents in particular; it appears that very little is being developed or research work being carried out to reduce the likelihood of incidents occurring.

So why are all these new safety-related facilities and systems being installed by tunnel owners? Is it because those responsible fear being accused of not doing everything they possibly can for the safety of the tunnel users irrespective of the cost effectiveness?

When the decision is taken to include these facilities and systems, how many of those responsible actually consider what hazards they are introducing into the tunnel? How many risk analyses have actually been done on safety related equipment and facilities? Or is it just assumed that because it is a safety-related system it must be safe?

The question of the cost effectiveness of all these measures has to be asked especially when considering the relative small amounts of money which need to be spent to save a life on open stretches of road. Would the massive investments currently being made for each and every tunnel actually be better spent trying to reduce the likelihood of incidents occurring? Measures such as better driver education and training, stronger enforcement of traffic regulations, etc have been shown to be effective and, most importantly, they are effective for every tunnel.

5. CONCLUSIONS

1. Systems and facilities introduced into tunnels to reduce the consequences of fire incidents do introduce real additional hazards into the tunnel
2. The risks associated with these additional hazards cannot be ignored; they need to be addressed.

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THE ORGANISATION AND COST OF TUNNEL SAFETY WITHIN THE ASFINAG GROUP

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ABSTRACT

ASFiNAG **plans, builds, maintains, and collects tolls** on Austrian motorways and expressways. It currently operates a network comprising approximately 2,104 km of roads. This network includes approximately 140 km of special toll roads such as the Bosruck tunnel, the Gleinalm tunnel, the Arlberg tunnel, and the Tauern tunnel. A further 400 km of motorways and expressways are currently either at the planning stage or under construction.

A total of 137 tunnel facilities with a total length of approximately 295 km are currently in operation on the network. This is the same distance as a journey from Vienna to Salzburg on the A1 West motorway. Approximately 152 km of tunnel facilities are either at the planning stage or under construction. This is the same distance as a journey from Salzburg to Villach on the A10 Tauern motorway.

In view of the large number of tunnels on the network, ensuring the highest possible level of safety and economic efficiency in motorway and expressway tunnels is one of ASFiNAG's main objectives.

On the basis of applicable directives and the Austrian Road Tunnel Safety Act (STSG), ASFiNAG has set up a streamlined, effective organisation to address the issue of tunnel safety.

1. INTRODUCTION

Ever since the tragic events of 1999, people in Austria have attached great importance to the issue of tunnel safety.

With the help of both technical developments and organisational measures, tunnel safety has been significantly improved in order to ensure maximum safety for tunnel users in the event of an incident.

2. ASFiNAG's TUNNEL SAFETY ORGANISATION

Each of the tunnel facilities on the motorway and expressway network is operated by one of ASFiNAG's four service companies: Servicegesellschaft Nord (north), Servicegesellschaft Ost (east), Servicegesellschaft Süd (south), Servicegesellschaft ASG (alpine region).

The Road Tunnel Safety Act (STSG) had a major influence of the way ASFiNAG organised its tunnel safety activities. This act, which came into effect for all tunnels >500m on the motorway and expressway network on 8 May 2006, contains instructions regarding the posts of tunnel manager and safety officer.

ASFiNAG's four service companies operate a total of 137 tunnel facilities.

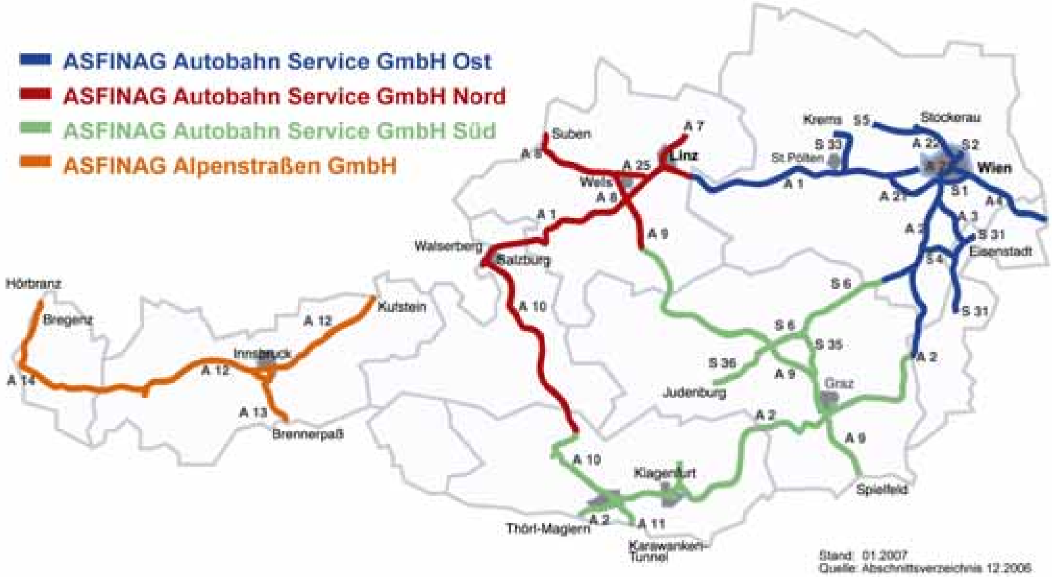

Figure 1: Support areas of the four service companies

The operation of the facilities is distributed among the four service companies as follows:

Servicegesellschaft Nord (north):	20 tunnels	approx. 44 km
Servicegesellschaft Ost (east):	25 tunnels	approx. 17 km
Servicegesellschaft Süd (south):	66 tunnels	approx. 156 km
Alpenstraßen GmbH (Alpine region):	26 tunnels	approx. 78 km

The table above shows that Servicegesellschaft Süd is responsible for about 50 per cent of all tunnel facilities.

Another aspect that was taken into consideration when structuring ASFiNAG's tunnel safety organisation was the tunnel facilities that are currently either at the planning stage or under construction.

The table below shows the distribution of planned tunnels/tunnels under construction among the four service companies:

Servicegesellschaft Nord (north):	24 tunnels	approx. 60 km
Servicegesellschaft Ost (east):	4 tunnels	approx. 30 km
Servicegesellschaft Süd (south):	16 tunnels	approx. 46 km
Alpenstraßen GmbH (Alpine region):	5 tunnels	approx. 16 km

In approximately 5 to 10 years, operation of the tunnel facilities will be distributed as follows:

Servicegesellschaft Nord (north):	44 tunnels	approx. 104 km
Servicegesellschaft Ost (east):	29 tunnels	approx. 47 km
Servicegesellschaft Süd (south):	82 tunnels	approx. 202 km
Alpenstraßen GmbH (Alpine region):	31 tunnels	approx. 94 km

Based on the number of tunnel facilities being operated by the service companies, the following human resources were made available (TM = tunnel manager, SO = safety officer, OP = operator):

Servicegesellschaft Nord (north):	44 tunnels	approx. 104 km	1 TM	3 SO	25 OP
Servicegesellschaft Ost (east):	29 tunnels	approx. 47 km	1 TM	1 SO	10 OP
Servicegesellschaft Süd (south):	82 tunnels	approx. 202 km	1 TM	5 SO	76 OP
Alpenstraßen GmbH (Alpine region):	31 tunnels	approx. 94 km	1 TM	2 SO	19 OP

Approximately 146 people at ASFiNAG are currently involved in tunnel operation.

In order to meet the provisions of the Road Tunnel Safety Act, several tools, including the tunnel safety database, were developed. This database has been in operation since May 2006. All accidents, fires, and cases of property damage relating to tunnel operation are recorded and entered in the database in order to allow improvements to be made as quickly as possible.

Thanks to the hard work and dedication of everyone involved, all requirements outlined in both the EU directive and the STSG have been met on time.

Figure 2: Tunnel database

3. THE COSTS OF TUNNEL SAFETY

In the period 1997–2020, ASFiNAG will invest approximately € 26 billion in the planning, construction, and maintenance of motorways and expressways. Investment has increased continuously since 1997. Approximately € 1.3 billion will be spent in 2008.

Examples of new-build investments include the construction of new expressways such as the S36 Murtal expressway. In the field of maintenance, ASFiNAG is investing in repairs and refurbishment (bridges, roads, tunnels, etc.) and the construction of extra lanes, second tunnel tubes etc.

Thanks to continuous investment since 1997, the network has grown from a total length of 1,902 km (1997) to 2,104 km (2007).

Between 2007 and 2010, ASFiNAG will invest approximately € 4.6 billion in new-build and maintenance projects.
This figure includes a budget of approximately € 850 million for the following projects (adding second tubes and repairing/refurbishing existing tubes):

- Pfänder tunnel (6,500 m)
- Ganzstein tunnel (2,100 m)
- Lainberg tunnel (2,200 m)
- Tauern tunnel (6,500 m)
- Katschberg tunnel (5,500 m)
- Roppener tunnel (5,100 m)
- Bruck series of tunnels
- Selzthal tunnel
- Wolfsberg tunnel
- and others

Approximately 18 per cent of the total investment earmarked for the period 2007–2010 (€ 4.6 billion) will be invested in the existing network.

The following new-build projects, which will cost approximately € 400 million, are currently in planning or under construction:

- S35 Brucker expressway
- S10 Mühlviertler expressway
- S36 Murtal expressway
- A26 Linzer motorway
- A10 environmental relief measures
- and others

Approximately 9 per cent of the total investment earmarked for the period 2007–2010 (€ 4.6 billion) will be invested in new-build projects.

ASFiNAG will invest € 1.25 billion in the construction and repair/refurbishment of tunnels on the motorway and expressway network between 2007 and 2010. This accounts for 27 per cent of the forecast investment of € 4.6 billion.

A further € 3.5 billion (30–35 per cent) will be invested in the construction and repair/refurbishment of tunnels between 2010 and 2020.

4. SUMMARY

A review of the past few years clearly shows that as a result of the current ambitious programme of investment (€ 4.75 billion) and the development of a streamlined organisation, the level of safety in tunnels on Austria's network of motorways and expressways has been significantly increased since 1999.

TUNNEL SAFETY – MORE THAN THE SUM OF THE INDIVIDUAL PIECES OF SAFETY EQUIPMENT

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ABSTRACT

Tunnel safety is more than the sum of the individual safety systems or components of the tunnel design. Inherent safety is the highest priority while the system response in the event of an emergency must be timely and accurate. The incorporation of new technologies without sufficient regard to their impact on timely and accurate safety system response undermines tunnel safety despite providing a superficially attractive list of tunnel safety features.

Keywords: safety, tunnels, systems, life cycle cost

1. INTRODUCTION

Safety theory clearly states that the safety of any infrastructure tunnels or otherwise, is a function of the built structures, the behaviour and equipment of the users and the effectiveness of the control systems.

The highest level of safety is of course achieved when there is no adverse event and the infrastructure is safe by design. But in a tunnel the confined environment coupled with limited alternative access following an emergency makes an effective response essential for achieving an appropriate level of safety.

The raft of equipment available to tunnel designers and operators claiming they make tunnels safe is broad and rapidly growing. With the expediential growth in new tunnel projects globally and the vast number of aging existing tunnels the challenges for tunnel safety engineers have never been greater and the opportunities for significant safety improvement more pronounced.

Tunnel safety is a function of sound engineering, systems analysis and integration. Tunnel safety is much more than the sum of the individual safety equipment used.

2. THE FIRE

There is always a great deal of expert speculation about fire growth, smoke generation and heat release rates when considering the functional performance of the tunnel. It is important to recognise that such scenarios are used as a tool to design the safety systems and that they may be applied to other scenarios requiring active ventilation to enhance tenability such as intentional security breaches and other undesirable events.

The most informative review of fire growth tests was performed by Ingason (2004) as part of the Swedish Road Administration review of the use of sprinkler systems.

The review by Ingason of fire growth rate data (Figure 1) dramatically illustrates the practical importance of effectively responding within the first 5 minutes or so of an incident. Experience from catastrophic fires coupled with the experience from countries using fire suppression systems suggests that the opportunity to effectively control the growth of fires and the consequent dramatic increase in the volume of smoke is limited to the first few minutes after an incident.

No matter what systems are installed unless they are effectively operated during this short time window the prospects for safe evacuation and even asset protection will be severely compromised. Speed and accuracy of event detection and location are essential for tunnel safety.

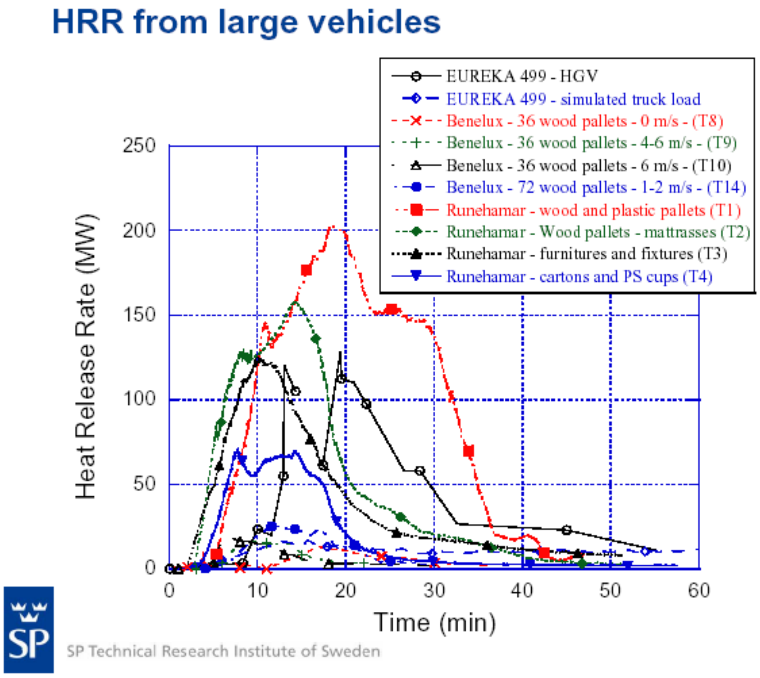

Figure 1: Summary of test data on fire growth rates (note importance at first 5 minutes.

3. DEVICES

Devices which are claimed to positively affect safety almost always focus upon one particular aspect of the risks to users of tunnels. A selection of safety equipment follows with brief examples of this point.

Device	Risk mitigated	Results from real emergencies	Comment
Emergency telephone	Inability for tunnel user to talk directly with tunnel controller.	Usually not used	If used they would help confirm incident location and provide a method to talk directly with tunnel control. In an emergency they are usually overlooked and the tunnel controller so busy that dealing with such phone calls would most likely be problematic.

Device	Risk mitigated	Results from real emergencies	Comment
Linear heat detectors	Rapid and exact location of fire	Slow to operate	Difficult to tune for both road and rail tunnels. Once activated often signal a cascade of alarms. Often too slow and too inaccurate for rapid emergency ventilation response.
Closed Circuit Television (CCTV)	Operator cannot see in tunnel.	Unless coupled to other alarm systems they are mind numbingly boring to monitor and prone to loss of vision downstream of an incident.	To be useful spacing should be close, yet close spacing creates a high number of images which need to be monitored. Without computer aided analysis such images become little more than visual noise in a control room as image after image cycles through the operators display. They are useful for traffic flow management.
Fixed suppression systems	Rapid fire growth rate and smoke release rate.	Rapid and accurate activation is essential if they are to be effective. Failure to maintain or lack of familiarity with their operation will compromise their effectiveness. When properly integrated, maintained and operated perform well. Delay or inappropriate application may compromise safety.	Extensively used in Japan and Australia to good effect. Currently installed in A86 Paris Ring Road, Madrid Calle 30, Madrid Metro but limited operational experience to date. Wrongly often described as making a tunnel safe without reference to the importance of integration in the operational safety systems.
Smoke extraction	Confined environment highly toxic to users.	When rapidly activated at the correct location can provide or maintain a tenable environment for a longer period over a greater portion of the tunnel.	Widely heralded as providing new levels of safety in tunnels but is subject to similar limitations to other complex engineered systems in that it must be rapidly activated at the correct location and integrated in the overall emergency ventilation response to provide the safety outcome sought.
Emergency escape routes	Users trapped in untenable environment.	Users choose not to avail themselves of these safe places. Despite their attractive engineering performance many people observed to remain either in their car or within the tunnel in preference to using these places.	Despite the improvements in the identification and ‘attractiveness’ of cross passages and other escape pathways, people still choose to stay in the areas they are familiar such as their vehicle or the tunnel.

The six features chosen above are selected to be illustrative of the fact that just because systems are installed in a tunnel it does not follow that the tunnel is safer than if they were not.

A fire suppression system which solely relied upon linear detection systems to positively locate an event will be slow and potentially inaccurate. An emergency ventilation extraction system which relied upon such heat detection systems would likewise suffer similar limitations.

4. SPEED OF RESPONSE

To respond rapidly demands timely incident detection coupled with accurate incident location and precise system activation.

This performance requirement is more than a simple engineering matter. It involves complex interactions between a range of technologies and most often the input of the tunnel operators.

The greater number of safety devices the higher the integration burden for a systematic response.

The demands upon the SCADA system and the associated computer systems to execute such a task in a timely manner must not be underestimated. This situation may be compounded if a series of minor incidents requiring more routine responses occurs prior to the major incident.

The magnitude of the task of controlling these many safety elements is depicted in the following photograph. Each line represents a command to a device, the many pages being generated over a period of single digit minutes. The computers unexpectedly burdened by the task. This can (and has) severely impacted the timeliness of emergency responses.

Figure 2:
Printed computer logs from a computer responsible for some electromechanical systems during the tunnel incident. Each new piece of equipment adds an incremental burden on the control systems ability to rapidly control critical equipment. These commands are dealt with sequentially. The computer does not recognise priority tasks.

4.1. The Operators

The more equipment that requires monitoring, interpretation or control - the greater the potential burden on the operator. While the importance of the human machine interface is often discussed in reality – during an emergency – the operators' task is complex and the time frames for decisions unrealistic. In this way the addition of equipment in the name of safety can compromise the effectiveness of the response through delay and potential operator error.

5. THE PHYSICAL REALITY

An analysis of any tunnel usually includes a checklist of its physical features. As with equipment, the underlying rationale is that the more features the safer the tunnel will be.

The effective integration of different physical features is critical to their performance in an emergency. The following two photographs are taken in two 'new' tunnels. One is a European Union country and the other is in Japan. Both have emergency egress to cross passages and escape-ways to the surface. Both use similar evacuation time criteria. Both use transverse ventilation and smoke extraction. Both offer protection for critical electro-mechanical control circuitry. Both abide by local regulations on signage and other emergency evacuation criteria. However as is evident from the photographs the Japanese example is more likely to perform because of the reality of the finished product.

Japan	*EU Country*

Figure 3: Depicts two functionally different emergency egress pathways.

The above photographs show two functionally very different approaches to emergency egress. Both taken in February/March 2008 – they show two different 'realities' for emergency evacuees. In Japan stairway lengths are limited to only 10 flights in deep tunnels, and great attention is paid to the resultant functionality. In the EU example high voltage cables share the escape path in a poorly constructed egress passage.

These photographs highlight the importance of not only incorporating safety features in a design but ensuring that they are truly integrated to provide the functional response. The European tunnel photographed above has many more safety features than its Japanese cousin however it is likely that the Japanese tunnel will perform better in an emergency.

On this basis more safety features does not mean a tunnel is safer.

6. SAFETY TRADING

One justification for including more safety 'devices' is that other expensive aspects of the civil works can be made more cheaply. For example the use of a fire suppression system may be justified due to less expenditure on fire protecting aspects of the infrastructure. Although such a process can be valid it is essential that it be coupled with a thorough engineering analysis and not merely be used as a polite cost saving exercise.

Integration of safety systems – and recognition of the importance of ongoing upgrading, training and maintenance must be factored into the costs associated with their adoption. Life cycle analysis is demanded.

7. CONCLUSION

The safety of the tunnel is not the sum of its individual safety components or features. A well managed, maintained and controlled tunnel will easily provide superior safety to a modern tunnel equipped with a vast array of safety equipment and features which are poorly understood, barely commissioned and effectively uncontrollable.

A systems approach to delivering safety with a life cycle perspective is essential when safety is the ongoing objective over the life cycle of the infrastructure.

Tunnel safety is not academic and cannot be measured like the amenity of a new car by referencing the number of accessories as a barometer of its safety performance.

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SAFETY IN TUNNELS ON MOTOR- AND EXPRESSWAYS

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ABSTRACT

Both the probability of accidents occurring and the probability of being injured is lower in tunnels than on open stretches of roads. However, if an accident does happen in a tunnel, the risk of being killed is significantly higher than on open stretches of motorways. In a tunnel the risk of being killed in a traffic accident is 1.5 times the risk of open stretches on motorways. In tunnels with bi-directional traffic the probability of being killed in a traffic accident is 1.4 times as high as in tunnels with unidirectional traffic. Both in tunnels with bi-directional traffic and in tunnels with unidirectional traffic the highest accident rates occur in the portal area. Based on the results of this analysis various measures aimed at raising traffic safety in tunnels are recommended.

Key words: tunnels, road safety, unidirectional, bi-directional

1. INTRODUCTION

The safety of road tunnels is still an important topic in road safety although the Austrian Tunnel Commission and the implementation of the EU directive “Minimum safety requirements for tunnels” already achieved improvements in the area of tunnel safety. Accidents and fires in tunnels must not be neglected because of the high potential of those catastrophes.

Every year, 93 accidents in motorway and expressway tunnels occur in Austria on the average. These accidents result in 9 fatalities, 24 severe injuries and 118 minor injuries. The macroeconomic costs amount to a total of 19.8 million Euros per year. The study “Safety in Road Tunnels” of the Austrian Road Safety Board commissioned by the Federal Ministry of Transport, Innovation and Technology (Nussbaumer C., Nitsche P. 2008) explores the traffic safety of road tunnels compared with safety on motorways and expressways and also compares traffic safety in tunnels carrying bi-directional traffic and unidirectional traffic.

The first part of the study represents a continuation of the study „Comparative Analysis of Safety in Tunnels” (Robatsch, Nussbaumer, 2005). This study dealing with accidents occurring in Austrian tunnels between the years 1999 and 2003 is now completed by the present study dealing with accidents occurring between 2004 and 2007. In the second part accidents in tunnels are evaluated by point of origin and cause. Based on the results of this study, recommendations are made on measures aimed at raising safety in road tunnels.

Relevant data for accidents in tunnels between 2004 and 2005 has been collected in an in-depth analysis carried out by using police and court files. For the period 2006 to 2007 data of the new developed tunnel database have to be corrected with official accident statistics. This evaluation is not yet fully completed (accident data for 2007 are not available for the last quarter and a reform of the court system delayed the accident record collection). For this reasons the results of this study may differ slightly when all accidents have been evaluated for the national report.

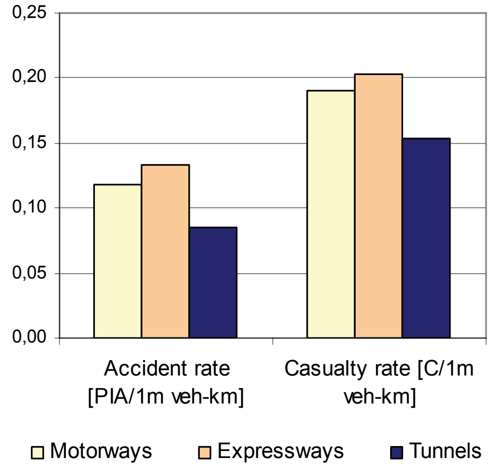
2. DEVELOPMENT OF THE TUNNEL INCIDENT DATABASE

The analysis of tunnel accidents in the accident statistics released by the authorities is difficult and a tunnel accident is not always clearly identifiable. Tunnels can be found by kilometer in the network and tunnel accidents are identified by code 30 in the category "identification of the scene of an accident". The problem is the inaccurate indication of kilometers and the code 30 is not used continuously for tunnel accidents. Mainly in the portal area it is uncertain if an accident happened before or in the tunnel. For the study „Comparative Analysis of Safety in Tunnels" (Robatsch, Nussbaumer, 2005) tunnel accidents of the official accident statistic have been checked and supplemented by collection of police records.

2004 the European Union has implemented reporting duties for incidents in tunnels but the collection of police records is time consuming and costly. Therefore the Federal Ministry of Transport, Innovation and Technology commissioned the Austrian Road Safety Board to develop a tunnel incident database. The Asfinag provided the company server for the database and personal for the data input in the tunnel control centers. The tunnel incident database contains data about tunnels on motor- and expressways as well as data about incidents in tunnels. The data are recorded since 1.1.2006 in the tunnel control centers according to the requirements of the EU directive and future research.

3. SAFETY IN TUNNELS VERSUS MOTOR- AND EXPRESSWAYS

Presently, 137 tunnels exist on motorways and expressways in Austria. According to the annual report of the Asfinag 2006 the road network of the Asfinag is 2.062 km long and thereof 193 km are tunnels. A variety of accident rates and the distance travelled in all of the tunnels studied are compared with the corresponding figures for motorways and expressways on open sections.



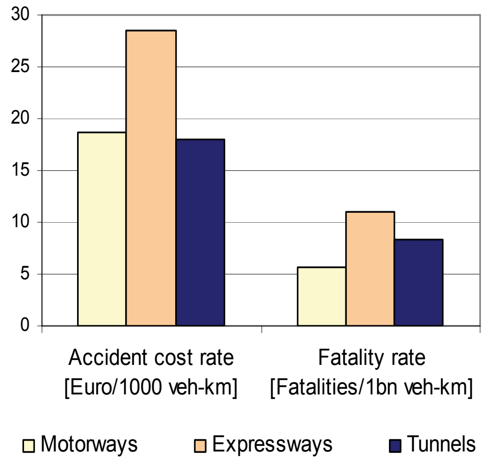


Figure 1: Relative accident rates for tunnels versus motor- and expressways (1999-2007)

In tunnels, the accident rate and the casualty rate are significantly lower than on motorways and expressways. A comparison of accident cost rates shows that the difference between tunnels and motorways is very small. By far the highest accident cost rate occurs on expressways. The probability of an accident occurring in tunnels is lower than on motorways and expressways. However, the risk of being killed in a traffic accident in tunnels is 1.5 times the risk on motorways but lower than on expressways.

4. SAFETY IN TUNNELS WITH UNI- AND BI-DIRECTIONAL TRAFFIC

This chapter compares accident rates occurring in the tunnels being surveyed with unidirectional and bi-directional traffic on motorways and expressways. In the present study, all Austrian tunnels with a length of at least 200 meters that have been opened before 1.1.2007 have been analysed. In the calculations below, 21 tunnels with bi-directional traffic are compared with 179 tunnel tubes carrying unidirectional traffic.

Table 1: Number, length and traffic intensity of tunnels with bi-directional and unidirectional traffic (status 2007)

	Tunnels with bi-directional traffic	Tunnels with unidirectional traffic
Number of tunnels studied	21	179
Total length [km]	87,959	206,346
Average length [km]	4,188	1,146
Traffic intensity [ADT]	13.628	12.678

On average, tunnels with bi-directional traffic are 3.7 times as long as tunnels with unidirectional traffic. At 13.628 vehicles per day, the average traffic intensity in tunnels with bi-directional traffic is slightly higher than in tunnels with unidirectional traffic, which carry 12.678 vehicles per day.

In the analysis below, a variety of relative accident rates have been calculated and compared for tunnels with bi-directional traffic and unidirectional traffic. The calculations below comprise accident rates, accident cost rates, casualty rates and fatality rates for accidents in tunnels with bi-directional and unidirectional traffic.

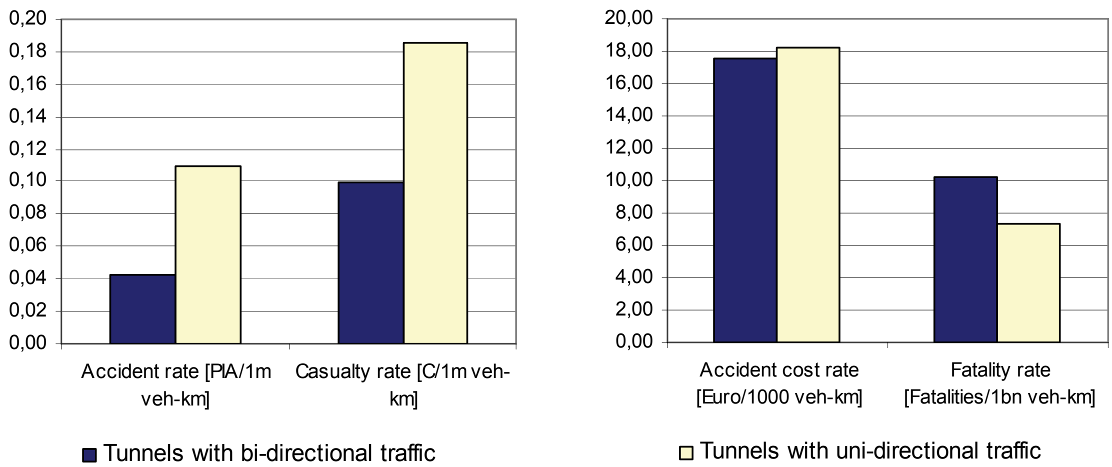


Figure 2: Relative accident rate for tunnels with bi-directional traffic and unidirectional traffic (1999-2007)

In tunnels with bi-directional traffic, the accident rate of 0.043 accidents per one million vehicle-kilometres is significantly lower than in tunnels with unidirectional traffic, where the corresponding rate is 0.109 accidents per one million vehicle-kilometres.

While the casualty rate in tunnels with bi-directional traffic is 0,099 casualties per 1 million vehicle-kilometres, the corresponding rate in tunnels with unidirectional traffic is 0.185 casualties per 1 million vehicle-kilometres. In tunnels with bi-directional traffic, the accident cost rate is slightly lower than in tunnels with unidirectional traffic. The accident cost rate in tunnels with bi-directional traffic is EUR 17.6 per 1,000 vehicle-kilometres and in tunnels with unidirectional traffic EUR 18.3 per 1,000 vehicle-kilometres.

It is worth mentioning that the fatality rate in tunnels with bi-directional traffic is 1.4 times the risk in tunnels with unidirectional traffic. While in tunnels with bi-directional traffic, 10.3 traffic fatalities occur per one billion vehicle-kilometres, the corresponding figure for tunnels with unidirectional traffic is 7.3 persons killed per one billion vehicle-kilometres.

5. IN-DEPTH ANALYSIS OF SAFETY IN TUNNELS

In this chapter, accidents with personal injury in tunnels are analysed by the parameters point of origin, accident type and cause. On the basis of the results, measures aimed at raising safety in road tunnels are formulated.

5.1. Accident rate and point of origin of the accident

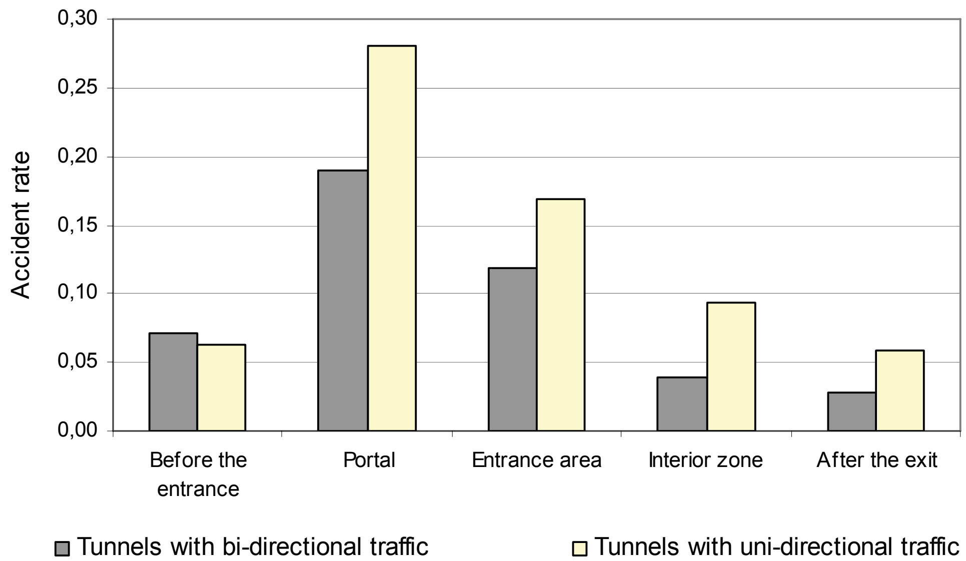


Figure 3: Personal injury accident rate [PIA/1 million vehicle-kilometres] in tunnels with bi-directional traffic and unidirectional traffic by point of origin of the accident (1999-2007)

In tunnels with bi-directional traffic and unidirectional traffic, the highest accident rates are reported in the portal area. In tunnels with bi-directional traffic, the accident rate in the areas before the entrance is higher than in the interior zone of the tunnel. The lowest rate of accidents occurring in the interior zone of the tunnel is reported in tunnels with bi-directional traffic, but at the same time the rate of accidents occurring before the entrance is very high due to the transition from unidirectional traffic to bi-directional traffic.

5.2. Accident type and point of origin of the accident

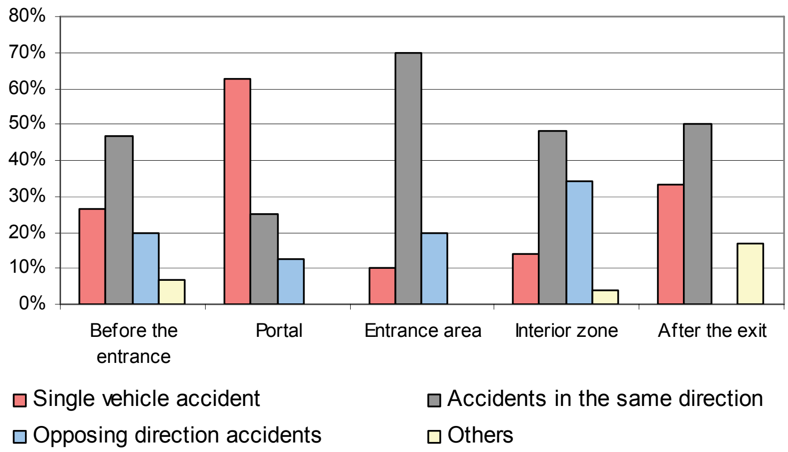


Figure 4: Types of accidents in tunnels with bi-directional traffic by point of origin of the accident, in percent (1999-2007)

In tunnels with bi-directional traffic, the most frequent accident type in all areas, except the portal area, is type 1, accidents in the same direction. These accidents include rear-end collisions sharing 47% of all accidents in tunnels with bi-directional and unidirectional traffic. They also include accidents due to overtaking and lane changing. As shown in Figure 4, the highest proportion of accidents in the same direction is reported in the entrance area (70%), which is mainly due to jams and to drivers not being attentive to the tunnel traffic lights installed in this area. The most frequent accident type in the portal area is single-vehicle accidents (62.5%).

Opposing direction accidents have an overall proportion of 30% in tunnels with bi-directional traffic. Most of those accidents occur in the interior zone of the tunnel. Aside from touching collisions, mainly frontal collisions occur in opposing direction accidents. In tunnels with bi-directional traffic most part of the accidents are due to the failure to maintain a safe distance to the vehicle in front, while in the portal area the main causes are overfatigue and speeding.

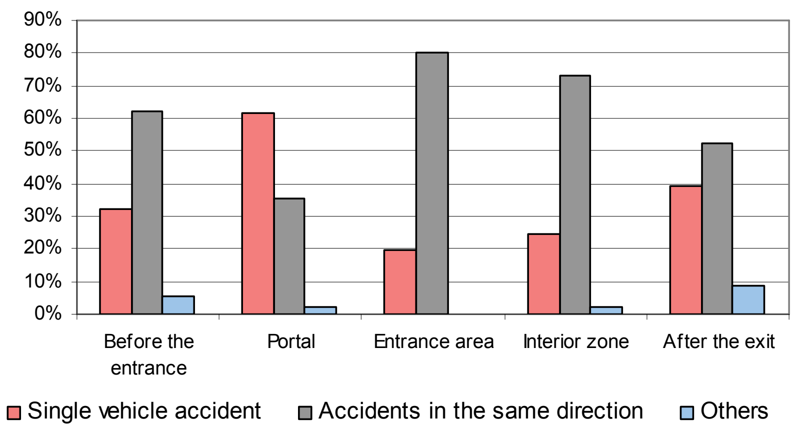


Figure 5: Types of accidents in tunnels with unidirectional traffic by point of origin of the accident, in percent (1999-2007)

In tunnels with unidirectional traffic single vehicle accidents mainly occur in the portal area (61.9%). In all other tunnel areas the accidents in the same direction (including rear-end collisions among others) have the highest proportion. Especially in the entrance area, most accidents occur is in the same direction (80.2%). In total, rear-end collisions are the most frequent type of accidents in unidirectional tunnels which is mainly due to the failure to maintain a safe distance to the vehicle in front. In the areas before the entrance and after the exit most of the accidents occurring are due to wrong driver behaviour like the failure to maintain a safe distance to the vehicle in front, wrong overtaking and the failure to remain within the marked lane.

Summing up, in tunnels the proportion of rear-end collisions is significantly high. In the portal area mainly single-vehicle accidents occur, whereas in tunnels with bi-directional traffic the high number of opposing direction accidents occurring in the interior zone of the tunnel represents an additional problem.

5.3. Relationship between cause of accidents and traffic directionality of tunnels

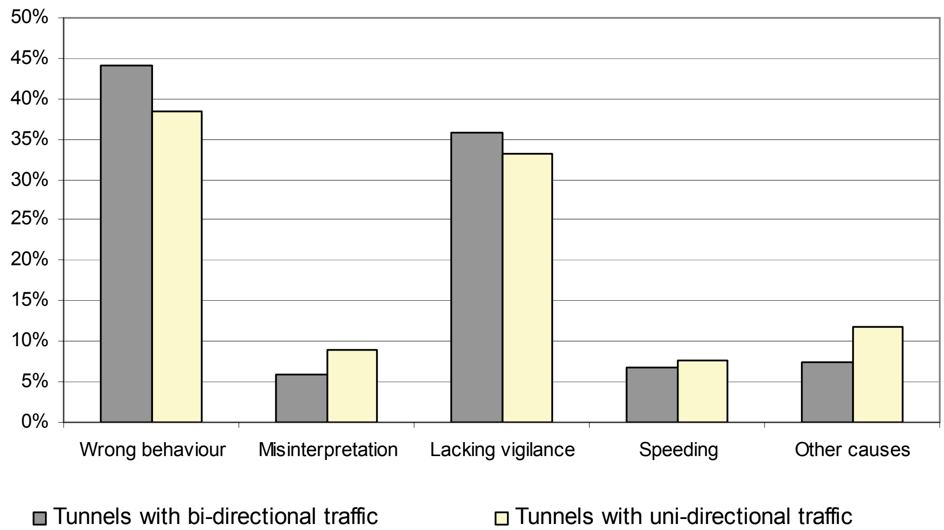


Figure 6: Causes of accidents in tunnels with bi-directional and tunnels with unidirectional traffic, in percent (1999-2005)

Generally, the most frequent cause of accidents in tunnels is wrong driving behaviour, followed by lack of vigilance such as overfatigue, distraction or inattentiveness. Wrong driving behaviour such as the failure to maintain a safe distance to the vehicle in front, wrong overtaking and the failure to remain within the marked lane has a proportion of 44.1% in tunnels with bi-directional traffic. This value is slightly higher than in tunnels with unidirectional traffic (38.4%).The third most frequent cause (6.89%) is misinterpretation of road design and layout, meteorological conditions and other vehicles. Speeding has an almost similar proportion with 6.0%. Other causes of accidents, such as unpredictable events and technical defects (motor, tyres and brakes) were negligible.

The accident causes speed, alcohol, drugs and over-fatigue are traditionally underreported in police records.

6. ANALYSIS OF INCIDENTS IN TUNNELS

Aside from accidents with personal injury other incidents also occur, which have a high impact on road safety. The development of incidents over time can only be analysed when data of the following years are available. It is possible that data in the first year of the new developed tunnel incident database are not reported completely.

Table 2: Accidents and fires in tunnels, absolute (2006-2007)

	Accident with personal injury	Accident with damage to property	Fire	Incidents total
2006	57	88	8	152
2007	73	246	8	327
Total	130	334	16	479
Share of all incidents (%)	27,1	69,7	3,3	-

Within two years, a total of 130 accidents with personal injury, 334 accidents with damage to property and 16 fires happened in tunnels on motor- and expressways. The highest share of all incidents in tunnels is accidents with damage to property (69.7%), followed by 27.1% accidents with personal injury. Fires are comparatively seldom in tunnels.

7. RECOMMENDATIONS

7.1. Enforcement

The analysis of tunnel accidents by type of accidents show that the main problem is not the tunnel as a construction but the generally lacking morality regarding maintaining a safe distance to the vehicle in front and/or observation of speed limits. Every 2nd accident in a tunnel is a rear-end collision (failure to maintain a safe distance to the vehicle in front) and many accidents are single accidents (mainly caused by over-fatigue, wrong driving behaviour and speeding). In order to reduce the accidents in tunnels, it is recommended to install distance measuring devices, radar devices and section control devices.

Based on the results of the comparison of accident rates in tunnels by point of origin of the accident, it is recommended that the measures aimed at raising tunnel safety should concern the area before the tunnel portal. For this reason the installation of a section control device and similar measures are also recommended for the area before the tunnel tube, beginning at least at 250 m before the portal, in order to raise tunnel safety in an optimal way.

As one of the most frequent cause of accidents in tunnels is lacking vigilance, the observation of the driving and resting times prescribed for lorry drivers and the driving ability of passenger car drivers should be checked more frequently.

At the same time, appropriate traffic education programmes and public relation campaigns should make people aware of the possible consequences of over-fatigue, distraction and alcohol. Particularly in longer tunnels, lacking vigilance may have serious consequences and lead to partly severe accidents with personal injury and, as a consequence, also to fires.

7.2. Traffic education

Driving lessons have already been intensified and, additionally to that, a focus should be laid on measures aimed at making people aware of the importance of a correct driving behaviour in case of accidents, breakdowns and fires in tunnels, as in most of the cases it is the behaviour of the individual driver deciding between life and death.

7.3. Infrastructure

As the portal area show the by far highest accident rates, a focus should be laid on the design of the portal. With this regard the installation of so called “impact dampers” should also be considered. The effectiveness of these dampers, however, should first be examined in a separate study. Another problem regarding the portal area consists in the fact that many drivers are not attentive to the red tunnel traffic light. To solve this problem the placement of the traffic lights at the tunnel portal should be re-considered.

8. SUMMARY

The probability of an accident occurring or being injured in a tunnel is lower than on the open stretches of motorways and expressways. However, if an accident does happen in a tunnel, the risk of being killed is significantly higher than on the open stretches of motorways. In tunnels, the risk of being killed in an accident is 1.5 times as high as on the open stretches of motorways.

In the present study, 21 tunnels with bi-directional traffic and 179 tunnel tubes with unidirectional traffic have been examined. The accident rate (accidents per 1 million vehicle-km) in tunnels with unidirectional traffic is 2.5 times as high as in tunnels with bi-directional traffic. Despite, in tunnels with bi-directional traffic the probability of being killed in an accident is higher than in tunnels with unidirectional traffic. This is due to the high severity in opposing direction accidents.

Both in tunnels with bi-directional traffic and in tunnels with unidirectional traffic most accidents relative to the distance travelled occur in the portal area. The accident rate before the entrance of tunnels with bi-directional traffic is higher than in the interior zone. The transition from unidirectional to bi-directional traffic may be the reason for those results.

In all tunnels, rear-end collisions are the most frequent accident type in all areas excepting the portal area. In the areas of the portals single-vehicle accidents are most frequent. Opposing direction accidents share 30% of all accidents in tunnels with bi-directional traffic. Most of those accidents occur in the interior zone of the tunnels.

Generally, the most frequent cause of accidents in tunnels is wrong driving behaviour. Every fifth accident in tunnels is due to the failure to maintain a safe distance to the vehicle in front. Approximately 28% of all tunnel accidents are caused by lacking vigilance consisting of over-fatigue, distraction and inattentiveness among others. Speeding and misinterpretation of road design and layout, meteorological conditions and other vehicles have almost similar proportions.

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INTEGRATING CAMERAS WITH TUNNEL CONTROL SYSTEMS

Tor Tybring Aralt: Norwegian Public Road Authority
Thomas Lyngtun Hansen: Norphonic AS

ABSTRACT

With many tunnels to supervise, and an increased demand from various sources for cctv surveillance in the tunnels, we were in the need of an open system for camera control.
We decided early to go for MPEG4, believing it was enough to say MPEG4 to get an open system. Unfortunately this was wrong. To get an open system we had to demand MPEG4 by RTSP (Real Time Streaming Protocol)

We also decided to develop our own video proxy, and our own video wall merged into the tunnel system
After negotiations with several development companies, we signed a contract with Trafsys AS, who has developed the tunnel system. Both systems are the propriety of Norwegian Public road Authority, Which mean no further cost for licences.
It is no limits in the numbers of cameras that can be connected. Limits are on numbers of monitors. But how many monitors, is it possible for one or two operators look at?

Keywords: camera, tunnel automation, simplified response, monitoring tunnels.

1. INTRODUCTION

New regulations and many new tunnels have increased our need for an integrated system, taking care of both tunnel control and CCTVs. Having one system for the CCTVs and one for tunnel control makes the situation for the operator unacceptable when you have many tunnels. The operators needed to easily find the proper tunnel and the proper camera without having to remember which camera is where, and to be able to issue commands directly from the same system that controls the cameras. A complete integration of the systems was necessary.

The tunnel control system that is used in the two largest tunnel regions in Norway is a system that was developed and is owned by the Norwegian Public Road Authority. In the western region alone, it controls close to 180 tunnels. This system is based on the OPC standard as well as well-described standards for data transfer between the tunnels and the central system.

As a result of this, 16 different companies have been able to deliver the local control systems for the tunnels. A very strong development criterion was that we should be able to buy cameras through open tenders, which in turn means that only open standards have been used.

2. SPECIFICATIONS

The only open standard we could find that satisfied our needs was streaming MPEG4 delivered over RTSP (Real Time Streaming Protocol).

We discovered that just specifying MPEG4 does not ensure an open standard. The RTSP streaming protocol is an important part of the open standard. Unfortunately, the demand for an open streaming protocol prevented the use of pan/zoom/tilt functions in the cameras. This means that pan/zoom/tilt functions must be performed by the PLC systems. Keeping the system open has a larger effect on price than anything else. Also, remember that automatic incident detection systems demand stationary cameras, and today, most of the systems demand analogue video input. This will probably change in the future, due to the fact that a high resolution digital camera contains more information than an analogue picture. It is often cheaper to by one or two extra cameras than to have a large camera house with zoom/pan/tilt functionality.

The proxy would have to be able to deliver the video stream to the specified monitors, or to a section of a monitor (on a 4-way split screen). We have prepared 4 large flat-screen televisions (42") as a "video wall". This is cheap to implement using one PC with four monitor outputs. **Using millions of euros on a video wall today is buying yesterday's technology for tomorrow's use.**

When a camera sends an alarm, its video output should pop up on the computer screen. From this point, the operator must be able to select a monitor or a screen section of a 4-way split monitor from the tunnel control system. It must be possible to select cameras from the tunnel control system by clicking on a camera symbol, and then to give commands by clicking on arrows for the previous or next camera. When no one is viewing the image from a camera, the video stream must be stopped.

3. CONTRACT

We signed a contract with Trafsys AS for the development of the system. This was done after long discussions with several potential suppliers. The selection was made based on the solution offered, the supplier's know-how, and the expected price. This was not a fixed-price contract. Trafsys AS developed the current system for tunnel management and control.

4. SOLUTIONS

All the implemented solutions are in accordance with the original demands. The solutions have either been published as open source or are owned by us. When we increase the number of cameras, there are no extra licensing costs, and the implementation is easy. The largest cost of implementation is testing as this is always time consuming.

5. TECHNOLOGIES BEHIND THE SOLUTIONS

At the start of the project, MPEG4 over RTSP was beginning to emerge as a standard, but was only supported in very few commercial products. However, as the project has progressed, the number of available products supporting MPEG4 over RTSP has increased steadily. This indicates that our choice of open standards is a good one.

On the server side, there are two main applications: The streaming proxy and the video wall. All clients that are authorised to view a camera will contact the streaming proxy for access to the video stream. If no other clients are currently watching the camera, the streaming proxy will open a new connection to the camera and start receiving the video stream. The video stream will be forwarded unaltered to the client. Any clients that subsequently request the same video stream will receive an identical copy from the proxy, and no new connections will be made to the camera itself. This means that although the camera may be located at the far end of a low-bandwidth connection, it can still be viewed by multiple clients through the streaming proxy. Since the streaming proxy does not alter the video stream in any way, the main limitation on the number of concurrent connections will be imposed by the available network bandwidth.

When the last client viewing a video stream exits, the streaming proxy will disconnect from the camera in order to save bandwidth.

The video wall server runs on a PC with a quad-head video card (4 monitors at the same time). The server is controlled by a client application available to the system operators, and requests video streams from the streaming proxy in the same way a standalone client does.

The video wall is able to support up to 16 concurrent video streams, showing 4 streams on each monitor. This can be supported by current high-end desktop computer hardware. Due to the processing power required to decode the MPEG4 streams for viewing, the video wall server had a lower limit on the number of concurrent video streams than the streaming proxy, which does no encoding or decoding.

The system is based on an open-source camera proxy server, where access control has been implemented on a higher level. The proxy will also disconnect any cameras that are not being displayed on any monitor. This was necessary due to the number of cameras and to protect the network.

6. SAFETY BENEFITS OF INTEGRATING THE SYSTEMS

The system saves time by merging the video image with commands such as “FIRE HERE” – you see the fire and press a button, unless the *system has already automatically done this.*

Automatic Response to Fire Alarms
A fire extinguisher removed from its holder is regarded as a confirmed fire alarm, and proper procedures are started automatically. Operators can point at fire extinguisher alarms, press “GO TO,” and open the nearest camera to confirm the fire, <u>or can re-open the tunnel</u>. In the mean time the tunnel will be closed and the fire-ventilation system be running.

Operator Response to Fire Alarms
We realize that only a minor part of the incidents in a tunnel will be reported in a manner in which an operator can easily identify where the incident is occurring in the tunnel. If a tunnel is equipped with automatic incident detection using cameras, a camera alarm will be reported to the operator if a vehicle stops.

By selecting the alarm, the actual picture will pop up on the computer screen. The operator then has several possibilities. He can:

1) select the video wall control and view the video stream from the relevant camera on the video wall,
2) choose a neighboring camera to the left or right,
3) select the command “FIRE HERE,” or
4) turn the camera off.

Everything is Web-based and is done from the same system. Due to this, the operator can access the system from more than one computer if necessary. This is the operator’s decision. Normally, operators will be watching the system on two computers, one for the main system and one connected to the redundant system located 120 km away.

In a complex highway tunnel, there might be several different fire-ventilation and tunnel-closing scenarios/procedures. It is then important for the operator to know where a fire is located in the tunnel. By selecting the camera nearest to the fire and the pressing the button "FIRE HERE," the appropriate ventilation and closing procedures will be activated.

The fire-plan control is then transferred down to the local automated system. The PLC system in the tunnel will then activate a predefined scenario. During a fire, we do not regard the operators as qualified to define levels of ventilation or to determine closing procedures. This must be predefined.

7. NETWORK

This kind of system integration puts high demands on network resources and network planning. It is essential that we have redundant networks, where every kind of information/data can be transferred using all available pathways.

Previously, we would have built on telephone-style star network configurations, with one for the PLCs and one for the cameras. One error would then normally knock out one of the systems completely. By using modern routing technology and Ethernet, you build one large redundant network for everything.

In this situation, no single point of failure exists. You may still have some errors that are more critical than others, depending on how the network is built. Monitoring the network is now just as important as monitoring all the other systems in the tunnel. If you don't discover that the redundant path is being used, then you are essentially ignoring the advantage of having a redundant path. Errors must of course be repaired quickly, but not necessarily the same night.

We feel that OSPF routers, in combination with smaller spanning three-ring networks, provide satisfactory security for the network, even when all the routers are critical for the networks below them. This could only knock out parts of the tunnel. This is equipment that rarely fails (has a high MTBF). We are now only using open and commonly-used standards. This reduces maintenance costs and is less dependent on a given producer. Producer dependency is always expensive in the long term. Producer-specific solutions would give shorter reconnect times during errors, but it does not matter if it takes 20 seconds or 1 microsecond to reconnect the network.

If you have one alarm a day or even one alarm an hour, then it the incidents are unambiguous. But what happens when you have several alarms in succession from different tunnels? What happens then? Will an alarm message with a possibility for "GO TO" provide the necessary reaction time? When one or two operators are monitoring 180 tunnels, there will be many alarms and the operator must realize which ones are significant. Many false or <u>unimportant</u> alarms are the operator's biggest problem, although they do ensure that he knows his way around the system.

MEASURING LEAKAGES IN ROAD TUNNELS

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ABSTRACT

Leakages in exhaust ducts can reduce the effective smoke-extraction rate to values below the ones required for effective smoke management and prescribed in guidelines. This aspect can have dramatic consequences from the point of view of tunnel safety but also in terms of engineer's liability. Leakages have been long accounted for in a very approximate manner. Due to the lack of reliable data in new and older structures, ventilation design is frequently based on questionable assumptions. The present paper deals with experimental techniques used for measuring leakages in exhaust ducts. Several techniques were applied in the Gotthard road tunnel. The results allowed for a comparison of different measuring techniques, from the point of view of accuracy, practical applicability and cost.

Keywords: tunnel ventilation, smoke extraction, leakages, experimental techniques

1. INTRODUCTION

One fundamental safety element in long road tunnels is concentrated smoke extraction from the immediate vicinity of the fire source. This capability is typically required for tunnels longer than 0.5-1.5 km in case of bidirectional traffic or frequent traffic congestion and 3-5 km in case of unidirectional traffic with low congestion frequency. The combination of two distinct elements is necessary for ensuring a proper smoke management: sufficient smoke-extraction rate and adequate control of longitudinal air velocity. The present paper deals with the experimental determination of smoke extraction rates and the evaluation of leakages.

In normal operating conditions, leakages of ventilation ducts can lead to non-ideal distributions of fresh air and exhaust. More serious consequences are unlikely. Conversely, in case of fire with concentrated smoke extraction, leakages from exhaust ducts can lead to substantial differences between the total exhaust flow rate provided by the fans and the net exhaust flow rate extracted at the fire location. This problem is widespread in older tunnels and becomes very serious while upgrading existing ventilation systems, particularly where substantial increases of smoke-extraction rates are required. In the latter case extensive investigations are frequently needed. The primary objective of such measurements is proving that the design goals are achieved. This requires the measurement at the flow rate in the exhaust duct, just downstream of the extraction location. A secondary objective, particularly important in the case of retrofits, is the measurement of leakages for assessing the duct quality. This allows for a correct specification of smoke extraction fans characteristics and, if required, for the planning and execution of periodic renovations of the infrastructure.

Measurement techniques for the leakages of exhaust ducts are therefore of utmost importance, particularly in the retrofitting process of older tunnels. Accessibility to existing tunnels is usually very limited and simple experimental techniques are called for. The following chapters deal with the experiences gathered with such measurements. On this basis recommendations are formulated concerning advantages and limitations of the different techniques. The content of this paper is mostly based on an extensive campaign carried out in 2002 in the Gotthard road tunnel. Additional information was provided by a number of measurement campaigns, including the Mont Blanc (2001-2002) and Branisko tunnels (2006).

2. DESIGN GUIDELINES AND THE NEED FOR VERIFICATION

Detailed prescriptions for evaluating leakages are given in the Swiss FEDRO (2006) directive in the Austrian RVS (2001). The leakages can be evaluated separately for the tunnel structure and for the dampers:

$$q_{Tunnel}\left[\frac{m^3/s}{m}\right]=\begin{cases}0.3\cdot\sqrt{\Delta p} & \textit{Switzerland}\\ 5 & \textit{Austria}\end{cases}$$

$$q_{Dampers}\left[\frac{m^3/s}{m^2}\right]=\begin{cases}0.003\cdot\sqrt{\Delta p} & \textit{Switzerland}\\ \left.\begin{matrix}0.07 & 1'000\,Pa\\ 0.10 & 2'500\,Pa\\ 0.13 & 4'000\,Pa\end{matrix}\right\} & \textit{Austria}\end{cases}$$

It should be noted that the Austrian values are prescribed as maximum allowable limits, while in Switzerland no limit is specified and the values mentioned are indications for design. The Austrian values are much lower in the typical operating range, 1’000-2’000 Pa. The German RABT (2006) and the French Circulaire (2006) clearly state the necessity for accounting for leakages in ventilation design, without specifying maximum values or detailed design criteria.

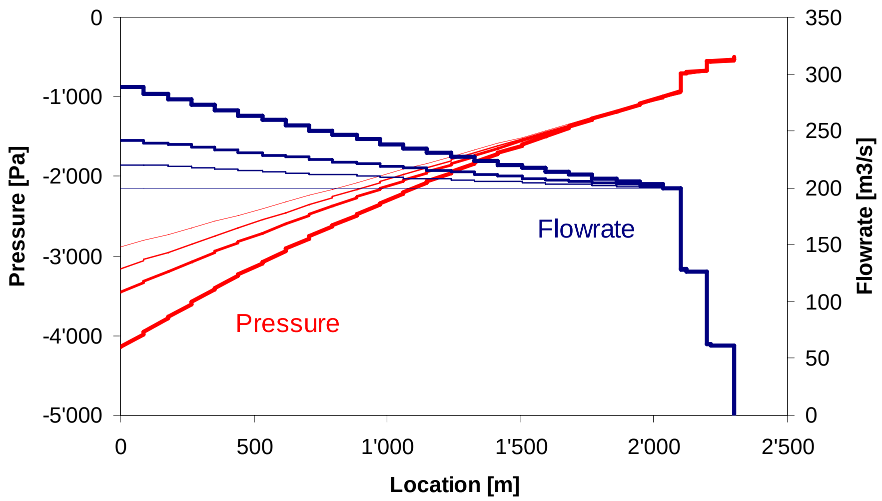

Figure 1: Flow rate and pressure distribution in case of fire for different leakage rates (Gotthard road tunnel, southernmost ventilation section, Airolo-Motto di Dentro). The curves indicate the results obtained imposing a constant extraction rate of 200 m^3/s through 3 open dampers with high (thickest lines), average and vanishing leakage rates (thinnest lines). The leakage rates correspond to the prescriptions of the Swiss directive as well as half resp. twice this value.

3. MEASURING LEAKAGES IN THE GOTTHARD ROAD TUNNEL

The 16.9 km long Gotthard road tunnel is in operation since 1980. In spite of continuous maintenance the tunnel structure and equipments are showing their age. The tunnel was originally equipped with fixed openings for smoke extraction, which allowed only for a uniformly distributed smoke extraction. Under such conditions leakages were not a serious concern. After upgrading the original tunnel ventilation system, by means of smoke exhaust dampers (Bettelini et al., 2003), it was decided to carry out a thorough investigation of the system’s performance and effectiveness, including leakages. The main goals were the determination of the smoke-extraction capability of the tunnel in case of fire, the verification of the system’s performance in normal operating conditions and the verification of the aerodynamic stability limits of the exhaust fans after this major ventilation upgrade.

The initial and most thorough part of the effort was carried out during 2002 and was mainly devoted to the southern ventilation sector. With a length of 2.3 km and smoke extraction concentrated on one side, in the ventilation station Airolo, this sector represented one of the weakest links of this powerful ventilation system. Moreover the tragic fire of 24 October 2001, which took place about 1 km from the southern entrance, contributed to an additional weakening of the structure. Owing to the thorough test of the different equipments it was then possible to simplify significantly the investigation of the remaining four ventilation sectors of the tunnel. It should be noted that the measurement campaign constituted also one essential basis for the subsequent upgrade of the ventilation station Airolo, completed in 2007 (Chinotti and Bettelini, 2006).

4. MEASUREMENT PRINCIPLES AND TECHNIQUES

The determination of the leakage rate requires an accurate measurement of the flow rate at the smoke-extraction location and at the end of the duct. The second measurement is mostly provided with sufficient accuracy by the fixed measurement devices installed on the fans.

The basic techniques available for measuring flow rate and leakages are:

- Direct flow rate measurement through a number of velocity measurements.
- Indirect measurement of flow rate through measurement of tracer gas concentration.
- Indirect measurement of leakages through measurement of the pressure distribution along the exhaust duct.

These techniques are discussed in the following chapters, based mainly on the experiences from the extensive measurement campaign carried out in 2002 in the Gotthard road tunnel. The main findings, conclusions and recommendations are summarized in chapter 11.

5. FLOW RATE MEASUREMENT

Direct measurement of the flow rate thorough the dampers is usually not possible with any reasonable accuracy, because of the complex flow filed. An exception is e.g. the Mont Blanc tunnel (e.g. Bettelini et al., 2001), where the exhaust duct is located under the road and the secondary extraction ducts are well accessible.

Net measurement techniques are long established. The measuring principle is simple: the average velocity can be computed with high accuracy as the arithmetic average of the velocity values measured at a number of suitably selected locations in the section considered. The techniques adopted vary in detail, depending on assumptions on the velocity profiles, but the results are quite consistent. For our validation it was decided to adopt the Log-Tschebyschew rule using a network encompassing 6 x 6 measurement points, **Figure 2**. As showed by Richter (1972), the flow rate measurement error can be expected to be in the range of 1% for regular profiles and increase to 4% for highly irregular profiles.

Two measuring stations, one just upstream of the exhaust fan of the station Airolo, the second just downstream of the smoke extraction section and close to the duct far end, were installed. The home-made Pitot tubes (diameter 2/1.5 mm) were tested in the ETH wind channel and proved to be pitch-insensitive in a range of ±10°. The pressure signals were conveyed by plastic hoses to a Scanivalve connected to pressure transducers. Signals were displayed on an oscilloscope. Reference pressure for calibration was provided by means of Betz water manometers. Data acquisition was conceived and carried out by personnel of the Institute of Fluid Dynamics of ETH Zurich.

Representative velocity profiles are presented in **Figure 3**. The results were entirely consistent and permitted to compute the flow rates. The results are discussed in chapter 9.

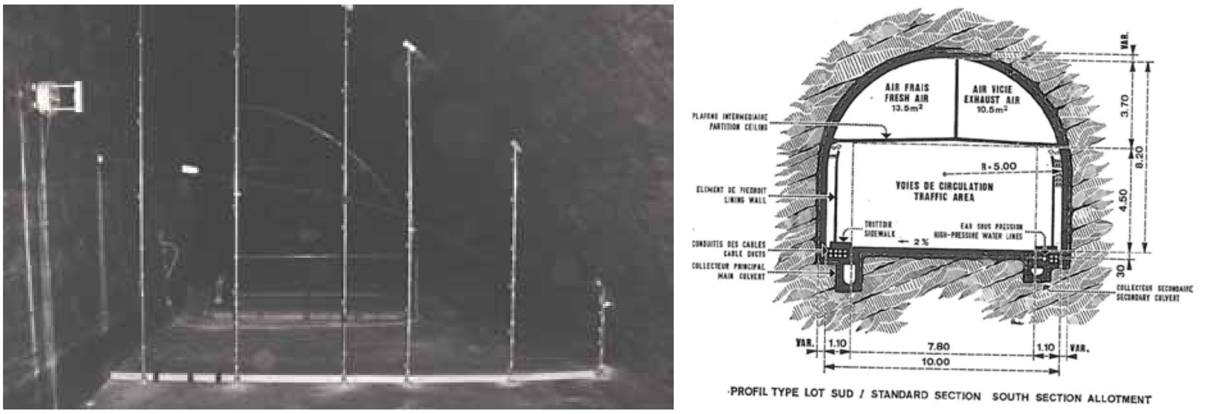

Figure 2: The array of 6 x 6 Pitot tubes used for measuring the flow rate in the exhaust duct of the Gotthard road tunnel. A point ultrasonic anemometer is visible on the left hand side of the picture. The ventilation station Airolo is visible in the background.

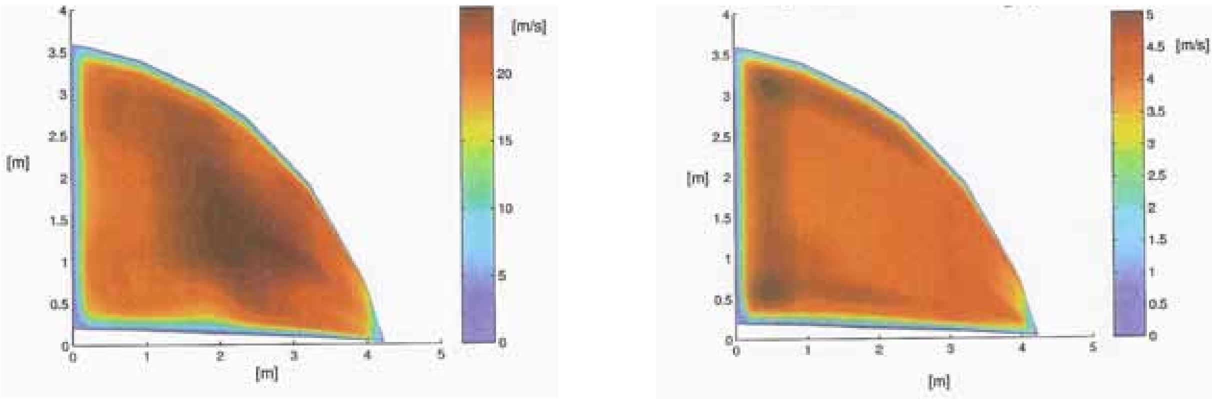

Figure 3: Velocity profiles in the tunnel (left) and close to the ventilation station Airolo (right). The peculiar shape of the second profile is related to the tunnel's curvature in the portal area (radius 760 m).

6. FLOWRATE FROM VELOCITY MEASUREMENTS

Much simpler methods for evaluating flow rate are direct velocity measurements. During the measurement campaign in the Gotthard road tunnel, where tunnel availability was critical and measuring time short, it was decided to validate reduced measurement techniques in the first tunnel section, in order to apply only them in the remaining ventilation sections of the tunnel. It was decided to use rugged ultrasonic point and line anemometers: 6 point measurement devices type TunnelCraft Flow 550 (range ±40 m/s, accuracy ±0.4 m/s, installation on the vertical wall, height 1.8 m, wall distance 35 cm), 2 line measurement devices type Flowsic 200 (range ±40 m/s, accuracy ±0.4 m/s, installation through the expected velocity peak) and data logger type EasyLog 4304 JUMO. All devices and the data acquisition system were delivered and operated by ACP (Bienne). Further verification measurements were carried out by means of conventional propeller anemometers.

The typical error to be expected from point and line measurements can be estimated based on a conventional 1/n power law for the velocity distribution in a circular pipe, with $n \approx 7\text{-}10$ for $Re \approx 10^5\text{-}10^6$. The error for point measurements will be in the range of the ratio of the maximum to the average velocity, i.e. about 16-23% for the present application. Smaller errors, about 10-15%, can be expected while using average values over the diagonal. CFD results for the fully developed flow in this particular exhaust duct, conducted for an average velocity of 20 m/s and vanishing curvature, show that the maximum velocity is 17% higher than the average. Line averages, assuming horizontal measurements, show errors in the range of 5 to 7.5% for measurements heights between 1 and 2 m from the duct bottom. Line-averaged values are typically too high, because they do not account properly for the proportionally larger surface of the boundary layer region.

The accuracy level mentioned for point velocity measurements cannot be expected to be sufficient for leakages measurements. However, the cross-section of exhaust ducts is mostly constant. In such cases it is sufficient to place the point measurements of all measuring stations at exactly the same geometrical location within every profile. If the velocity profile is fully developed, the measured velocity is related to the average velocity by a constant proportionality factor, which can be determined by means of only one accurate flow rate measurement. This can be achieved by means of one Log-Tschebyschew or tracer measurement at one station or directly using the readings from the anemometers installed on the fans. After careful calibration in the southernmost ventilation sector, this technique was used in all remaining ventilation sectors. The same approach was used in the Branisko tunnel, chapter 10.

7. TRACER MEASUREMENT

The tracer measurement technique was originally developed for the measurements in the Gotthard road tunnel described here and was later used routinely in several tunnels. This investigation was carried out by HTA's (Fachhochschule Zentralschweiz, Lucerne-Horw) Prüfstelle HLK. The measuring principle is based on the injection of a known flow rate of an inert tracer gas, in this case SF6, into the exhaust duct, downstream of the last open damper, and measuring its concentration at two downstream locations. The flow rate it the exhaust duct at both locations can be computed using the known tracer flow rate and the measured tracer concentration. The downstream reduction of the tracer's concentration is a direct measure for the leakage rate. In this case the relevant parameters were: injection of 2-5 g/s SF6, first measuring station 190 m downstream, second station 1'750 m further downstream. The SF6 concentration, in the range of 2 to 10 ppm, was measured by standard Bruel & Kjaer IR-PAS analyzers (measuring range 0.005-5'000 ppm) with an uncertainty estimated at 6.7%. The estimated resulting uncertainty was of the order of 7% for the flow rate and 4% for the leakage rate. Gas sampling at different locations within the measuring section confirmed that the gas concentration was sufficiently uniform at both locations.

8. MEASUREMENT OF PRESSURE DISTRIBUTION

The axial pressure gradient for fully developed flows in straight ducts with constants cross section is proportional to the longitudinal velocity squared. This inexpensive measurement proved to deliver a very useful verification of the results gathered by means of other techniques. In the Gotthard tunnel campaign the pressure difference between exhaust and main tunnel was measured at 6 locations by means of standard pressure transducers (Jumo 4304, 0-10 kPa) and self-constructed water manometers. Both measurements showed entirely consistent results.

9. ANALYSIS OF RESULTS

The decision of applying different measurement techniques in the Gotthard road tunnel was motivated by the urgency of the investigation, necessary for planning upgrades of the ventilation system, and by the reduced time slots which could be allotted for the measurements (the tunnel needs to be closed before accessing the exhaust duct and this is only possible for 20-25 nights yearly). The possibility of comparing several experimental techniques was a very useful side effect.

The results are presented in **Figure 4**. Depending on the data available, the reference flow rate is either the Log-Tschebyschew or the tracer value. If both values were available, their average was used. For velocity measurements the diagrams show the product of the velocity with the duct cross-section, without correction.

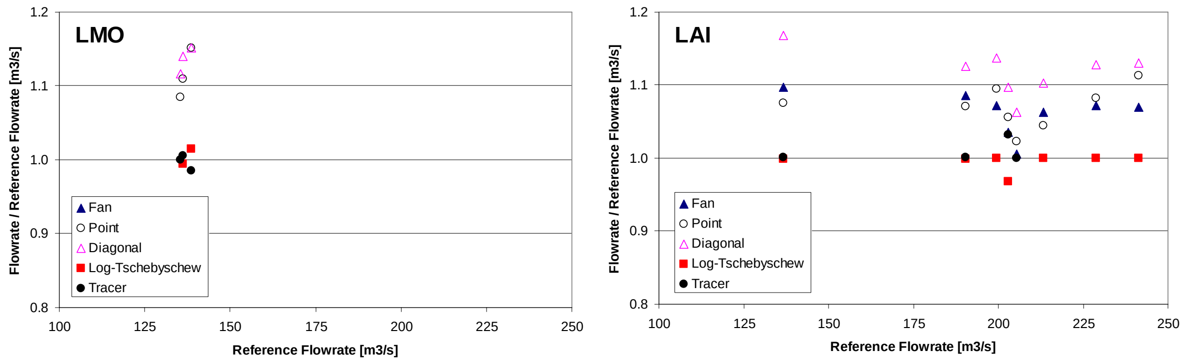

Figure 4: Comparison of the different measuring techniques tested in the Gotthard road tunnel, measuring station in the tunnel (left) and close to the ventilation station Airolo (right).

The main findings can be summarized as follows:

- The Log-Tschebyschew and tracer measurements are entirely consistent and the difference is, with the exception of one point with a difference of 6%, typically well below 3%.
- The values based on diagonal velocity measurements are, as expected, consistently too high. The correction if of the order of 10-15% but can vary depending on the installation location. Once this correction is applied, an uncertainty of about ±5% can be expected.
- The point velocity measurements obviously need calibration and the correction factor depends on the location of the measuring point. Once this correction is applied, the resulting values have an uncertainty of about ±5%.

Based on these results it was decided to reduce the subsequent measurements campaigns in the Gotthard road tunnel, for the remaining ventilation sectors as well as for all measurements carried out after extensive sealing efforts in the exhaust duct, to rely mainly on direct velocity measurements (point and diagonal) and pressure. Significant economic savings and time reductions, important considering the tight tunnel closure schedule, could be achieved.

The initially measured leakages in the southern ventilation sector of the Gotthard road tunnel proved to be very high, up to 30-40%. Much lower leakages were observed in the other ventilation sections, not or only marginally affected by the 2001 fire. An extensive intervention for reducing leakages was subsequently carried out. A second series of measurements showed that this intervention was successful.

10. MEASURING LEAKAGES IN THE BRANISKO TUNNEL

The Branisko Tunnel in Slovak Republic is in operation since 2003. The tunnel system consists of a single tunnel of nearly 5 km length with bidirectional traffic and parallel emergency escape gallery, transversally connected to the main tube by 13 cross connection galleries. The semi-transverse ventilation system allows, in case of fire, for a conventional smoke extraction through dampers, exhaust duct, vertical shaft and ventilation station in the central part of the tunnel. A safety analysis was carried out, according to the EU/EC 2004/54/EC (Bakos et al., 2007). It quickly was clear that the performance of the fire ventilation system played a central role in this tunnel and it was decided to investigate its performance in great detail, by means of 1D and 3D simulation techniques as well as an experimental investigation of the key performance parameter, the effective smoke-extraction rate (Bettelini e al., 2007). Since the tunnel is in operation, all investigations had to be conducted on a tight schedule during nighttime closures. Based on the experiences reported in the previous chapters, it was decided to combine several experimental techniques. The measurements were carried out based on SF6 injection and concentration measurements, precision anemometers, pressure gauges and the built-in fan flow rate measuring devices.

Figure 5: Measuring techniques in the Branisko tunnel. Left: SF6 injection; right: SF6 suction and velocity measurement. The damper shown in the right picture was sealed by a steel plate.

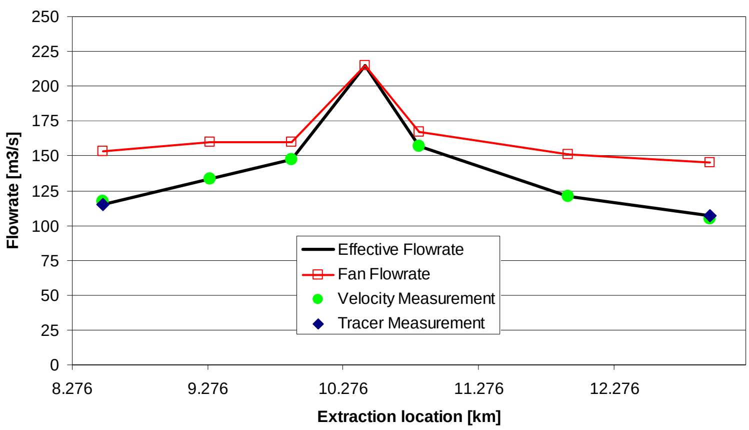

Figure 6: Leakages measured in the Branisko Tunnel.

The results presented in **Figure 6** allowed for an accurate determination of the effectively available smoke-extraction rate. They also allowed confirming the presence of very substantial leakages, of the order of 25% for fire locations in the vicinity of the portals. This comparatively simple and inexpensive campaign provided therefore results, which are considered fundamental for the tunnel's safety.

11. CONCLUSIONS AND RECOMMENDATIONS

Several experimental techniques have been validated under real life conditions in the Gotthard road tunnel and applied to other tunnels. The main findings and recommendations regarding the applicability of different techniques for measuring leakages in tunnels, in terms of accuracy, flexibility, time requirements and cost are:

- The Log-Tschebyschew and tracer techniques are very accurate (better than 3-5%) and (particularly for the tracer technique) insensitive towards "irregular" velocity profiles, related to tunnel curvature, variable cross-section, obstacles etc. Both techniques are comparatively time consuming (this holds particularly for the Log-Tschebyschew technique). They both require specialized equipment and personnel. Specialists can carry out tracer measurements without the need for much "customization" while the Log-Tschebyschew technique requires substantial adaptation to different tunnels but has the advantage of delivering an accurate velocity profile.
- Techniques based on one or a few point velocity measurements are quick and very inexpensive but usually require calibration at least at one station. The problem is easily solved if the accuracy of the fixed fan flow rate measurement is adequate. If some basic requirements are satisfied (well established velocity profiles, weak tunnel curvature, aerodynamically correct positioning etc.) a suitable calibration allows for accuracy of the order of ±5%. This technique is particularly interesting where several measuring locations are required, e.g. while looking for concentrated leakages, and in order to realize quick approximate evaluations.
- Techniques based on diagonally averaged velocity measurements represent an intermediate level between the simplest point measurements and the more complex Log-Tschebyschew and tracer techniques, both in terms of accuracy and requirements. The main disadvantage is related to the specialized equipment required and to the needs for a careful installation.
- Pressure measurements are simple and inexpensive. They are recommended as an additional mean for verifying the consistency of the results from other techniques.

While preparing measurements it should be evaluated if a few quick but careful CFD simulations of the exhaust duct can help simplifying a measurement campaign.

12. AKNOWLEDGEMENTS

It is a pleasant duty to express my gratitude to some friends and estimated colleagues for actively supporting this and other efforts, particularly to W. Steiner, M. Gagliardi, M. Chinotti and coworkers (Gotthard road tunnel), ETH's Institute for Fluid Dynamics (Zurich), HTA's Prüfstelle HLK (Lucerne-Horw), ACP's team (Bienne).

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