TUNNEL SAFETY MANAGEMENT IN CONTEXT WITH THE EU-DIRECTIVE

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ABSTRACT

Tunnel safety management is a subject of many national and international activities. since the last years. In this connection basic trends and developments can be find out.
On the international level a need for harmonisation of safety requirements is requested aiming an integrated view of all safety aspects of road tunnels. Safety management systems should fulfil these requirements by an integrated approach of tunnel safety.
The EU-Directive 2004/54/EC is an international legislative document providing an integrated approach for a tunnel safety management system.
The background for tunnel safety management systems and their application on the EU-Directive is described.

Keywords: tunnel safety management, safety requirements, risk analysis

1. INTRODUCTION

Tunnel safety management plays a key role for many initiatives funded at the European and international level. Many countries agree on the fact that there is a need for a framework in which all relevant aspects of tunnel safety, such as regulations, technical and operational measures, safety assessment operating experiences are taken into account in a holistic way.
In this context the EU Directive 2004/54/EC on minimum safety requirements for tunnels in the trans-European road network implies the standardization of the institutional, organizational and operational aspects of tunnel safety management systems across the member states of EU.

2. OBJECTIVES OF TUNNEL SAFETY MANAGEMENT

A basic prerequisite for providing an integrated view of the tunnel safety management system is to define its major objectives and outline its basic elements and structure. A tunnel safety management system involves a set of measures in order to safeguard the efficient and safe operation of the tunnel.
The definition of the objectives of safety management systems are the same in various international activities of the last years. Both the international work of PIARC (report on fire and smoke control in road tunnels of 1999), the UN ECE report of the group of experts on road tunnel safety of 2001 and European Union (Directive on Minimum Safety Requirements for Tunnels in the Trans-European Road Network) agree in following basic objectives:
1. Prevent critical events that may endanger human life, the environment and tunnel installations
2. Reduce the consequences of accidents, such as fires by creating the prerequisites for:
- people involved in the incident to rescue themselves;
- road users to intervene immediately to prevent greater consequences;
- ensuring efficient action by emergency services;
- protecting the environment; and
- limiting material damage.

Prevention is of course of primary importance, but unfortunately it is not possible to prevent all incidents. In case of an accident or fire , the most effective response is self-rescue of users inside the tunnel. The experience of past large fire incidents shows that an intervention of the fire brigade can be ineffective after e.g. ten minutes or emergency services cannot reach the fire place in such a short time

The above mentioned objectives are connected with the definition of risks as product of the tunnel incident probability and the incident consequences. This definition implies that risk mitigation can be achieved through the provision of a set of preventive and repressive measures in order to minimize the probability of tunnel incidents und reduce the tunnel incident consequences.

3. INTEGRATED VIEW OF SAFETY

An illustration of all safety aspects in road tunnels is the "bow-tie" model (see figure 1) contained in the European research project Safe-T This model incorporates the different stages of an accident. In most cases, incidents are determined by certain pre-conditions (causes), in other words a disruption of the normal course of the traffic. An accident is composed of different stages, beginning with an incident. The accident development process determines the seriousness of the accident effects. This can be expressed graphically by regarding the incident as a nodal point between the pre-conditions

The chain with causes - incident - effects has the shape of a bow tie.

Both tie sides contain the points of action to influence the events before or after the incident. on the one hand, attention should be given to incident prevention (e.g. brake overheating of trucks). On the other hand. the mitigation and suppression of accident effects (e.g. smoke or toxic gases) is of crucial importance.

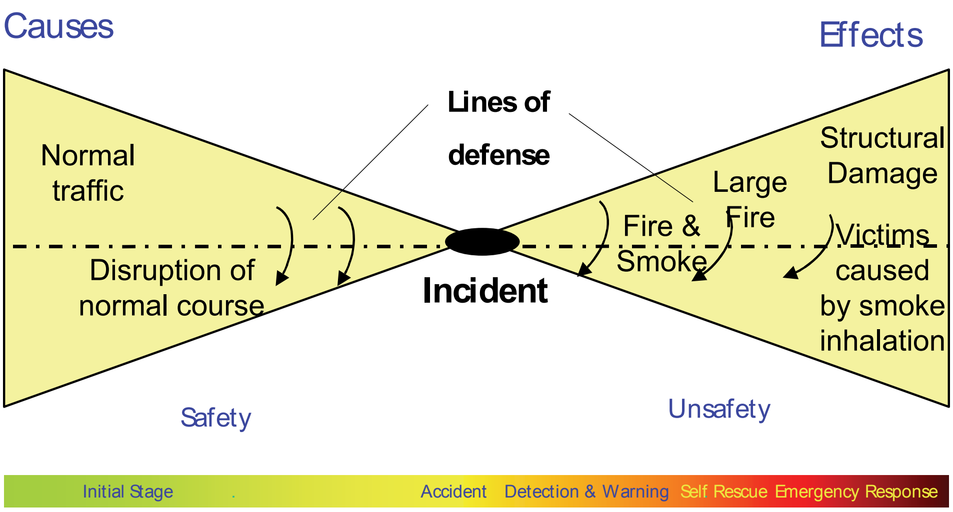

Figure 1: Bow tie model applied to tunnel accidents with fire and smoke

In the past regulations concerning tunnel safety were mostly dealing with infrastructure. The first international regulation with a holistic approach was published by the UN ECE. A multidisciplinary group of experts on road tunnel safety (with members of PIARC and ITA) was launched 2000 in Geneva and published 2001 the final report of UN ECE which includes recommendations on all aspects of road tunnel safety: user, operation, infrastructure and vehicles. The current state of international regulations and research works are based on this holistic approach of tunnel safety.

4. THE EU- DIRECTIVE 2004/54/EC

The EU- Directive 2004/54/EC on minimum safety requirements for road tunnels follows this trend but provides more safety measures regarding the infrastructure and operation and only information campaigns for users. Other EU legislations will deal with vehicles.
But the EU Directive 2004/54/EC provides additionally several levels of responsibilities, a risk analysis and procedures for the different planning stages of tunnels.

4.1. Responsibilities

The EU Directive regulates the responsibilities in the tunnel safety management designating the following actors involved within the tunnel safety management:

- Administrative Authority
  shall ensure that all aspects of safety of a tunnel are assured and shall assess their compliance with the requirements of the Directive both for tunnels in the designing stage, before opening for the public traffic and existing tunnels. Several tasks are defined in detail e,g. that regular inspections are carried out by the inspection entity.
- Tunnel Manager
  is responsible for the management of a tunnel in the design, construction and operating stage. The Tunnel Manager nominates with the prior approval of the Administrative Authority one Safety Officer for each tunnel, who can be a member of the tunnel staff or the emergency services.
- Safety Officer
  shall coordinate all preventive and safeguard measures to ensure the safety of users and operational staff.. He is responsible for assessing the effectiveness of the tunnel safety measures and ensures the coordination of the tunnel manager and the emergency services with respect to the emergency response planning.
- Inspection Entity
  is established by each Member state in order to perform evaluations tests and inspections by or on behalf of the Administrative Authority on the technical and operational conditions of the tunnel.
- Emergency services
  including police services, fire brigades and rescue teams, intervene in the event of an incident.

4.2. Risk analysis

The European Directive requires a minimum safety level for new and existing tunnels and provides various parameters for a systematic consideration of all aspects of the safety system. For tunnels with special characteristics regarding the mentioned parameters, e.g. percentage of heavy goods vehicles, additional safety measures should be proven to reduce the risk in the tunnel by the use of a well-defined risk analysis methodology. The type of risk reduction measures is entirely up to each member state to determine. The risk analysis shall take into consideration possible accidents, which clearly affect the safety of road users in tunnels and which might occur during the operating stage and the nature and magnitude of their possible consequences.
The Austrian risk model for road tunnels was developed on a system based approach, consisting of a quantitative frequency analysis and a quantitative consequence analysis.

4.3. Safety measures

The safety measures proposed by the EU Directive shall be implemented at a minimum in order to ensure a minimum level of safety in all relevant tunnels. They are prescriptive i.e. they are depending on limits as traffic volume or on the length of a tunnel and consists of following infrastructure measures:

- Structural measures
- Lighting
- Ventilation
- emergency stations
- Water supply
- Road signs
- Monitoring systems
- Communication systems

According to the EU Directive, the tunnels should be provided with the essential operating means that ensure the safety of the traffic flow inside the tunnel. In addition, proper traffic arrangements should be applied when maintenance works are performed. These arrangements refer to the traffic inside and nearby the tunnel.
Traffic management plans should be developed covering the procedures of closing the tunnel in case of an emergency situation.

4.4. Tools for safety tunnel management

The European Directive stipulates tools for safety tunnel management to ensure a constantly safety throughout the life of a tunnel. For this purpose general demands are defined for safety documentation, collection and analysis of incident data and safety inspections of tunnels

The tunnel manager shall provide safety documentation for the three different stages of a tunnel project: The design stage, the commissioning stage before opening the tunnel for public traffic and the operation stage. The safety documentation shall contain all safety-relevant information about the respective tunnel as defined in the European Directive:

- a precise description of the tunnel e.g. the geometry, emergency facilities
- traffic situation e.g. characteristic traffic data, portion of heavy goods vehicles , traffic regulation
- transport of dangerous goods with an estimation of relevance of risk of hazardous goods transport
- safety organization and emergency response e.g. emergency response plan, coordination with the emergency services
- feedback of experience e.g. documentation on safety exercises carried out, implementation of findings from exercises

Collection and analysis of incidents are essential for the risk assessment of a tunnel and for the improvement of safety measures. The EU-Directive requires a report when a significant incident or accident occurs in a tunnel by the tunnel manager and every two years an information about the frequency and causes of significant incidents by the member states. Significant incident which have to be reported are incidents, accident or fires in tunnels which clearly affect the safety of road users in tunnels.
The collected data allow in particular, evaluating the frequency and the causes of significant incidents or accidents and provide information on the actual role and effectiveness of safety facilities and measures and on users behaviour.

In Austria a web-based data collection sheet for tunnel incidents is developed and used since the beginning of 2006.

Safety inspections of tunnels are another tool of safety management which is required by the European Directive. At least every 6 years periodic inspections are mandatory to make sure that the tunnel meets the safety requirements. The inspections shall be carried out by the inspection entity, which have to be independent from the tunnel manager. The administrative authority may execute the inspection entity or transmit it to a private entity.
Considering a possible change of relevant parameters of tunnel safety, e.g. traffic density, status of safety equipment, the safety level of in service tunnel must be regularly assessed in order to

- secure the tunnel management team on its organisation and safety measures applied
- check that the initial safety level has not decreased regarding possible new conditions of operation

The safety inspection which is in progress in Austria since several years ensures the high level of safety of the operational and infrastructural measures.

5. CONCLUSIONS

The EU-Directive 2004/54/EC provides a tunnel management system for road tunnels considering all aspects for tunnel safety in a holistic way in order to gain uniform minimum standards for road tunnels in the European Union. Beside the requirements of safety measures regarding infrastructure, operation and tunnel user additionally the use of a risk analysis considering the particular risk relevant influence parameter for a specific tunnel is provided. A new element in the EU-Directive is the definition of several levels of responsibilities and compulsory procedures ensuring the minimum safety level in the planning stage and when opened for traffic and for existing tunnels, with regular inspections of the infrastructure and operation. A systematic collection and analysis of incident data in tunnels should enable the efficiency of the various safety measures and improve the data for risk estimation and risk evaluation.

IT'S TIME TO "*SHOUT*" – RISK MANAGEMENT AT THE TEST BED A NEW ERA OF RESPONSIBILITY FOR TECHNICIANS

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ABSTRACT

In this new age of risk management by committee, and risk mitigation through mischief the importance of technical opinions for ACTUALLY managing risk has never been so acute.

Technicians are often relegated to lowly positions in organizations and their opinions vilified by powerful – yet technically ignorant – managers. This paper examines some recent fatal disasters in which warnings from the "experts" were trivialized by bureaucrats' intent on process but ignorant of actual risk.

Key words: professional responsibility; operability; communicate.

1. INTRODUCTION

Monday 15 May 2006, another conference, many learned papers and even more learned people. All of us wanting to be heard, all of us wanting to be seen as clever (preferably more clever than the person sitting next to us!) papers on metro tunnels, ventilation of short and complex tunnels, computer analysis of video images, fixed fire suppression systems, operational issues, the latest equipment and even some comparisons of safety between tunnels.

So fertile is interest in these very important issues that there is another conference dealing with many of the same questions in Italy today.

With all of these conferences and all this talk there must be action and responsibility. At a time when 'performance based engineering' and concepts of equivalence are being promoted, so to are often extremely restrictive financial constraints, management arrangements and other sophisticated organizational tools.

The late 20th century and early 21st century is to be remembered not as the age of enlightenment but as a period in which those people technically competent were overwhelmed by the managers, the bureaucrats, the politicians and the bankers. This must be stayed. It cannot be stopped overnight but each of us has a duty to discharge our professional responsibilities and that duty extends - when necessary to '*shout'*.

So why do I travel to Austria – the land famous for its mountain people and their technical excellence (originally in mountaineering) to promote such a message?

The answer is simple – traditionally the Austrian people developed a detailed understanding of the mountains, their special risks and how to manage them. This expertise provided the Austrian people with the ability to identify and manage mountain risks – practically, effectively and on a daily basis as a community.

In a modern world there is no general understanding and appreciation of tunneling risks except in some broad, vague, hand waving kind of way. Here in lies the urgency of our task for it is we as professionals working with the tunnels – their design, operation, maintenance and refurbishment that this special expertise lies. Tunnel experts can identify the real risks and have the ability to put them in perspective. This is why we must *shout* about the problems we see and understand and not readily be silenced by those whom, despite their best endeavors, know not that of what we speak.

2. EXAMPLE 1: FIXED FIRE SUPPRESSION SYSTEMS

In Europe an America there has been a long standing unease about the use of fixed fire suppression systems as a matter of course in road tunnels. Both PIARC and NFPA through a series of iterations of guidelines and standards have expressed concern about the consequences of such systems including:

- Loss of stratification
- Steam burns
- Ineffectiveness at extinguishment
- Reliability; and
- Cost

In Asia – and in particular Japan - a catastrophic fire in the 70's prompted the mandatory installation of deluge fixed fire suppression systems despite the potential issues noted above.

In Europe and potentially America it was the catastrophic fires of the late 20th century and early 21st century that propelled a reevaluation of the use of these systems – a reevaluation which will be the subject of detailed discussion in one of the parallel sessions this afternoon.

The fact that these fire suppression systems are now generally considered worthy of consideration to manage a combination of both human and asset protection tasks does not mean that the technical issues originally raised against their use no longer exist.

In countries such as Japan and Australia where such systems have been used for many years the focus has turned to issues of rapid detection, rapid response (by both the fixed systems and emergency services) and the importance of maintaining the functionality of both the suppression, detection and response systems. These support systems and the importance of constant functionality review are of a paramount and ongoing concern and functional review.

There are those whom will argue that the inclusion of such systems (by whatever name) deliver the safety and asset protection demanded of a modern tunnel. The technical reality is that reliance upon these systems to deliver that outcome demands vigilance and ongoing technical attention.

In the current climate where fixed suppression systems are being promoted so heavily regard should be had to the vast range of evidence upon both the strength and limitation of these systems.

For example in March 2006 I was fortunate enough to visit Japan. There I learnt of research conducted on the risk posed to human beings by the application of water droplets of various sizes to tunnel fires. In short this detailed Japanese research suggests that in a range of credible scenarios the application of water with too small a droplet size significantly deceases the tenability of the in tunnel environment and thereby reduces safety. This extremely interesting research has never been published. A specialist in the use of optimized water droplet size technologies to develop tunnel safety systems will be presenting a paper this afternoon – if this research interests you then make yourself known to Professor Amano.

If this research on droplet size and tenability is correct the earlier warnings from PIARC and NFPA about fixed suppression systems should not only be heralded, they must, as a matter of professional standards, be addressed when deciding to use such systems in a tunnel. To ignore, or perhaps worse superficially deal with such matters is fraught with peril, albeit that from a non technical perspective the bold use of these suppression systems is encouraged.

The likely outcome of the technicians' analysis of issues such as tenability impact at droplet size is that such technologies will have their place in a range of circumstance where a number of preconditions are met and perhaps more importantly can continue to be met as a tunnel ages over the systems service life.

Verification and validation of incident detection systems in terms of speed, accuracy and reliability are likely to be as fundamental to success of these systems as the validation of the suppression systems themselves.

It is as a direct result of these technical developments that emerging technologies such as computer interpretation of visual CCTV data for incident detection, location and response goes hand in hand with the expanding role of suppression systems.

3. EXAMPLE 2: MANAGERIAL DILUTON OF THE TECHNICIAN

The peculiar wisdom of the technician is often brightest when close quite literally to the 'nuts and bolts' of a situation. The loss of operability of a bank or perhaps just one jet fan in a tunnel is often interpreted by the non technical management hierarchy as a 'percentage' loss of capacity or perhaps as a recurrent (and annoying) maintenance issue.

But for the technician, armed with special knowledge about the importance of managing tunnel air during exceptional circumstances (such as in a fire or during an incident) the loss of such ventilation capacity should be assessed in terms of its impact on the degraded manageability on the tunnel. At a time when there is real and substantive debate about the appropriateness of the design fires used to calculate emergency ventilation capacity (in terms not just of peak megawatt output but also smoke volumes and toxicity) the technicians assessment of such a simple matter as inoperative fans is more than just an exercise in percentage ventilation from the perspective of normal operation.

Along with this duty comes the need for effective communication of the technicians' opinion. What is safe for normal operations is not always appropriate for the degraded conditions many of these systems have been designed to combat, let alone the actual degraded conditions they are more likely to experience in the event of an incident.

Ensuring safety implications of daily maintenance issues are understood and effectively communicated – is another reason it is time to *shout*. Such matters must be both heard and understood. Shouting can at least attract attention; technicians rarely lack something substantive to say.

4. EXAMPLE 3: CONSTRUCTION

A pertinent example of how management structures can stifle both the communication and effective response to the technicians' legitimate concerns come from a recent tunnel collapse in Asia.

In the Asian case a technical issues management structure had been created (which apparently created a means of expressing technical concerns relating to construction issues during the building phase of the project. Once raised these technical concerns were referred to an expert panel. The expert panel could in turn make recommendations about management of the technical issues referred to it.

A series of concerns were raised expressing, with increasing vigor, the fear that there would be an imminent collapse of the construction works. Instruments in the construction zone consistently recorded deflections in the rock far beyond what the models suggested. Managerial debate raged about what to do – but nothing was done, normal work continued.

Over a period of months all technical indicators pointed towards an imminent collapse, yet the financial imperatives of pursuing the cheap construction method coupled with a desire not to lose valuable construction time led to nothing being done.

The technicians were unable to effectively communicate the seriousness of their concerns. At least one such technician resigned out of sheer frustration. When the inevitable occurred and the tunnel collapsed killing a number of construction workers, the flow of correspondence recording the technicians' recognition of the risks and their failure to effectively communicate it led directly to each of the individual's computer email boxes. There was no hiding, just remorse for not having tried a little harder to get something done. The prosecution legal proceedings are currently being heard.

5. CONCLUSION

As technicians attending this conference you are already seen by the community as experts entrusted with the protection of both our people and their assets.

There is nothing surer than at the reception by invitation of the Governor of Styra Mr Franz Voves, the Governor's warm hospitality will be extended to us expressing his good wishes for our intellectual endeavors, wishing us well in our debates and praying that our good work will deliver better (safer) tunnels for Styra and the world. Let us not disappoint him in his good wishes, let us begin the inevitable reversal of power from the bureaucrats to the technicians, let us be fair and critical in the one breadth to those that bring new opportunities through technologies and techniques but above all else we must bring our collective wisdom and critical evaluation skills to the task of managing our limited and precious resources to deliver the safe use and development of tunnels.

It is time to *shout* because we as the collective experts have opinions which demand to be listened to. It is time to '*shout*' because for too long such opinions have been discredited by those least capable of understanding our messages.

If an insurer demands fixed suppression, '*shout*' detection, response, maintenance, verification and validation.

If a tunnel operator refuses to fix critical ventilation '*shout*' Mont Blanc, Gotthard, Frejus.

It may be true that there is no reward without risk but where the risk is not understood by those whom choose to take it the consequences are not rewards – they are penalties.

ADJUSTMENT OF THE VENTILATION IN A COMPLEX TUNNEL SYSTEM

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ABSTRACT

The complex tunnel system in Tromsø, consisting of three main tunnels and three roundabouts, a parking area, shorter connecting tunnels, all inside the mountain has difficulties with achieving acceptable air quality.

Due advanced monitoring and new software wit a large number off possibilities to parameterize the ventilation an attempt to achieve better conditions have been made.

One on the main result is that a correlation found in one tunnel, is near to worthless in other tunnels.

Keywords: tunnel ventilation; correlation between dust and CO

1. INTRODUCTION

The tunnel complex in Tromsø is a complex system consisting of three tunnels and an underground parking area. All connected by three roundabouts, and a short connecting tunnel, inside the mountain. Se figure 1 for principal connections.

Tunnel segment Breivika has concrete surface, the other segments have asphalt.

This causes an increased amount of airborne dust in this segment.

During an upgrade of software and communication in the tunnel system it was installed dust monitors in segment Breivika and Sentrumstangenten. We also set the number of steps for the ventilation to 11.

2. RESULTS

Due to demands from the local fire brigade, who has one entry wherever a fire will start, all air has one entry, and is then spread throughout the tunnel complex.

During normal operation the ventilation starts in accordance with pollution. Figure 2 show where the pollution is measured. Table 1 gives what is measured.

The changes in ventilation had two goals.

1) Improvement of air quality
2) Reduction of bill for electricity.

These goals are in opposition to each other.

Experience from the Bømlafjord tunnel [1,2] indicated that this should be easily achieved. And the first preliminary results indicated that it would be so. But as winter was going on, without any possibility to clean the tunnels, conditions was getting worse.
(It is not wise to use water when the temperature is well below freezing point.)

Originally the pollution had only been able to start the ventilation in three steps.
With the new possibilities we has 11 steps to tune, and parameterizes.

Without the benefit of flow measurement in the system, we have to ensure that the number of fans started in every segment results in the desired direction of flow.
This would of course have been easier if we had several flow monitors.
Ultrasonic, time of flight flow monitors are expensive, and it is difficult to convince tunnel owner to by these, without proof of cost saving for ventilation. (Any kind of point measurement for flow inside a bidirectional road traffic tunnel is worthless [3])

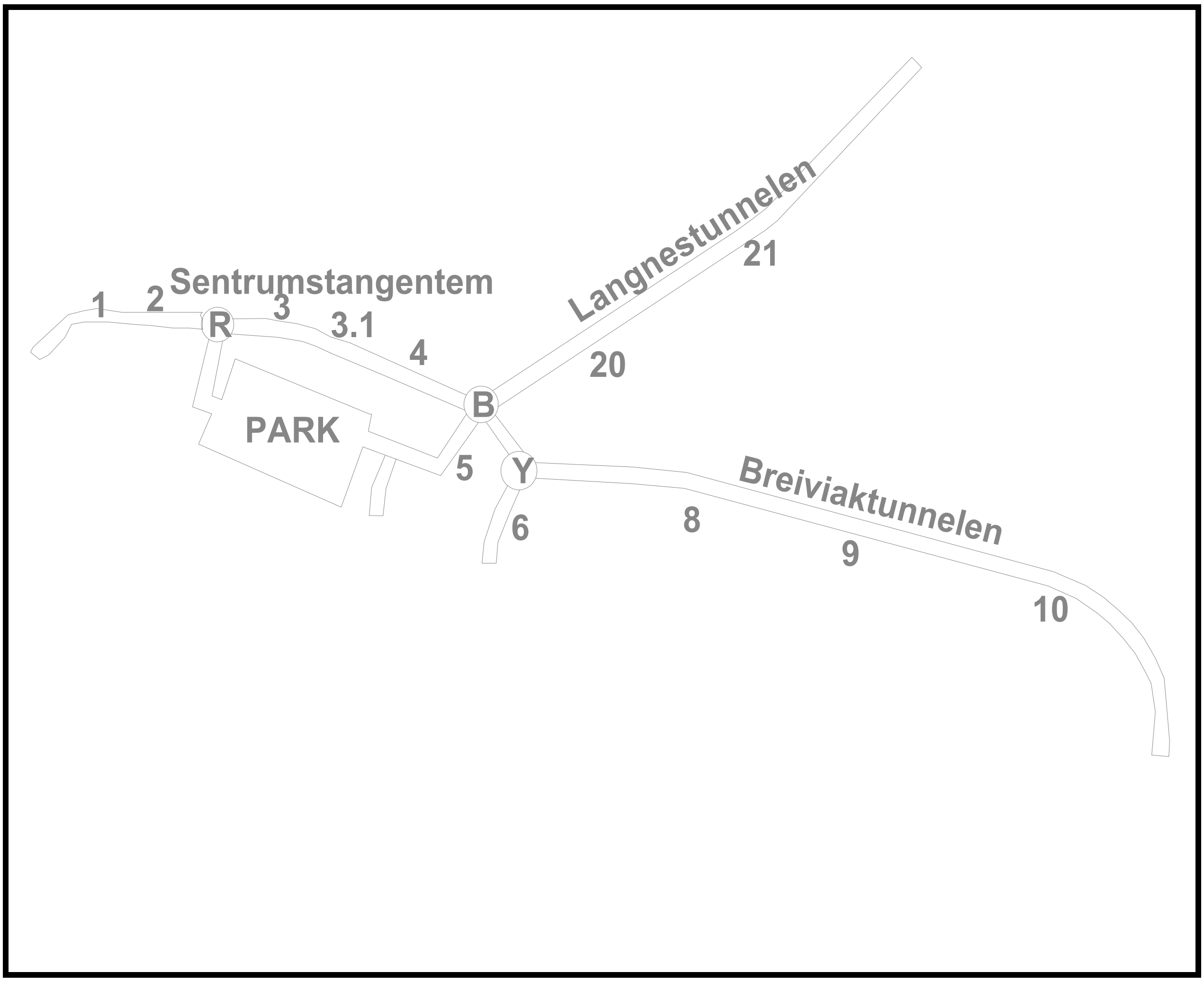

Fig. 1

The numbers shown in Figure 1 gives approximately placement of measuring stations.
The letters R, B and C indicates Red, Blue and Yellow roundabout inside the mountains.
Each of the main tunnels is bidirectional, with traffic on approximately 8000 to 11000 vehicles a day.

Length of tunnels:

Langnestunnelen 1800m.

Sentrumstangenten: 1600m

Breivikatunnelen: 2500m

Table 1: Measuring stations				
1	CO	NO_2		
2	CO	NO_2	Rh	Dust
3	CO	NO_2		
3.1			Rh	Dust
4	CO	NO_2		
5	CO	NO_2		
6	CO	NO_2		
8	CO	NO_2		
9	CO	NO_2	Rh	Dust
10	CO	NO_2	Rh	Dust
20	CO	NO_2		
21	CO	NO_2		

Table 2: Number of fans activated in the different sections, by different steps

Step	Sentrums tangenten	Park From middle of Sentrumstangenten to Parking	Between B and Y	Langnes	From Y to exit	For y Breivika
Step 1	1	1	1	3	2	1
Step 2	3	1	2	3	2	3
Step 3	4	1	2	3	2	7
Step 4	4	1	2	3	2	8
Step 5	7	1	3	5	4	9
Step 6	10	1	2	2	4	8
Step 7	8	1	2	6	4	6
Step 8	8	2	3	4	4	12
Step 9	10	2	2	4	4	12
Step 10	10	2	3	11	8	12
Step 11	29	3	4	11	8	22

By changing the number of fans, started in each segment in different steps, we have 11 scenarios for ventilation.

For each measuring device as a dust monitor, CO monitor etc we has the possibility to set 11 different start criteria and average time for the measurement. Average time has been 300 seconds for all measurements. Calculation of average is done by first PLS reading the instrument. We are saving all data to a log each minute.

During the first months of logging we had indications that showed a reduction in effect compared to the previous year.

With actual settings this was later on showed to be wrong. When the situation is that the measuring limit of the dust measurement is exceeded most of time, we got a problem. The measuring area of the instrument will be increased later this year.

Due to extended analysis of the use of ventilation, at what caused the start of the ventilation we have changed the setting for start.

This is done by logging start criteria, and pollution values over time, and then analyzing this.

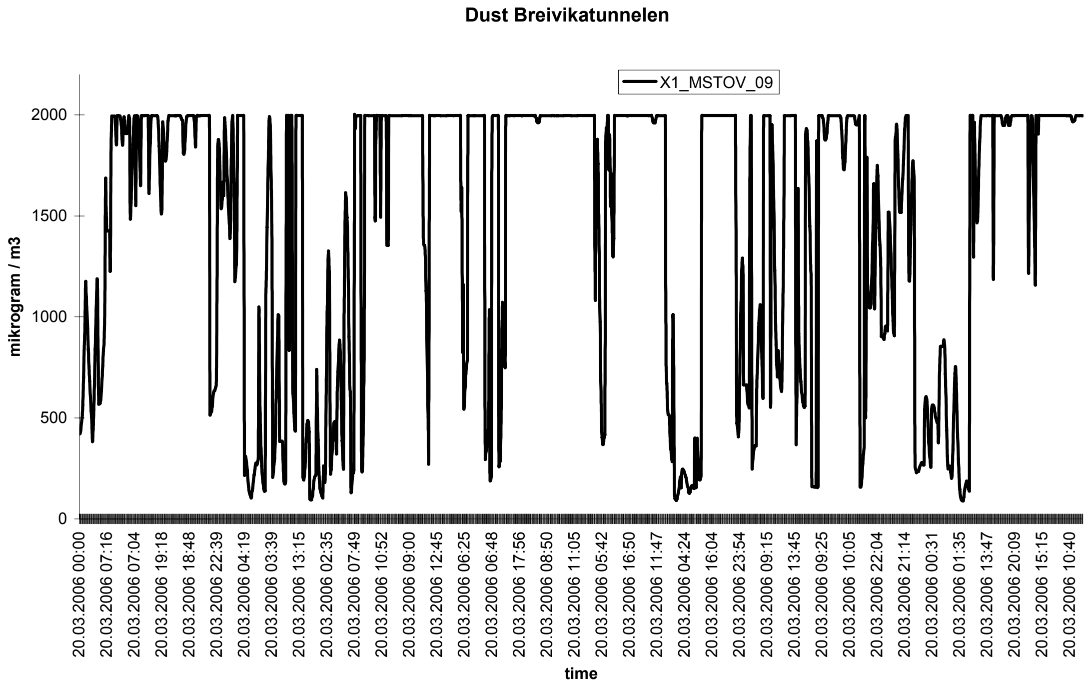

Fig. 2: Dust measurement one day in the Breivikatunnel

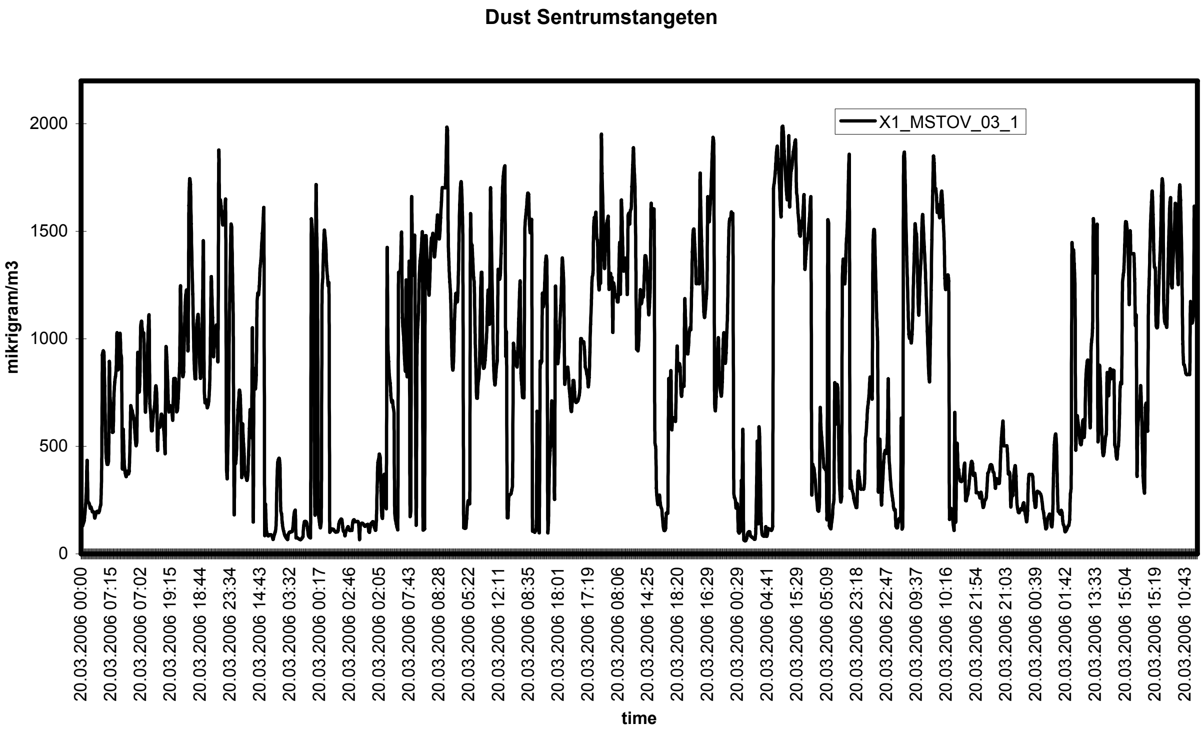

Fig. 3: Dust measurement in the Sentrumstangenten tunnel for one day

Unfortunately the only information available from earlier years is kWh used, and that the pollution in the tunnels has been not acceptable, concerning dust.

Experience from the Bømlafjordtunnel showed that acceptable dust levels could easily be achieved, by starting ventilation after dust levels. But in the Bømlafjordtunnel main dust component is soot, not concrete dust. It is no problem to ventilate out soot. Concrete dust is larger particles, and not easily ventilated. This was well known. Because of this they regularly use MgCl salt as dust binder in the tunnels. The effect of MgCl salting, shows imminently in the airborne dust levels. But this is only visible for a few days, with the existing settings for dust measurements. These settings, in the dust monitors will soon be changed.

One of the other results is that a correlation between NO/NO_2/CO and dust in one tunnel is nearly worthless in an other tunnel.

Where we in the Bømlafjordtunne could find a correlation between CO and dust, NO and dust, we see that in these tunnels we will have a very different correlation between dust and CO

Where the correlation for the

Bømlafjordtunnel is $\text{Dust} = 8{,}5301 * CO_{(ppm)} + 72{,}983$

we have for the Breivika tunnel $\text{Dust} = 37{,}186 * CO_{(ppm)} + 127{,}1$

These values are a quick calculation for one day only. For both tunnels you will individually have a correlation on approximately 0.75.

So be aware, **results from one tunnel can not be used in other tunnels,** without testing, when you are considering correlations between dust and CO and dust and NO_2.

These differences are also visible in the results. When optimizing the Bømlafjordtunnel, we had a reduced cost of electricity, and improved conditions in the tunnel. In the complex system I Tromsø, we have according to the public improved garrulity, but at a high cost.

We are by today not satisfied with the results, and will do some more changes to the system.

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PROBLEMS ON VENTILATION IN COMPLEX CITY TUNNELS

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ABSTRACT

In most cases city tunnels are characterised by heavy traffic and involve complex connections to adjoining surface roads. This results in many cases in on and off ramps inside the tunnel. Such ramps, together with traffic guiding installations increase the problems in both ventilation design and in ventilation control in the case of a fire. Based on the case of a city tunnel in Austria which carrying some 60,000 veh/day and involving a complex connections to the surface roads, the experience gained during the installation and testing phase of ventilation systems are discussed.

Keywords: ventilation design, city tunnels, incident ventilation

1. INTRODUCTION

National and international guidelines require the installation of ventilation even in short tunnels as soon as the traffic volume exceeds a certain threshold value. As soon as mechanical ventilation is necessary the design has to be appropriate for normal operation as well as for incident ventilation. Normal ventilation does not play a significant role as most of the city tunnels are twin tube tunnels with unidirectional traffic, and as long as traffic is free flowing, the piston effect results in self ventilation. This is not the case in incident ventilation, where parameters like design fire load, road gradient and cross section play a decisive role.

Many tunnels in cities carry heavy traffic. In addition they may have on and off ramps in the tunnel, which have an almost unpredictable influence on the ventilation behaviour in incident cases. However, it is necessary to adapt the ventilation design and the procedure for ventilation control in such as to come as near as possible to the goals proposed in the respective guidelines.

In many cases the benefits of ventilation design are counteracted by various other factors, e.g. construction constraints on tunnel height which might result in small fans being mounted in the corners of the cross section, or the sitting of road signs in combination with on and off ramps inside the tunnel. A prerequisite for well functioning ventilation control in incident cases is high quality information about the air speed inside the tunnel. This implies that the sensors have to be mounted at locations not influenced by running fans, road signs or other installations which might disturb the flow field.

2. VENTILATION DESIGN GUIDELINES

In Austria, ventilation design is based on the guidelines RVS 9.261/9.262. These guidelines state the requirements for normal and incident ventilation. Normal ventilation control can be based either on in-tunnel air quality (visibility or CO concentration) or the number of vehicles passing through the tunnel. Correct incident ventilation involves the provision of a predefined air flow with a defined velocity of the smoke/air mass at the incident location.

In the current version the requirements are stated as follows:

- Mechanical ventilation is required for tunnels with a length of more than 500 m and more than 10,000 veh/day/lane or more than 700m and a traffic density of more than 5,000 veh/day/lane.
- Design fire load: 30 MW
- Unidirectional traffic: max. air velocity 2 m/s in the direction of the traffic flow
- Bidirectional traffic: max. air velocity 1 – 1.5 m/s in the direction of the air flow just before the incident. Reversal of the air flow is possible at special locations (e.g. near portals) when it enhances the self-rescue possibilities of tunnel users.

These simple requirements concerning air velocity and direction can cause big problems as soon as complex tunnels have to be considered.

3. COMPLEX CITY TUNNEL

The problems which can occur shall be demonstrated by taking the Bindermichl tunnel in the city of Linz/Austria as example. This tunnel is part of the A7 highway which leads traffic through the city in a north-south direction (see **Figure 1**). The Bindermichl tunnel is connected to the Niedernhart tunnel, having the connections to the city center between them. Both of the tunnels carry some 60,000 veh/day and are important for commuter traffic as well as for transit traffic from Austria to the Czech Republik.

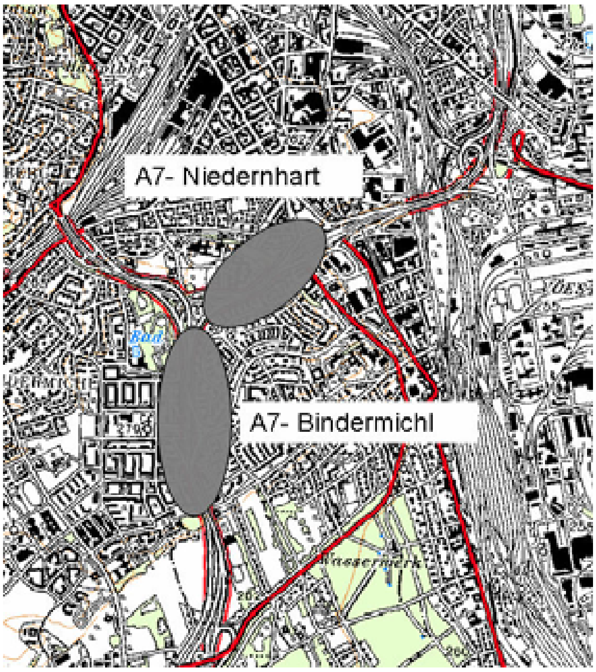


Figure 1: Location of the Bindermichl and Niedernhart tunnels at the A7 highway in Linz/Austria

3.1. Technical details of the Bindermichl tunnel

The Bindermichl tunnel has a length of 1 km and was built in cut and cover. The on- and off ramps “Muldenstrasse” are located roughly in the middle of each of the two bores. While the east bore (south to north) has two on- and off ramps, the west bore has only one on- and one off ramp. The gradient is roughly 1% from south to north with the exception of the most northern 400 m, where the gradient reaches 4%. The on- and off ramps have a gradient of 4%. Although the tunnel was designed to be used in unidirectional mode, bidirectional traffic was to be taken into account as during the first year only the east bore was in operation.

The cross sections vary throughout the whole length, and reach up to 120 m² (180 m² at one portal). **Figure 2** shows a sketch of the east tube. The west tube is similar, with the exception that the Muldenstraße ramp is only on one side. **Figure 3** depicts the south portal section (section A-B in **Figure 2**).

Ventilation design came up with a necessary thrust of some 7300 N to be produced by 18 fully reversible jet fans (408 N each). These were grouped into 2 fans per cross section.

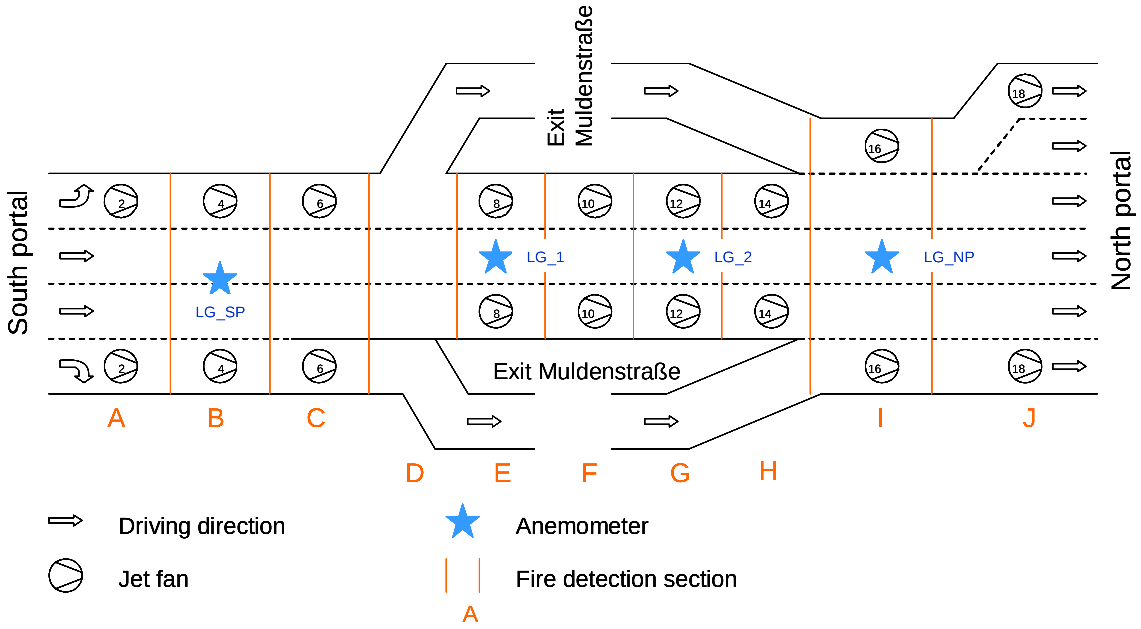


Figure 2: Sketch of the Bindermichl East tube

The Muldenstraße ramps split the tunnel more or less into three sections. The entrance section between the portal south and the Muldenstraße off-ramps (zones A – D in **Figure 2**) with three lanes plus pull off lane (hard shoulder), the central section between the off- and on ramps (zones E-H in **Figure 2**), two lanes plus pull off lane, and the exit section from the on-ramps to the exit portal (zones I – J in **Figure 2**), with up to 6 lanes.

Figure 3: View of the south portal section (zone A and B in Figure 2)

3.2. Fan positioning

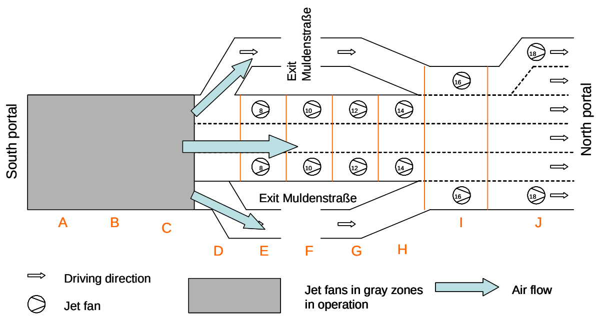
The positioning of the fans was restricted by the following facts:

- No more than two fans per cross section were possible due to problems with ceiling fixed fans.
- The fans had to be wall mounted wherever possible. The direction signs for the traffic had to be placed exactly above the respective lanes.
- The minimum distance between two cross sections with fans should be at least 80 – 100 m.
- Any loss of thrust due to interference with the traffic signs has to be avoided.
- Fans have to be mounted such that the thrust is not lost through the on- and off ramps.

Due to the short length of the tunnel and the huge number of fans it was almost impossible to keep the minimum distance of 80 to 100 m between the fans without running into problems either with the ramps or the position of the traffic signs or lights.

After a first installation of the fans and some flow field measurements throughout the whole tunnel a very inhomogeneous flow field was observed. While in the sections close to the wall the wind speed was relatively high, the air flow in the centre was much slower. In some cases recirculation was even observed in the sections between portals and ramps. Only in the middle part of the tunnel (between the ramps) was a more or less uniform wind profile achieved. As it was not possible to change the position of the fans, the fans were upgraded by installing bent entrance and exit parts (so called banana jets). With this type of fan the negative flow field effects of having only two wall mounted fans per cross section were reduced (but not fully resolved).

The ramps are more or less open holes in the tunnel. The length of the 4 ramps is some 100 m each with a road gradient of 4% (exit positive, entrance negative). If fans are mounted too close to the ramps, the ramps impair the performance of the fans and each fan downstream of a ramp pushes a large part of the air out of the tunnel instead of providing the required thrust for in-tunnel air movement. In addition, each position between the on-ramps and the exit portal mainly results in introducing new air into that part of the tunnel instead of moving the air inside the main part of the tunnel. **Figure 4** and **Figure 5** show the main features of the air flow inside the tunnel, as dependent on the location of the activated fans. The influence of wind pressure from outside the tunnel is not taken into account in these sketches.



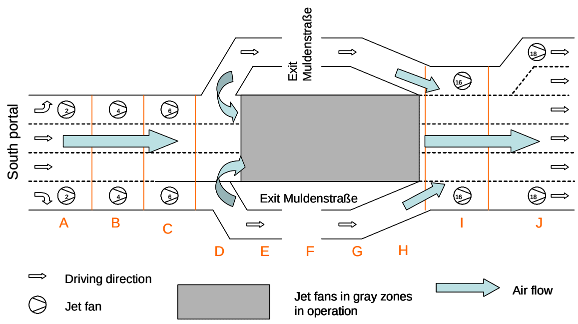


Figure 4: Sketch of the air flow as dependent on the active fans (section south and centre)

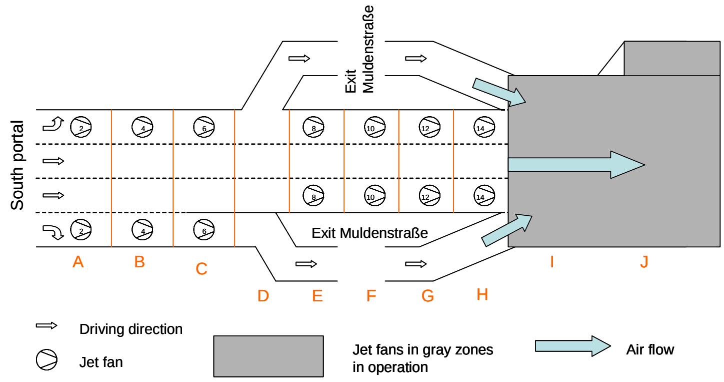


Figure 5: Sketch of the air flow as dependent on the active fans (section north)

The negative effects of the ramps on the air flow have to be taken into account when designing ventilation procedure for cases of fire. Despite having all the power (thrust) available for controlling the air flow inside the tunnel in practise “false” air from the ramps or air leaving over the ramps has an almost unpredictable influence on the in-tunnel situation.

3.3. Positioning of air velocity sensors

The ventilation procedures for incident cases are based in many countries on achieving and retaining a certain air velocity during the incident case in order to support rescue operations. Hence, the exact knowledge of the air flow inside the tunnel is imperative in cases of fire inside the tunnel. The air velocity sensors are a very important part in the ventilation procedure in incident cases. Without proper working sensors a useful ventilation strategy is almost impossible. The Austrian guidelines require proof of the accuracy of the sensors. In the case of point measurements it has to be proved that the results given by the sensors are representative of the average air velocity over the respective cross section of tunnel.

When looking at the outline of the Bindermichl tunnel (**Figure 2**) there is almost no appropriate place for an unbiased measurement of the average air velocity over a cross section. First, the cross section is too big to work with single point measurements. Second, most locations at which a positioning of sensors might be possible are either influenced by the jet fans (when in operation) or in some way influenced by air flows over the ramps.

In the end, the tunnel was equipped with sensors in four different locations. All of them are in the same cross section as the fans, but this was the only position where the influence of the jet from the fans could be eliminated. The location of the sensors is depicted in **Figure 2**. In order to have a picture of the average velocity within the cross section a sonic measurement system was chosen. While in the middle part of the tunnel the distance between the two walls of the tunnel did not exceed the maximum distance between sender and receiver, this was not the case for the sensors in the north and south sections. At these locations it was necessary to have a special installation for the receiver on the ceiling of the tunnel, while the sender had to be mounted on the wall.

Data collected by the velocity sensors are mainly used for ventilation control during specific incidents. If the incident is located near a velocity sensor these data can not be used as they may be biased either by the hot temperature or by turbulence generated by the fire. Thus, data from a different measurement section have to be taken. In the case of the Bindermichl tunnel the measurements in the south and north sections are not as reliable as those in the middle section. The reason for this is the unpredictable influence from airflows over the ramps. Therefore, for most incident cases the velocity information is taken from the sensors mounted in the middle section (LG1, LG2, see **Figure 2**). However, these data are taken at a location with a totally different cross section compared to the sections south and north. Hence, correction factors have to be applied when these data are used for the ventilation control in the other sections. The correction factors are mainly based on the relative proportions of the tunnel cross sections at the incident and the measurement location, and adapted by on site measurements in order to include influences caused by the ramps.

3.4. Incident ventilation

In tunnels with dense traffic and a high risk of congestion the probability of having an accident is higher than that expected in tunnels in rural areas. In the case of the two A7 tunnels the ramps inside the tunnel as well, as the complex traffic situation outside, further increase this probability. A big effort was made to take this complex situation into account during the planning stage.

3.4.1 Simulation

Intensive numerical simulations were already performed during the design phase in order to take the influence of the incoming/outgoing air into account. These simulations were made using a CFD code which allows the coupling of tunnel and ramps (Almbauer et al. 2004). They showed clearly that due to the influences from the Muldenstraße ramps the requirements for ventilation in incident cases can not be achieved at all possible locations inside the tunnel. The only solution to this problem would be to separate hydraulically the Muldenstraße ramps from the main tunnel during fire incidents. In such cases the main tube could be considered as a simple tunnel and the ventilation goals could be achieved without any major problem. Measures to implement such a hydraulic separation have not been applied for several reasons (see section 3.4.3).

The incident ventilation procedure was developed on basis of the results of numerical simulations. This procedure was later tested in the tunnel in order to improve the ventilation performance and to adapt the scheme wherever necessary.

3.4.2 Ventilation tests

The Austrian guidelines for tunnel ventilation require a hot smoke test in each tunnel before the tunnel goes into operation. As the situation in the Bindermichl tunnel – especially in the east bore – is very complex an intensive test phase was applied. Hot and cold smoke tests were performed at different locations and for different ventilation schemes (uni- and bi directional traffic). The incident ventilation procedures were tested for all of the 10 fire detection sections, as all of them apply different activation levels of the fans and they use the air flow information from different velocity sensors. The test of all of the sections (A-J) was performed without smoke, with manual triggering of the incident and monitoring of the response of the system (fans) and the air velocities inside the tunnel.

Special emphasis was put on tests in the ventilation sections I and J, as these sections are in the region with the highest gradient, have a very big cross section and are influenced most by the airflows over the Muldenstraße ramps. As almost no time was available for tests in the west bore of the Bindermichl tunnel, the ventilation situation for the west bore was also simulated in the east bore. The west bore north portal site, is the most critical location, as in this section the Austrian guidelines require an airflow in the direction of the traffic, i.e. downwards the 4% gradient. This results in the highest power requirement for ventilation.

The hot smoke tests were performed in the zones D and I. The simulation for the west bore entailed physically closing Muldenstraße the on and off ramps at the east side of the tunnel. In accordance with the Austrian guidelines 40 l diesel and 10 l gasoline were burned in a pool with an area of 2 m². Such a fire results in a heat release of some 3 MW. In order to simulate the buoyancy generated by a higher fire load, a mobile fan with a maximum thrust of 3000 N was employed. The position of the test fire and the mobile fan is depicted in **Figure 6**.

Figure 7 shows the test performed at the location in zone I with one Muldenstraße on- and one off ramp open. This test served to simulate unidirectional traffic in the west bore. The ventilation goal was smoke movement from the north to the south portal (which is the driving direction in the west bore) with a velocity between 1.5 and 2 m/s. In such a case the ventilation system has to overcome the buoyancy forces caused by the fire and to blow the smoke against the updraft in the tunnel. The picture was taken shortly after ignition. The large cross section allowed the smoke to rise. Although a wind velocity in driving direction was present, back-layering built up quickly.

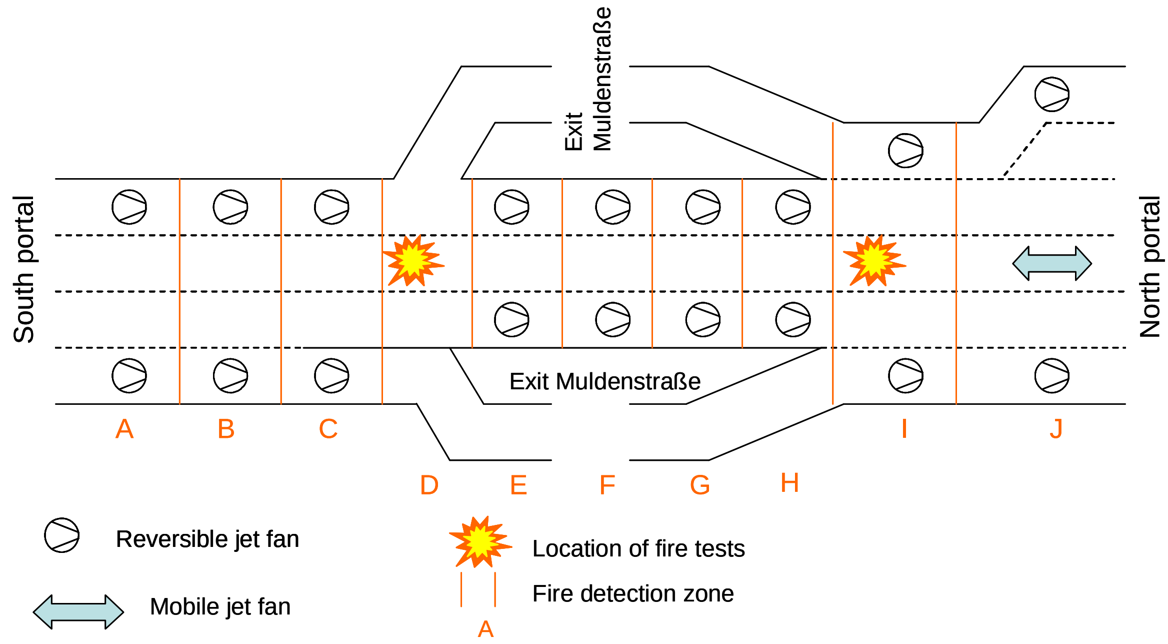


Figure 6: Location of the hot smoke tests

Figure 7: Test fire section I (north) with the open Muldenstraße ramp (right hand side)

Figure 8 shows the results for the test. The black solid line represents the velocity in the fire region. A target velocity of -1.5 m/s needs to be achieved. The value at sensor LG1 was the control value for the ventilation. This sensor was located in the central part of the tunnel (see **Figure 2**). As the ratio between the cross-section in the central and north part of the tunnel has to be taken into account, the wind velocity at that location had to be in the range of 3 m/s (shaded range in **Figure 8**). Back-layering cannot be prevented. In order to minimise the risk of a down mixing of smoke in the region between entrance portal (north) and fire location, the fans in section I and J were not activated. The main work was done by the fans in the middle part of the tunnel (sections E-G). This resulted in an overpressure in the region downstream of the fire. Hence, a positive pressure drop between tunnel and outside existed and smoke polluted air was pressed out also through the Muldenstraße south ramp. This can be seen in the broken and dotted line in **Figure 8**. During this phase the ventilation power was insufficient and the target velocity at LG1 was not reached. The control system reacted by activating the fans in the south section (A-D), inducing in an inflow of air through the Muldenstraße on ramp (south). The opposite effect occurred at the Muldenstraße north ramp. At the beginning, air with some smoke was moving out (positive values). The increased ventilation power resulted in a reversal of the flow and an inflow occurred (20:20 in **Figure 8**). The increasing ventilation power resulted mainly in an increased air inflow over the Muldenstraße north ramp instead of pulling the smoke from the fire location downwards through the tunnel. In order to simulate higher heat releases the mobile fan positioned north of the fire location was turned on (20:26). This even resulted in a reversal of the flow direction in the incident region. The region between incident and entrance portal, i.e. the region where people might be trapped and the rescue operations are expected, was fully covered with smoke. After a few minutes the mobile fan was stopped (20:31) and the flow and smoke turned back in the right direction.

Although all available fans were running at that time (except those at the incident location) and the target velocity was reached at the control sensor LG1, the available thrust was mainly used to bring in air from the Muldenstraße north ramp where the wind speed went up to 4 m/s.

The main results of this test were:

- For small fire loads the target velocity in the incident zone was reached
- The back-layering at that time was already massive, but due to the unusual height of the tunnel in that region (more than 7m) there was no risk for people.
- An increase in fire load resulted in a reversal of the flow in the incident region and a fully smoke filled zone between incident location and entrance portal. The ventilation system was not able to provide the conditions required by the guidelines.
- Any increase in ventilation power would not help as a big part of the air enters the tunnel through the north ramp Muldenstraße. There is no positive effect for the fire zone, but there is a negative effect for the remaining part of the tunnel.
- In such cases, additional, non ventilation related measures have to be taken to improve the self-rescue possibilities for persons captured in the region between tunnel entrance and fire.

For all other locations the ventilation system performed well.

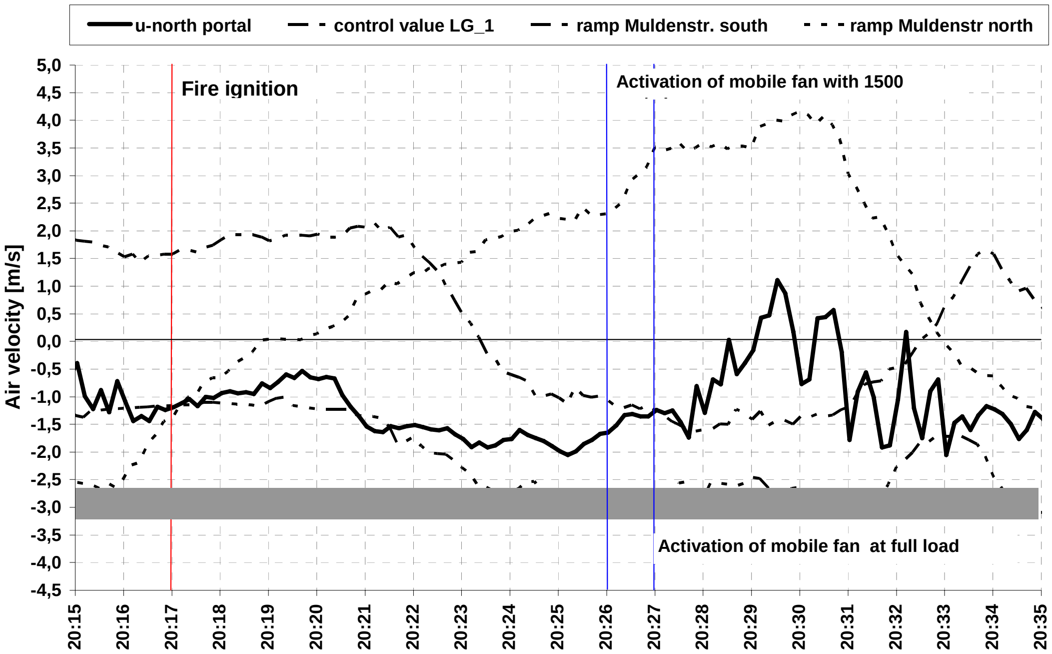


Figure 8: Results of test with open Muldenstraße on- and off ramp and activation of mobile fan.

3.4.3 Separation of the ramps in incident cases

As mentioned above the Muldenstraße ramps have a negative impact on the performance of the ventilation in incident cases. The only way to overcome the problems caused by the air movements over the ramps would be to separate them from the main tube. In such a case a simple hydraulic system would result and ventilation control would not be biased.

There are two principal possibilities to establish such separation:

a) Separation by mechanical installations

b) Separation by extra ventilation inside the on and off ramps

When looking at mechanical installations, either a fixed installation using solid doors or a flexible installation using movable curtains are both possible. Solid doors have been rejected due to the expense required in their installation, and due to specific maintenance and material constraints (e.g. the need for stainless steel and temperature resistance). The installation of flexible curtains (Öttl at al. 2002) has been discussed in detail as it would allow separation without cutting off any of the escape routs. The tunnel operator has rejected the latter option on grounds of lack of existing experience with such systems.

From the tunnel operator’s point of view option b) is the preferred one, as any malfunction of the system would not cause any problem for the tunnel users and fan maintenance is not considered a problem. However, the drawback of additional fans on the ramps is that this would include a further unknown influence on the ventilation control. The control system would become unmanageable as the flow in the regions where the ramps enter the main tunnel would be almost unpredictable. Thus option b) was rejected too.

It was decided to work with uncontrolled air flows over the ramps and to compensate for lack of conformity to guidelines by introducing other safety increasing measures such as additional escape routes.

4. CONCLUSIONS

City tunnels are often characterised by complex situations involving high traffic loads, complex links to adjoining surface roads, on- and off ramps inside the tunnel, etc. This complexity in construction and traffic situation is a challenge for ventilation design. Very often the ventilation requirements conflict with other requirements e.g. for traffic management. High traffic loads and high gradients inside the tunnel result in a high demand in ventilation power. In many cases city tunnels are quite short (up to 1 km), often making it difficult to find enough space for fans, velocity sensors etc. Ramps inside the tunnel complicate the flow situation. Hence, the official requirements for ventilation control are not easy to comply with. In order to meet requirements as closely as possible, proper ventilation strategies have to be developed. Simulation techniques are a prerequisite; however final adjustment has to be based on tunnel tests. Despite all the care taken, situations can still occur where ventilation capability is not sufficient, and where additional measures have to be taken to support rescue possibilities and to increase safety for tunnel users.

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VENTILATION OF SHORT ROAD TUNNELS IN CASE OF AN INCIDENT

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ABSTRACT

Great importance is attached to the ventilation in the event of an incident in a road tunnel. Appropriate operation of the tunnel ventilation system should first and foremost allow users to find their way to the next accessible emergency exit. Despite optimal operation of modern detection, traffic management and ventilation control systems, a rapidly spreading fire can cause smoke to stretch over several hundred metres. Today, the distance between the emergency exits does not generally depend on the length of the tunnel: in the event of an incident, users escaping a 400 m tunnel may have to travel the same distance to reach the emergency exit as users of a 10 km tunnel. In short tunnels it is important to remember that due to the required effective length, ventilation systems can cause serious disturbance in the primary incident zone. The authors believe that in such cases the ventilation system should not be operated in automatic mode, as this cannot adequately register the current and rapidly changing situation in most circumstances. Manual operation of the ventilation system is possible; however, this requires the deployment of experienced staff in a control room or on site at a later stage.

The considerations in this paper are based on the requirements valid in Switzerland for tunnel ventilation systems and the distances between emergency exits. The specifications regarding the areas of application of the ventilation systems are reasonable. However, in the case of short tunnels it is important to assess the effect of the ventilation system and its operation, particularly in relation to the gradient of the tunnel.

Key words: short tunnels, ventilation, emergency exit, safety

1. INTRODUCTION

Prompted by several horrific fires in road tunnels, there has been a great effort to increase safety for tunnel users over the last number of years. Many countries are already tending to enforce more stringent requirements for systems and their operation. Some of these requirements, for example, adding a second tube to single tunnels or even equipping new and refitting existing tunnels with state-of-the-art systems – particularly ventilation systems – are extremely costly. In addition to the prickly cost-benefit issues in the field of safety (this is addressed in [1] with regard to various safety systems) the advantages of a mechanical ventilation system in short tunnels are open to debate. Experience has shown that operating a ventilation system can further endanger tunnel users.

In Switzerland the generally applicable regulations governing the design of tunnel ventilation systems of 1983 were superseded by those of the FEDRO directive of 2004 [2]. In the event of an incident in a tunnel, the primary objectives in the first stage of self-rescue are to alert the tunnel users so that they can leave the tunnel via the emergency exits. In some cases, however, those involved in an accident may not be able to leave the scene, neither by themselves nor with the help of the other tunnel users. These people are dependent on the help of the emergency services with special equipment. Generally speaking, the emergency services only arrive at the scene 5 to 30 minutes after the alarm is raised.

The fundamental concepts for alerting the tunnel users and the emergency services, switching on the lighting, the signalling and the traffic management are well known. The basic ideas and objectives with regard to operating the ventilation system are very simple: gases which are harmful and which reduce visibility must be kept away from the tunnel users. There are two different approaches here, depending on whether there are people on one side of the incident or people on both sides. In the first case, which is more straightforward, the problem can be solved by longitudinal ventilation. In the second case, the smoke has to be directed through a separate duct. This ventilation system is expensive, especially in shorter tunnels.

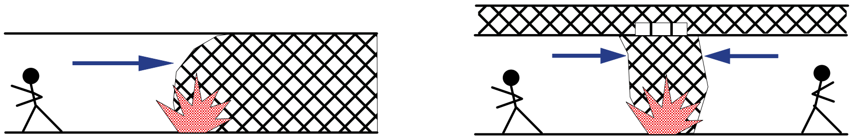

Figure 1: Basic ventilation strategies

This paper looks at some of the issues that arise in the ventilation of short tunnels and proposes some possible solutions.

2. BASIC REQUIREMENTS

2.1. General note

The following considerations focus on the relevance of ventilation in the self-rescue stage. Other safety devices may be just as important as ventilation, or possibly even more so, in short tunnels. The need for and the usefulness of ventilation at a later stage of an incident are mentioned briefly.

Not least because of the requirement in the EU directive [3], much effort is put into developing risk assessment methods. There is, however, no widely recognised means of selecting individual safety features in tunnels as yet. In Switzerland, these decisions are currently taken jointly by the consenting and the operating authorities on recommendation of the design engineer. Different countries have different policies regarding responsibility. It is essential to note that the safety benefits of complex ventilation systems in short tunnels are small and in certain cases can pose additional risks.

2.2. Escape routes

The spacing between the emergency exits out of the tunnel determines the maximum distance the tunnel user has to travel by foot in an emergency in the primary danger zone. The exits must be clearly visible and – obviously - it must be possible to open the doors of the emergency exits. Often the pressure distribution in the tunnel during an incident is not taken into account during the design of the doors.

In Switzerland emergency exits in new double tunnels must be at 300 m intervals. This spacing is generally a fixed distance as opposed to a maximum distance. Reasons against shorter distances, for example in cut-and-cover tunnels or in tunnels with a parallel escape gallery or a second tube, include non-requirement, costs or problems with exits at the surface. According to SIA 197/2 [4, Section 8.8.2.3] and on the basis of the EU directive [3], tunnels without a second tube and tunnels without an escape gallery can have up to 500 m between the emergency exits depending on their gradient. The dependency on the gradient was determined using a simple approach which takes into account the tunnel user's escape speed and the time available for escape. The information contained in SIA197/2 is limited to gradients of up to 5%.

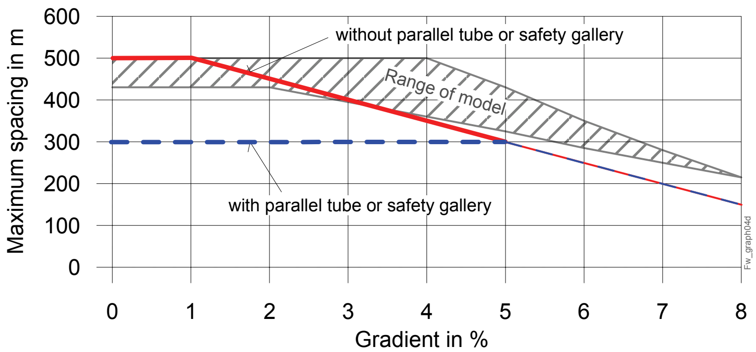

Figure 2: Escape route distances in SIA 197/2 [4] and the range of the primary model specification [5]. SIA 197/2 specifies gradients in the range of up to 5 %.

The longer distances between escape routes in single tunnels without parallel tubes or escape galleries is solely due to the increased costs; after all, the ventilation requirements for tunnels with two-way traffic are much stricter (Figure 3). In Switzerland it was assumed up until 1998, on the basis of the knowledge of the effect of tunnel ventilation at that time that no emergency exits at all were required in tunnels with transverse ventilation.

2.3. Ventilation

The basic objective of operating the tunnel ventilation system in the event of an incident is to minimise the spread and concentration of the harmful substances produced in the tunnel and escape routes. This is intended to aid the self-rescue of tunnel users, keep the access paths of the emergency services free from smoke and extract smoke from the tunnel after a fire. In case of an incident without a vehicle fire, the ventilation system should in the same way help to keep any volatile, toxic substances away from tunnel users.

The Swiss guideline has stipulated a standard in this respect which must also be applied when refurbishing existing tunnels. Deviations from these specifications are permitted provided they are adequately justified on the basis of special project-specific circumstances.

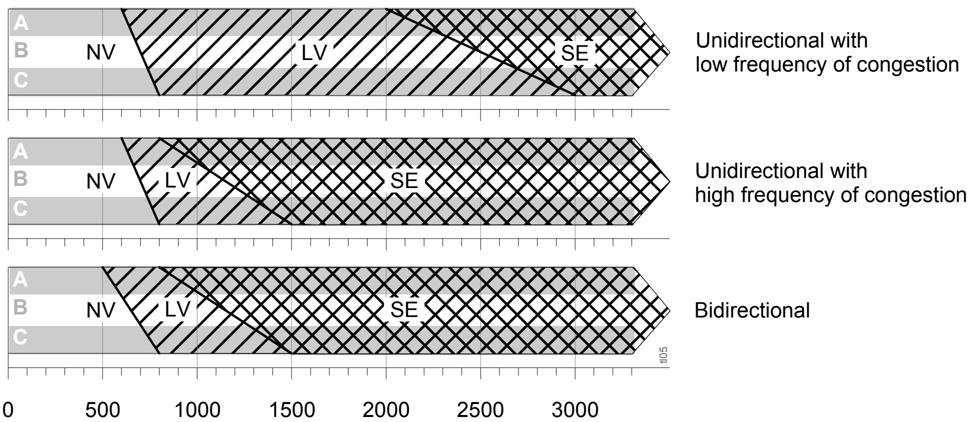

Figure 3: Area of application for ventilation systems as per guideline [2] valid for gradients up to 5%. NV: natural ventilation, LV: longitudinal ventilation without extraction, SE: with extraction. Classification into areas A, B or C is based on the volume and composition of traffic as well as the relevant gradient.

Below is a discussion of the issues raised when changing the basic ventilation systems natural ventilation (NV) to longitudinal ventilation (LV) and longitudinal ventilation to extraction (SE). The transitional areas illustrated in figure 3 are based on general risk considerations. It is not possible to provide a quantified explanation in this general form.

2.4. Supplementary measures and systems

As a matter of principle the systems are to be operated automatically in the event of an incident according to the situation. This is conditional upon the incident being quickly and accurately detected and the status being adequately monitored. A special guideline [6] has been formulated for detecting smoke very quickly. The sensors at intervals of 100 m should be able to automatically trigger the emergency ventilation programme within one minute. This system should be used in addition to a linear temperature detector and event detection via traffic video monitoring.

Manual override of the automatic ventilation response must be possible at any time. Experience has, however, shown that this can only be expected from highly experienced staff.

Figure 3 illustrates the marked difference in requirements concerning the system choice for tunnels with one-way traffic depending on whether situations with full congestion are likely. This specification is based on the PIARC publication [7]. The operation of the system depends strongly on the traffic condition at the time of the incident. It is difficult to continuously and reliably detect the traffic status. The intention is to perform this by means of event detection via traffic video monitoring.

Some fire brigades are already equipped with mobile fans which are designed for use in tunnel fires. In short tunnels without ventilation a mobile fan can be useful for fighting the fire. In tunnels with a fixed and adequate ventilation system the use of mobile fans is not generally recommended due to the risk of adverse interaction with the tunnel ventilation.

The Swiss guideline [2, Section 7.2.6] requires that structural measures be taken in twin tube tunnels to prevent harmful gases from being recirculated from the tunnel in which the incident occurred into the opposite tube, which is mostly used as an escape and access route. Generally a 30 m long inflow zone must be separated from a 100 m long exhaust zone with a portal offset or a high partition wall.

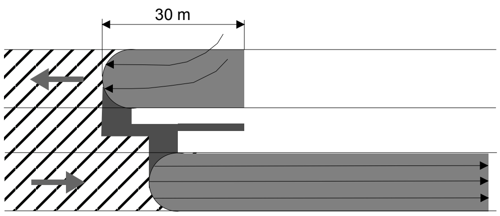

Figure 4: Structural separation of portals in tunnels with two parallel tubes

This may even be of relevance in short tunnels without mechanical ventilation (see case study 4).

3. VENTILATION CONSIDERATIONS

3.1. General

The longitudinal ventilation system is appropriate for tunnels with one-way traffic without congestion. If, however, there is the possibility of people on either side of the incident scene, the situation can no longer be fully controlled with longitudinal ventilation alone. The following looks at the suitability of the systems from the point of view of ventilation under various constraints.

3.2. Systems without extraction

There is no linear correlation between the length of the tunnel and the sum of the pressures contribution by buoyancy, tunnel friction, traffic and meteorology. Calculated according to the respective tunnel length, short tunnels require higher values.

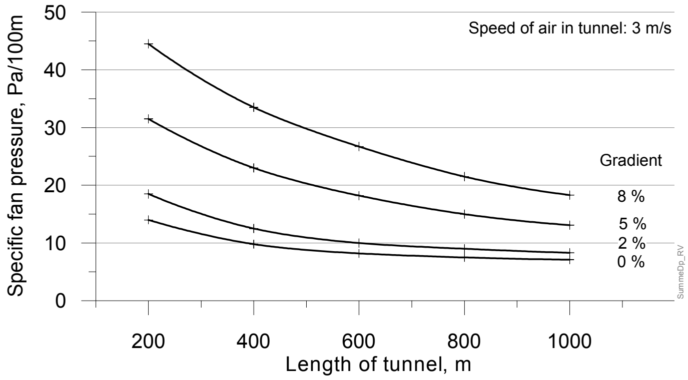

Figure 5: Required pressure of jet fans per 100 m of tunnel in accordance with the specifications in [2] depending on the tunnel length and the gradient

In short tunnels the arrangement of jet fans is problematic. To ensure that an adequate thrust is generated, the jet fans should be at about 80 m intervals. Generally speaking there should be more than one group of jet fans (except in case study 6) and, in order to reduce the number of groups endangered by the fire, there must be at least 100 m between the groups.

In tunnels with one-way traffic, where congestion does not need to be taken into account for operating the ventilation in the event of an incident due to the volume of traffic, the flow measurement is of no great consequence - unlike in tunnels with two-way traffic where the jet fans have to be controlled in accordance with the current flow measurements. In this case it is essential to ensure that the flow measurement can adequately represent the effective volume flow at the measuring section. Readings from appliances which can be distorted by the jets of the fans or the effect of the fire must be eliminated. The target low longitudinal flow is extremely difficult to achieve. It must be noted that in short tunnels it is virtually impossible to prevent smoke from spreading throughout the whole tunnel section with jet fans. Consequently, this is highly likely to further endanger tunnel users.

3.3. Systems with extraction

The Swiss guideline demands the smoke extraction system with controllable exhaust air dampers to be designed depending on the tunnel cross section. Other countries use smoke production values derived from the design fire load as their basis. To control the situation in accordance with today's assessment, the extraction rate at the place of the fire generally needs to be between 120 and 220 m^3/s. The length of the tunnel is irrelevant in this respect. This means that the cost efficiency of the mechanical ventilation equipment is small for short tunnels.

In tunnels with a gradient in particular, an extremely one-sided pressure can build up, even in a stationary state. In order to generate the desired symmetrical flow to the extraction point, this pressure must be compensated by using jet fans with the inevitable result of de-stratifying the flow in the tunnel. The problems with regard to controlling the air flow in the system are discussed in 3.2.

4. CASE STUDIES

4.1. Tunnel 1

Tunnel description

- Planned tunnel in suburban centre
- Length 580 m, varying gradient averaging 2.3%
- Two lanes, two-way traffic, with short separate tubes at each end
- High average traffic volume with low heavy traffic ratio
- Longitudinal ventilation with jet fans
- Two escape routes to the open

Problem

The project intends to equip the tunnel with six groups of two jet fans and to control the system according to the flow measurements taken in between. The layout of the flow sensors is problematic. Automatic operation of the longitudinal ventilation system can jeopardise the safety of tunnel users. It is not possible to separate the traffic flow in opposite directions due to lack of space.

Proposed solution

The ventilation system is exclusively designed for manual use following the instructions of the emergency services on site or by an operator via TVM. Two emergency exits should be planned at approx. 200 m intervals: this is already below the minimum requirement of 500 m.

Conclusion

When defining the operation scenarios it is important to take into account non-ideal operation of the longitudinal ventilation system due to the variety of possible sources of error. The short distance between the emergency exits considerably increases safety in the event of an incident.

4.2. Tunnel 2

Tunnel description

- Existing tunnel at Alpine crossing
- Length 1,000 m, gradient 6%
- Two lanes, two-way traffic
- Low average traffic volume but high ratio of heavy traffic, high peak values due to holiday traffic
- Longitudinal ventilation with jet fans
- No escape routes to the open

Problem

The longitudinal ventilation system cannot guarantee the safety of tunnel users in two-way traffic. Given the steep gradient in the relatively short tunnel it is not worth installing an extraction system because there is still the problem of controllability.

Proposed solution

To solve the problem, a second tube needs to be built. The situation could then be brought under sufficient control using a longitudinal ventilation system. Alternatively, consideration should be given to installing emergency exits at short intervals - say 200 m.

Conclusion

Tunnels with two-way traffic and a gradient greater than 5% should not be built, otherwise the distance between the emergency exits must be reduced.

4.3. Tunnel 3

Tunnel description:

- Planned tunnel at Alpine pass road at 2,000 m above sea level
- Length 800 m, gradient 8%
- Two lanes, two-way traffic
- Low average traffic volume with high peak values due to holiday traffic
- Longitudinal ventilation with jet fans
- No escape routes to the open

Problem

The longitudinal ventilation system cannot support the safety of tunnel users in two-way traffic. Given the steep gradient it is not worth installing an extraction system because there is still the problem of controllability.

Proposed solution

It is not considered worthwhile building a second tunnel due to the overall low traffic volume. The route needs to be revised. If the tunnel were to be built as planned, emergency exits would have to be installed at short intervals (Figure 2: 150 m).

Conclusion same as for case study 2

Tunnels with two-way traffic and a gradient greater than 5% must not be built.

4.4. Tunnel 4

Tunnel description:

- Tunnel under construction
- Length 600 m, gradient <1 %
- One-way traffic, two parallel tubes
- Medium traffic volume
- Natural ventilation
- One crossway in the centre of the tunnel (opposite tube is escape and rescue route)

Problem

The portals are directly beside each other. The tunnel opens directly to a bridge and heavy structural precautions to prevent smoke recirculation at the portals are complicated.

Proposed solution

Instead of a partition wall, it was considered installing low-powered jet fans in the opposite tunnel. Since the effect of such an installation would be too late this measure is not worthwhile.

Conclusion

Incorporate structural measures to prevent smoke transfer right from the early planning stages. A light construction (noise protection) wall can do the purpose as well.

4.5. Tunnel 5

Tunnel description:

- Planned underpass in urban area reserved for development
- Length 700 m, U-shaped length profile with gradients up to 3%
- Two lanes, two-way traffic
- High average traffic volume with high peak values due to rush-hour traffic
- Longitudinal ventilation with jet fans
- Two escape routes leading outside

Problem

The longitudinal ventilation system is only of minimal benefit to the safety of tunnel users. Automatic operation is therefore not recommended.

Proposed solution

In the middle section the underpass could be opened to a length of 150 m and equipped with noise protection. A central emergency exit should be constructed in each of the two tunnels. An escape stairway to the surface is to be installed in the open section.

Conclusion

If possible the length of the short tunnel should be reduced to such an extent that a ventilation system is not required. There should be adequate space between the tunnels.

4.6. Tunnel 6

Tunnel description:

- Existing cut-and-cover tunnel
- One-way traffic in two tubes of three lanes
- Tube lengths of 800 m and 1,000 m respectively, gradient 1.5%
- Very heavy rush-hour and through traffic
- Longitudinal ventilation with jet fans
- Escape routes to the open or to an escape gallery (not into opposite tunnel) at short intervals

Problem

The tunnel currently features a spot extraction system in the middle of the tunnel. In the foreseeable future frequent congestion is expected in the tunnel. It is planned to keep congestion in the tunnel to a minimum by implementing traffic management measures. Jet fans cannot be accommodated in the tunnel due to lack of space.

Proposed solution

The tunnel will firstly be extended at the entrances in order to accommodate a group of powerful jet fans. These are to be fitted directly at the entrance and can only function in the direction of traffic. Together with the traffic management measures a ventilation system which conforms to the guidelines for a tunnel with low frequency of congestion is to be developed. Smoke is to be prevented from being transmitted to the opposite tunnel at the entrances by way of an additional partition.

If the congestion frequency cannot be reduced to a suitable level, the installation of an extraction system with controllable dampers and inwardly blowing jet fans at the exits should be considered.

Conclusion

In tunnels with one-way traffic and low frequency of congestion jet fans can be positioned directly at the entrance without redundancy. In the event of a fire in close proximity, the ventilation system does not need to be operated. In the above case the fact that the escape routes do not lead into the opposite tube alleviates the problem.

4.7. Tunnel 7

Tunnel description:

- Existing tunnel at Alpine pass at 1500 m above sea level
- Length 870 m, gradient 11%
- Two lanes, two-way traffic
- Open six months per year, on good weekends heavy tourist traffic for short periods
- Longitudinal ventilation with jet fans (low installed thrust)
- No escape routes

Problem

Even with low thermal power, the longitudinal flow is greater than the speed of escape. The advantages of a ventilation system are limited to a few scenarios. On the other hand, a ventilation system could further jeopardise tunnel users in many situations. It would take the emergency services at least 30 minutes to be deployed.

Proposed solution

The ventilation system should not be operated in the event of an incident. As a lesser priority, the tunnel should be fitted with emergency exits 100 m apart.

Conclusion

The ventilation in this system does not increase safety in case of an incident. The focus should be placed on rapid detection, alerting and short escape routes.

5. CONCLUSIONS

Ventilation aspects must be taken into account right from when the route is being planned. The required jet fan thrust depends strongly on the length profile of the tunnel. The design fire load plays an important role here. In tunnels with two-way traffic the spread of smoke becomes difficult to control with high gradients. Tunnels with two-way traffic and gradients over 5% should therefore not be built.

The general requirements for ventilation systems contained in guidelines must be verified according to the specific tunnel. Possible negative consequences of the ventilation must be assessed and included in the operating specifications. The non-ideal and often difficult to simulate interfering factors are fundamental here. If the proposed solution diverges from the general specifications, detailed documentation about the factors that led to the decision is imperative for legal reasons.

In borderline cases regarding the suitability of a ventilation system it may be necessary to refrain from automatic operation. It can be assumed that there is room for improvement in the control algorithms used today, but especially in short tunnels the acquisition of accurate data is difficult.

Passive, structural measures such as partition walls or sufficient distance between the portals can prevent the recirculation of harmful gases.

In addition to the usual measures such as a fast detection, a clear alarm and signalling steep tunnels should have short distances between emergency exits. In any case, short distances are intended to complement other measures and should not be regarded as a substitute. All technical measures can only support the primary important self-rescue. This presupposes that the tunnel users are informed about the possible emergency situations in tunnels in order to act correctly.

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THE IMPACT OF CONTROLLABILITY ON THE DIMENSIONING OF SMOKE EXTRACTION SYSTEMS FOR BIDIRECTIONAL TRAFFIC ROAD TUNNELS

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Abstract

To fulfil the requirements of the Swiss design guidelines, the ventilation system in road tunnels with bidirectional traffic with smoke extraction at the fire location must achieve a minimum air flow of 1.5 m s^{-1} towards the fire from both sides. To control this airflow jet fans are installed and controlled based on measurements of the air velocity in the tunnel. Inaccuracies in the airflow chain of measurement and the lack of flexibility in the controlling of the jet fans leads to the need for higher exhaust flows to ensure that the required airflows in the tunnel can be achieved.

A method to estimate the minimum exhaust flow needed to satisfy the design requirements and the related problems of controlling the air flow in the tunnel are described and discussed in the first part of this paper. The impact on the exhaust flow – and hence on the cost – of the principal design variables such as the type of detector, data acquisition and analysis system and the control strategy are also assessed.

In the second part of this paper an attempt is made to quantify the accuracy of several flow measurement systems (detectors, measurement chain, etc.) by statistically analysing a series of tests carried out in the Gotthard road tunnel between 2001 and 2002.

Keywords: ventilation design, bidirectional traffic, controllability, exhaust flow

1 Background

In tunnels with bidirectional traffic and smoke extraction, the strategy in the event of a fire is to exhaust the smoke from the traffic space near to the fire location through remotely actuated mechanical dampers (Figure 1).

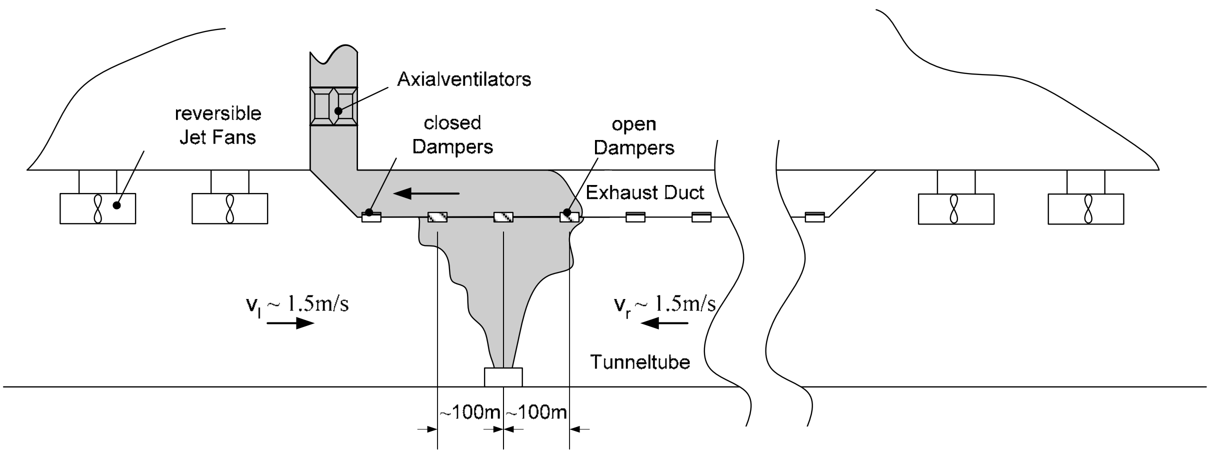


Figure 1: Ventilation of a bidirectional traffic tunnel with smoke extraction at the fire location

The Swiss design guidelines for tunnel ventilation (ASTRA 2004) require that jet fans should be used to ensure that a minimum air flow of 1.5 m s^{-1} towards the fire from both portals is achieved. However the air flows from the tunnel's portals towards the fire depend on the ratio of the pressure drops in the two sections of the tunnel and these are not known when the fire is detected. Furthermore there are significant time-dependent pressure fluctuations during a fire emergency that make it necessary to actively control the jet fans based on measurements of the air velocity in the tunnel.

There are two main problems in controlling the longitudinal air velocity:

1. The jet fans usually have just two states – on or off – so their thrust can only be controlled in finite steps.
2. Errors in the measurement of the air velocity lead to inaccuracies in controlling the longitudinal air velocity.

These two factors both have a negative impact on the ability to be control the longitudinal air velocity. With the minimum required exhaust flow equal to 3 m s^{-1} x A_T, the required air velocity on each side of the fire cannot be assured leading to a reduction in the security for the people in the tunnel.

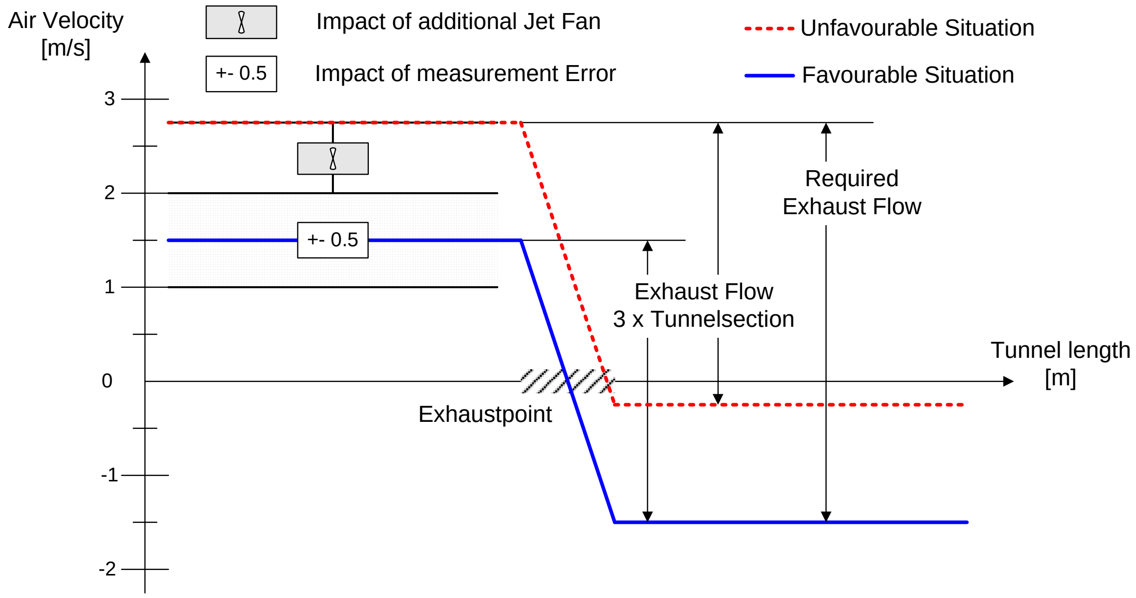


Figure 2: Unsymmetrical flow yields unfavourable situations

In the first section of this paper the issues associated with controlling the longitudinal air velocity during an emergency in tunnels with bidirectional traffic are discussed and analysed and solutions are proposed.

Equally important when designing the capacities of the tunnel's ventilation system are the inaccuracies of the airflow measurement and the consequences of these are addressed in the second section where the results of a series of tests are statistically interpreted.

2 Impact of the jet fans

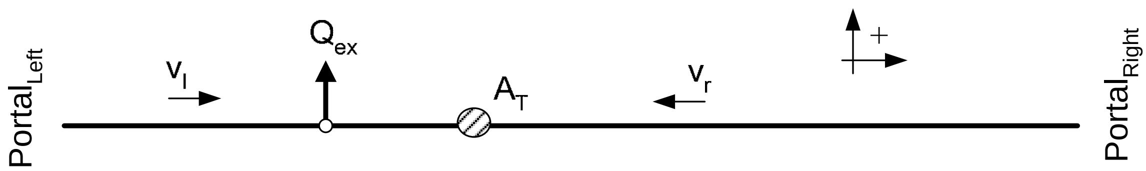
2.1 Methodology

For a better understanding of the impact of the jet fans on the air velocities in the tunnel a study was carried out to determine the magnitude of the velocity changes when a jet fan is turned on and how large the exhaust flow rate has to be to satisfy the design requirements irrespective of the jet fans. The study was carried out in three steps:

Step 1: The required thrust of the jet fans was calculated based on the most unfavourable combination of the tunnel and vehicle friction; the meteorological pressures and the buoyancy forces caused by the fire. Then, taking into account the redundancy conditions required by the guidelines and the numbers of jet fans that could physically be installed in the tunnel, the thrust per jet fan was defined.

Step 2: The variable parameters were defined – the exhaust flow rate, the exhaust location and the starting velocity in both tunnel branches. With these data and the boundary conditions from step 1, a pressure source or sink term was calculated to achieve a stable flow situation. The pressure term was given by the static pressure balance between the portals (see Eq 2 with $\Delta p_{SV} = 0$).

Step 3: Equations Eq. 1 and Eq. 2 were then solved with the unknown velocities v_l and v_r and $\Delta p_{SV} = F_{SV} / A_T$ as a equation system. The velocity independent pressure terms are irrelevant for these calculations so are not included in the pressure balance (Eq. 2).



$$v_l * A_l - Q_{ex} + v_r * A_r = 0 \qquad \text{[Eq.1]}$$

$$\Delta p_{D\,l} + \Delta p_{F\,l} + \Delta p_J + \Delta p_{JF} + \Delta p_{F\,r} + \Delta p_S + \Delta p_{D\,r} = 0 \qquad \text{[Eq.2]}$$

Figure 3: Topology and equations of the flow calculation

2.2 Boundary conditions for the study

For the study a single tube tunnel with bidirectional traffic (one lane per direction) was used with the following principal dimensions: length 2 km, cross-sectional area 50 m², longitudinal gradient 2%.

The dimensioning of the jet fans in this particular tunnel is not determined by the flows required during normal tunnel operation but by the most unfavourable fire situation. In this case the pressure required to be produced by the jet fans is 74 Pa of which 21 Pa is as a result of the friction forces caused by the walls and the stationary vehicles and longitudinal flows of 1.5 m s^{-1}; 28 Pa is due to the thermal buoyancy forces created by a 30 MW fire; and 25 Pa is due to the meteorological conditions - a 10K temperature difference between inside and out and a 10 km/h adverse wind.

Taking into account the redundancy requirements, the effective thrust per jet fan depends on the numbers of jet fans that can be installed:

Table 1: Effective thrust required for different numbers of jet fans

Number of jet fans installed	4	6	8	10	12
Thrust required per jet fan, N	1850	925	620	460	370

To calculate the impact on the flows when an additional jet fan is switched on the least favourable situation is when there are only a few vehicles in the tunnel because the friction forces due to the vehicles will be low. In all cases a traffic density of just 50 veh km^{-1} was used. In the calculations the blowing direction of the additional jet fan is in the positive direction, i.e. from left to right.

With respect to the control of the longitudinal flows, the most unfavourable location for the exhaust is at the beginning of false ceiling near the left portal (see Figure 4) assuming that the jet fans blow from left to right. All the calculations reported here are with the exhaust point located 300 m from the left portal.

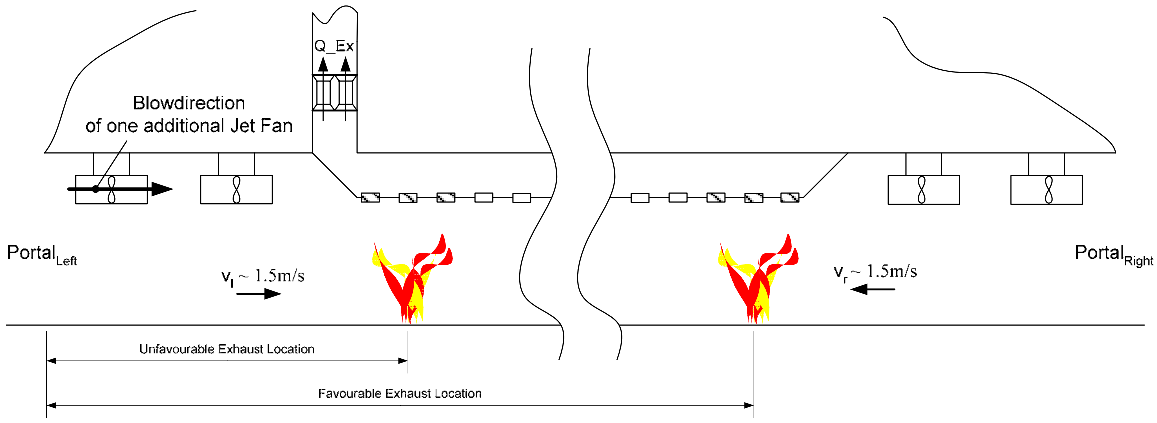


Figure 4: Unfavourable exhaust location regarding the controllability of the longitudinal air flow

2.3 Discussion of the results regarding jet fans

The flow situations before and after switching on a additional jet fan with two exhaust flows equivalent to 3.0 and 4.5 m s^{-1} for the five different jet fan thrusts are shown in Figure 5. In each case the starting condition was with equal air speeds towards the fire, i.e. $v_l = -v_r = Q_{EX} / (2A_T)$.

The air flow in the tunnel reacts strongly to the thrust of the jet fan. With a low exhaust flow and large thrust from the jet fan, the flow in the right tunnel branch reverses. In such a situation the smoke would flow past the open dampers creating a particularly bad situation for the people in the tunnel as the smoke would travel all the way to the right hand portal.

With a higher exhaust flow rate the velocity in both branches is increased before the jet fan is switched on and the flow in the right hand branch does not reverse when it is turned on – an improved situation regarding the ventilation aim. The results for four exhaust flow rates and five different jet fan thrusts are summarised in Table 2.

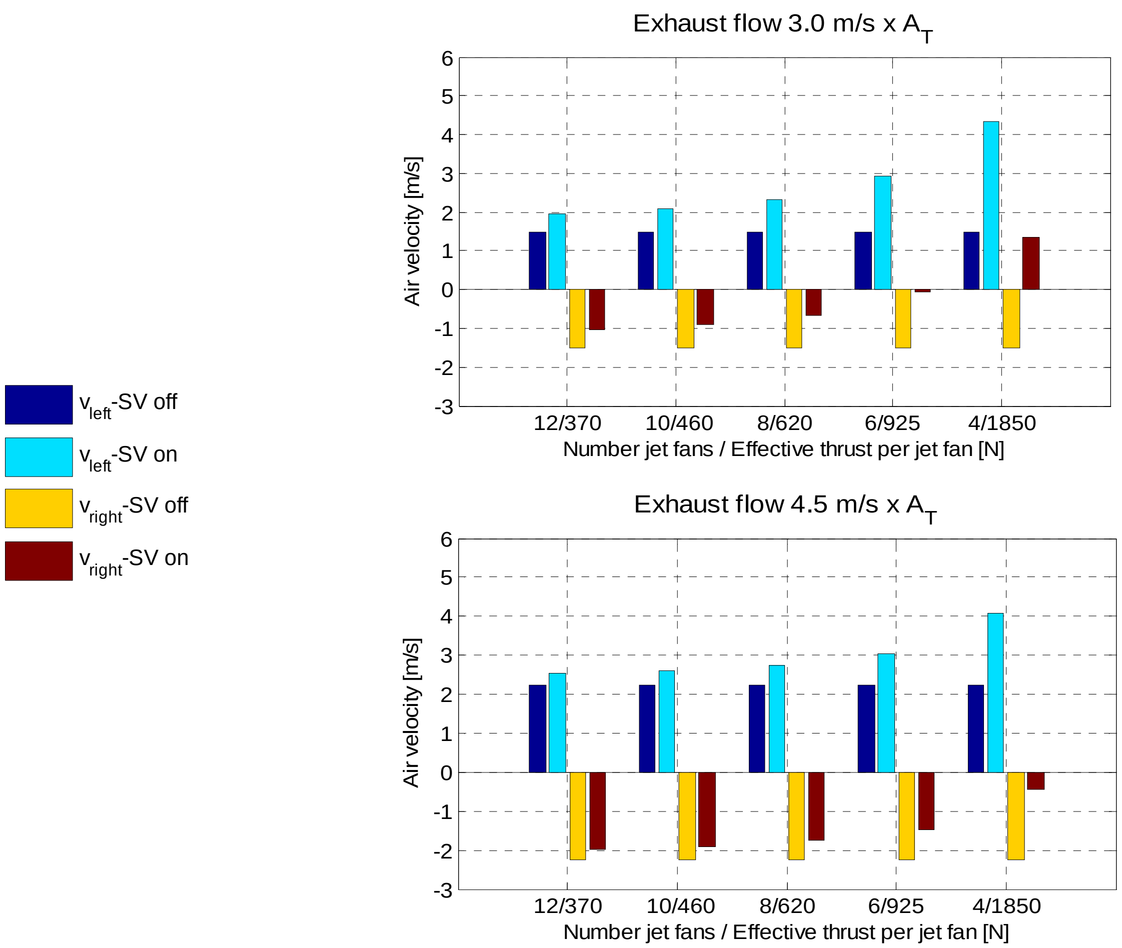


Figure 5: Flow situations for the bidirectional traffic case, required longitudinal velocity = 1.5 m s^{-1} toward exhaust point

Table 2: Degree of performance

		Exhaust flow [m^3/s]			
		3.0	3.5	4.0	4.5
Thrust [N]	1850				
	925				
	620				
	460				
	370				

Legend	
	Air flow toward the fire from both sides not satisfied
	Air flow toward the fire from both sides satisfied, $\lvert v_{min} \rvert$ > 1.5 m s^{-1} not satisfied
	Air flow toward the fire from both sides and $\lvert v_{min} \rvert$ > 1.5 m s^{-1} satisfied

With an exhaust flow of 3 m s^{-1} it is not possible to reach the design requirements in any situation. The higher the exhaust flow used the higher can be the maximum thrust of each jet fan, i.e. the larger the jet fans can be.

An attempt has been made to calculate an approximate value for the minimum exhaust flow that is needed to achieve the design requirements. It is mainly dependent on the thrust of a single jet fan and the two loss coefficients z_L and z_R given by Eq. 3 and Eq. 4.

$$z_L = 1.6 + \lambda \frac{L_{EP}}{d_{hyd}} + \frac{L_{EP} \cdot N_{FZ} \cdot Cp_{FZ}}{A_T} \qquad \text{Eq. 3}$$

$$z_R = 1.6 + \lambda \frac{L_T - L_{EP}}{d_{hyd}} + \frac{(L_T - L_{EP}) \cdot N_{FZ} \cdot Cp_{FZ}}{A_T} \qquad \text{Eq. 4}$$

In many tunnels the distance between the left portal and the exhaust point (L_{EP}) is 300 m in the "worst" case so z_L has a typical value of 2.7 to 3 and the lower value is the one used to obtain the results shown in Figure 6.

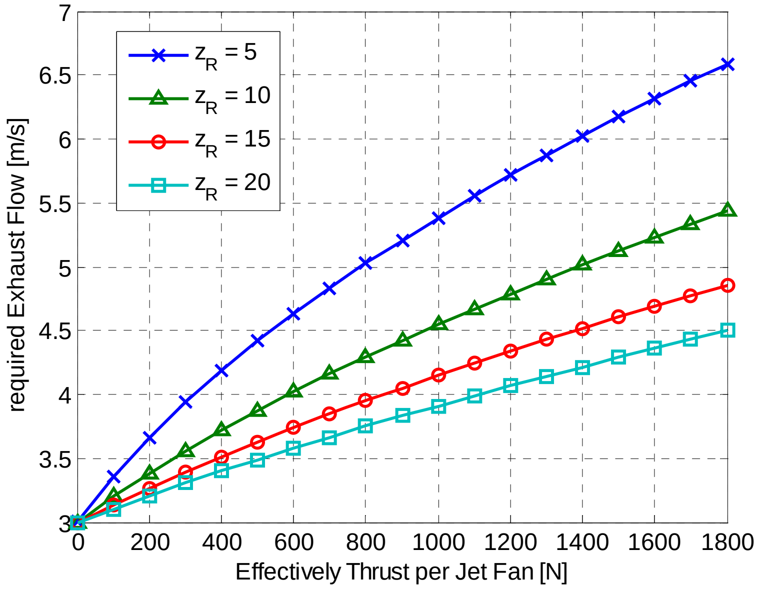


Figure 6: Minimum exhaust flow as a function of the thrust per jet fan and zR with zL = 2.7

For any particular tunnel the value of z_R is constant and cannot be changed by the designer of the ventilation system. If the value of z_R is low (i.e. the tunnel is relatively short), the exhaust flows need to be significantly higher than in longer tunnels with higher values of z_R. The only approach available to reduce the required exhaust flow is to reduce the effective thrust from each jet fan.

However, in many tunnels, particularly those with steep gradients, a large total thrust has to be installed to overcome the possible thermal buoyancy caused by the fire. Furthermore extra thrust is often included in the design as "reserve". However, as the exhaust duct within the tunnel physically limits the numbers of jet fans that can be installed in the tunnel, this means that the thrust from each jet fan has to be high and a correspondingly high exhaust flow would be needed to able to control the flows in the tunnel as required.

To avoid unreasonably high exhaust flows the aim should be to provide the smallest possible steps in thrust and this can be achieved by:

- spreading the required total thrust over as many jet fans as possible,
- using jet fans with multiple speed motors, or
- using jet fans with frequency converter driven drives

Although this analysis has been carried out for single tube tunnels with bidirectional traffic operation it is equally applicable to twin tube tunnels with smoke extraction systems, particularly those where congestion is likely and the required emergency ventilation is comparable to that in bidirectional tunnels.

It is clear from the foregoing that the subject of controlling the longitudinal air velocities in the tunnel during an emergency should be considered during the early stages of the dimensioning of the tunnel ventilation system; it cannot be left until just before the system is commissioned.

3 Impact of measurement uncertainties

3.1 Boundary conditions

For the dimensioning of the exhaust flow and the control strategies it is necessary to know the uncertainties in the air velocity measurements in the tunnel.

Between July and March 2002 a series of tests were carried out in the Gotthard road tunnel to investigate the measurement behaviour of six common air velocity measurement devices (see Table 3) that were installed over a length of 30 m of the tunnel and monitored during normal operation of the tunnel (Zumsteg 2002).

Table 3: Measurement devices that were investigated in the Gotthard road tunnel

Name	Measurement principle
M1	Impeller - 2 Point
M2	Pitot tube - 2 Point
M3	Thermal - 2 Point
M4	Ultrasonic - 2 Point
M5	Ultrasonic - Section
M6	Ultrasonic - Section

To determine the measurement uncertainty the test results have been analysed statistically. The measurement devices each provided an averaged value of the air velocity every 10 s. To reduce the amount of data a further average value every minute was calculated and saved. For the statistical interpretation a total of 30’000 measurements were used taken from 24 days distributed throughout the year with weekdays and weekends proportionally included.

For every measurement time the expected value was calculated on the basis of the six devices (M1 – M6) according to Eq. 5.

$$\Delta v_{(Mi,t)} = v_{(Mi,t)} - Median(v_{M1 \ldots M6,t)}) \qquad \text{Eq. 5}$$

3.2 Discussion

The results in Figure 7 show the arithmetic mean, the standard deviation and the 95% boundary value. The deviation for the thermal device (M3) is remarkably poor. For all others (M1, M2, M4, M5, and M6) the deviation is of the same magnitude and can be specified as (neglecting M3):

Average value: 0.2 – 0.3 m s^{-1}

95% boundary value: 0.4 – 0.7 m s^{-1}

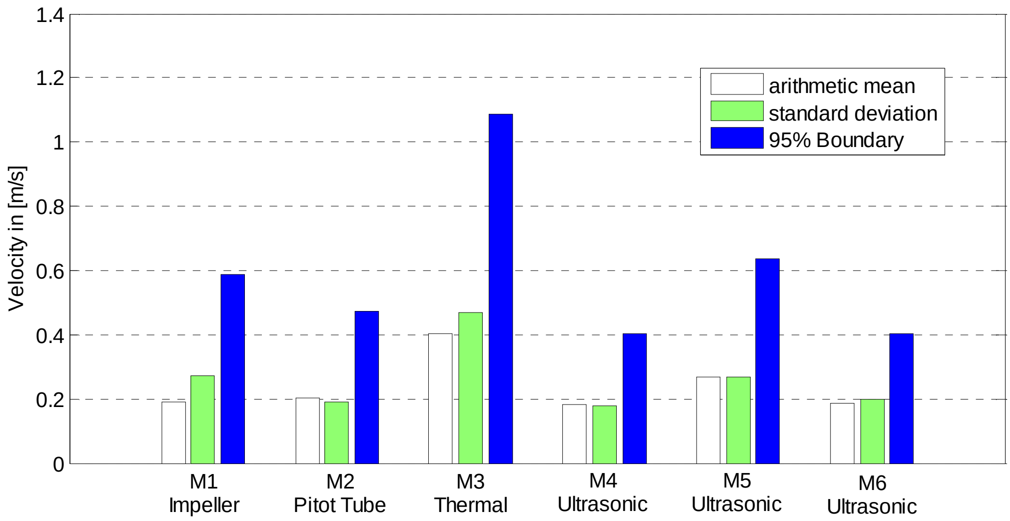


Figure 7 Key data for the analysed measurement devices

The effect of the measurement uncertainty on the achievement of the required air velocity in the tunnel can be compensating with a higher target value and hence a higher exhaust flow. As a result the target value for the velocities has to be increased because of the uncertainty in the velocity measurement and the exhaust flow by the equivalent of double the uncertainty in the velocity measurements.

The magnitude of this measurement uncertainty is dependent on the measurement interpretation and the acceptable confidence interval but it can be reduced if numerous and adequate devices are installed. It should be noted that particular attention should be paid to the outliers since they can adversely affect the control of the jet fans and it is strongly recommended to use an approach to filter out the outliers. An example therefore is to calculate the median value from the measured data (a minimum of three values is needed). Rather than the average value as the median value is almost unaffected by outliers (Figure 8).

It is also worth using the measured volume flow through the exhaust fan in the data interpretation because of its high accuracy.

Considering the above mentioned recommendations, a measurement uncertainty of 0.15 – 0.25 m s^{-1} seems comparative, thus the exhausted flow has to be increased by an amount equivalent to 0.3 – 0.5 m s^{-1}.

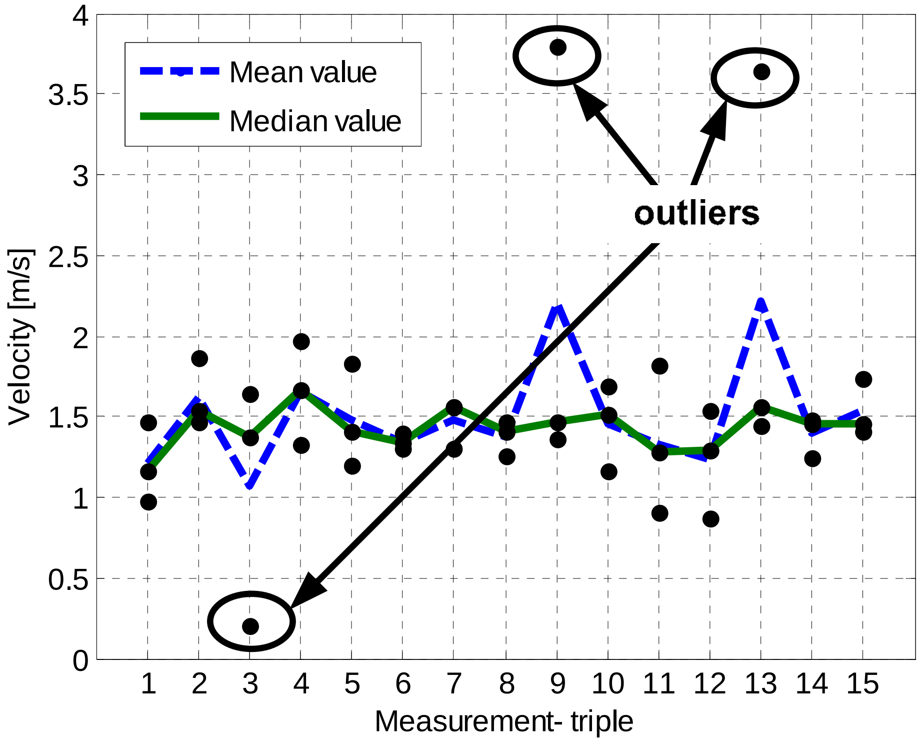


Figure 8: Comparison of arithmetic and median mean considering outliers

4 Conclusions

1. The thrust from the jet fans is normally only controllable in finite steps.
2. Increasing the exhaust flow is an effective method of improving the ability to control the longitudinal air velocity in the tunnel.
3. The minimum exhaust flow needed is determined by the thrust step per jet fan, the air velocity measurement uncertainty and data related to the pressure losses in the tunnel.
4. The uncertainty in the air velocity measurements in the tunnel means that the exhaust flow has to be increased by the equivalent of 0.3 – 0.5 m s^{-1}, favourable conditions presumed.
5. To achieve the required longitudinal air velocity in the tunnel regarding measurement uncertainly and thrust jump of jet fan, an exhaust flow of 4 m s^{-1} or more would be necessary in most cases.
6. The required exhaust flow can be minimised by reducing the steps in thrust due to the jet fans.
7. The steps in thrust from the jet fans can be reduced by either using a larger number of smaller jet fans to provide the total thrust required or by using jet fans fitted with multi- or variable speed motors using frequency converters.

5 Nomenclature

A_T	Tunnel cross-section area [m^2]	λ	Wall friction factor [-]
Cp_{FZ}	Vehicles friction factor [m^2]	Δp_D	Dynamic pressure loss [Pa]
D_{hyd}	Tunnel hydraulic diameter [m]	Δp_F	Friction pressure loss [Pa]
F_{SV}	Jet fan thrust [N]	Δp_J	Junction pressure loss [Pa]
L_{EP}	Length portal to exhaust point [m]	Δp_{JF}	Jet fan pressure gain [Pa]
L_T	Tunnel length [m]	Δp_S	Starting pressure term [Pa]
N_{FZ}	Vehicle density [veh km^{-1}]		
Q_{EX}	Exhaust flow [m^3 s^{-1}]	Suffix	
v	Air velocity [m s^{-1}]	l, r	left / right

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THE CURRENT STATUS OF THE TUNNEL VENTILATION DESIGN OF THE PLANNED BRENNER BASE TUNNEL BETWEEN AUSTRIA AND ITALY

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ABSTRACT

The key element of the Brenner railway line from Munich to Verona is the currently planned Brenner Base Tunnel (BBT) with a length of about 55 km.

The following paper provides an overview of the current status of the planned tunnel ventilation system for the Brenner Base Tunnel. The tunnel ventilation system ensures that the ventilation goals, based on the requirements of operation, are achieved for the normal, maintenance and emergency mode. In this way, the tunnel ventilation system ensures that the temperature and humidity of the tunnel air during normal operation and the quality of the tunnel air during maintenance work fulfil the requirements during operation of the tunnel. For the eventuality that a burning train stops in the tunnel, the tunnel ventilation system ensures that the passengers are protected from smoke in a safe place up to their evacuation. The design of the tunnel ventilation system for the Brenner Base Tunnel includes the know-how of the Swiss AlpTransit Projects (Gotthard Base Tunnel and Loetschberg Base Tunnel).

1. INTRODUCTION

Various requirements exist for the ventilation concept of the operation phase of the Brenner Base Tunnel. On the one hand it must be guaranteed that the tunnel climate allows a reliable and in this way secure operation of the tunnel system. For this purpose the temperature and the humidity levels must be kept within certain limits. On the other hand an incident case (i.e. train fire) has to be considered in the determinationof a suitable emergency ventilation concept. Finally, appropriate ventilation must be provided during maintenance work in the tunnel. The present paper contains an overview about the ventilation system currently planned by the planning group of the Brenner Base Tunnel (PGBBT) within the framework of the UVE planning and the technical project preparation. The following topics are handled:

- the most important requirements for the ventilation,
- a current overview of the state of the ventilation concept and
- calculations of aero- and thermodynamic issues.

Since the project planning is not yet finished, it cannot be excluded that single tunnel elements as well as tunnel ventilation facilities will still change during the further planning.

2. DESCRIPTION OF THE BRENNER BASIS TUNNEL SYSTEM

2.1. Tunnel description and main data

The planned Brenner Base Tunnel between Innsbruck and Franzensfeste is the key element of the railway line from Munich to Verona. The tunnel consists of 2 single track tubes, with a total length of 55'410 m, west tube, and 55'140 m, east tube. The tunnel portals are longitudinally shifted in order to avoid air recirculation. Figure 1 shows schematically the main elements of the tunnel system:

- 3 multifunctional stations (MFS by-pass Innsbruck, MFS Steinach, MFS Wiesen), containing emergency station, cross-over, and overtaking track (only in the MFS Steinach)
- by-pass tunnels and the branching tunnels to the Base Tunnel (number 5, 6) in Innsbruck and the branching tunnels east and west in Franzensfeste (number 7)
- 3 access tunnels (number 1,2 and 3) to the MFS
- cross-passages with a length of 35 m at a regular distance of 333 m between the 2 main tubes and cross-passages of up to 220 m length between the branching tunnels in Innsbruck,
- Escape shafts along the branching in Franzensfeste

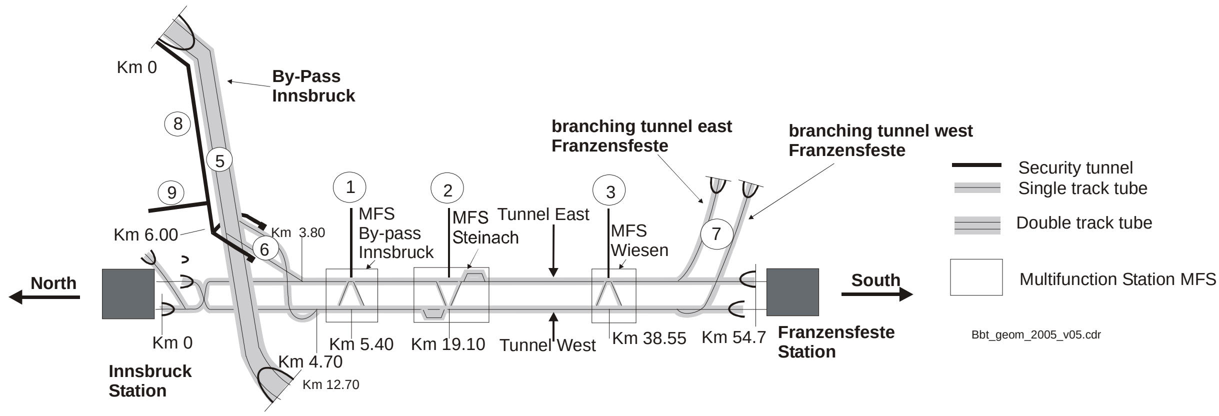


Figure 1: Schematic tunnel description, explanation in text.

The Base Tunnel shows a maximum gradient of 8.3 ‰. However, at the time a reduction of the tunnel gradient to 7.4 ‰ is planned. The portal Innsbruck lies 586 m above the sea level and the portal Franzensfeste lies 742 m above sea level.

2.2. Operation mode

Three main operation modes have been defined for the Brenner Base Tunnel:

Normal mode:

The Brenner Base Tunnel is planned for a daily traffic of 264 trains, 140 in the north-south direction (21 passenger trains) and 124 in the south-north direction (21 passenger trains). In the normal mode the north-south traffic takes place in the east tube and the south-north traffic in the west tube.

Maintenance mode:

Two different scenarios are possible:

- Maintenance work in tunnel east or tunnel west. The traffic takes place in the opposite tube with alternating running direction of the trains from north to south and from south to north.
- Maintenance work in a single tunnel section. Three maintenance sectors are defined: between Innsbruck and MFS Steinach, between MFS Steinach and MFS Wiesen and between MFS Wiesen and Franzensfeste. In this mode only the maintenance section is closed for train traffic Trains are redirected through the tunnel section parallel to the maintenance section.

Emergency mode:

Depending on the event location three different scenarios are possible:

- Event in emergency station. Self-rescue in the safe waiting area of the station.
- Event outside the emergency station. In case of an event in the main tube the opposite tube serves as a safe place and is reached through open doors in the cross-passages. In case of an event in the by-pass tunnel Innsbruck the security tunnel serves as a safe place (see Figure 1). In case of an event in the branching tunnels Franzensfeste self-rescue takes place over the escape shafts.

3. REQUIREMENTS OF THE TUNNEL VENTILATION

3.1. Requirements of operation

The relevant regulations for ventilation derived from the requirements of operation may be specified as follows:

- Normal mode: sufficient air exchange in order to satisfy the temperature and humidity limits
- Maintenance mode: acceptable air quality during the work
- Emergency mode: The ventilation supports the self-rescue phase by creating safe waiting areas and escape ways.

3.2. Ventilation objectives:

The ventilation objectives depend on the operation mode. For the three defined operation modes the ventilation objectives are as follows:

Normal mode

- Maximum temperature in main tubes, cross-passages and branching tunnels: 35°C.
- Maximum air humidity in main tubes, cross-passages and branching tunnels: 70%.

Maintenance mode

- A sufficient air flow must be provided by the ventilation, however the air velocity in the maintenance tube or section should not exceed the comfort value of 5 m/s.
- The amount of pollutant gases (CO, NO, NO_2, Methane) and particles in the air should be kept under the limiting values and the concentration of oxygen in the air should be over 19%.
- The pressure variation in short and long time period should not exceed the comfort and the health limits (1.5 kPa in 4s and 10 kPa in a working period).
- The temperature during long and short working periods should not exceed the limit of 30° C and 35°C respectively.

Emergency mode

- The ventilation in emergency mode should primarily support the self-rescue and evacuation phases by creating safe waiting areas and ensuring safe evacuation ways.
- Secondarily the propagation of smoke near the safe waiting areas should be kept as low as possible. In case of event in the emergency station, the smoke propagation in the escape tunnels should be avoided and in case of event outside the emergency station, the smoke propagation in the opened cross-passages should be avoided by ensuring a sufficient counter airflow (≥ 2 m/s).

- Thirdly the ventilation should support the rescue team.

- Finally the propagation of smoke to sensible locations (closed cross-passages, portals, branching and by-pass tunnels) should be kept as low as possible.

4. CONCEPT OF THE TUNNEL VENTILATION

4.1. Main ventilation equipment

The diagram on l.h.s (left-hand-side) of Figure 2 shows schematically the ventilation equipment of the multifunctional station. The fresh and exhaust air are supplied and extracted through 3 access shafts (one for every multifunctional station) at the portals of which 3 ventilation stations provide the required flow rates. Several dampers are used to direct the fresh and exhausted air, depending on the ventilation mode. Fresh air can be supplied in the west and east tubes through 6 lateral doors, of which each includes a ventilation opening, or the supply points in the area of the cross-overs. In the case of a fire event these doors and the ventilation channels work as escape ways. The exhausted air can be extracted from the middle of the emergency station of both tubes.

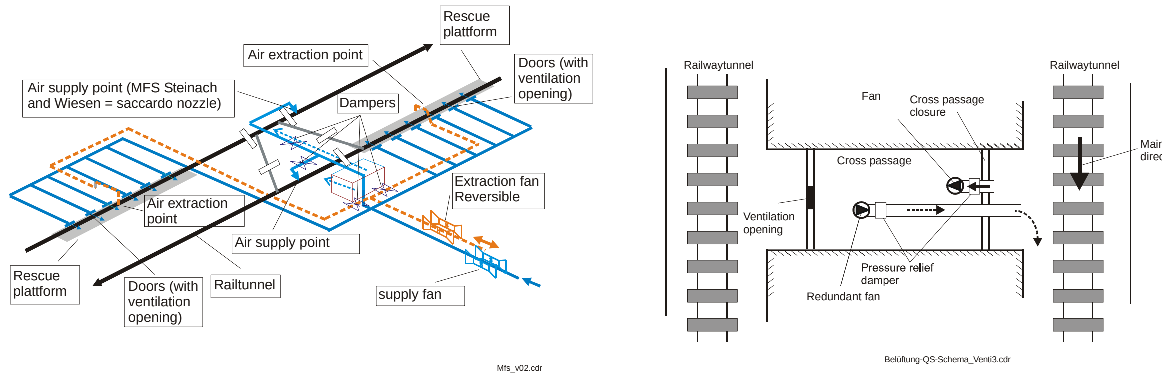


Figure 2: l.h.s: schematic of the ventilation in the emergency station with the transport of fresh air (full line) and the exhausted air (dotted line). r.h.s: schematic of the ventilation equipment in the cross-passages. Arrows show the air flow in the cross-passage ventilation in normal mode.

The cross-passages between the main tubes (short cross-passages) and between the tubes of the branching Innsbruck (long cross-passages) are also provided with ventilation equipment in order to ensure a minimum air exchange between the cross-passages and the railway tube, Figure 2 r.h.s. This air exchange should limit the temperature in the cross-passage to ensure a safe operation of the technical equipment which is installed there. The ventilation system of the short cross-passages consists of two ventilation tubes (with fans) and a ventilation opening, the ventilation system of the long cross-passages consists of a long ventilation tube (with two fans) and 2 ventilation openings.
A 100% fan redundancy is provided for each ventilation stations in the MFS as well as for the fan in the cross passages. Table 1 summarizes the gross specifications of the axial fans used for the tunnel ventilation in the MFS.

Table 1: Specification of the fans in the ventilation stations of the MFS.

	flow rate [m^3/s]	el. power [kW]
MFS by pass Innsbruck		
- supply	215	1'186
- extraction	250	1'929
MFS Steinach		
- supply	215	1'556
- extraction	250	2'254
MFS Wiesen		
- supply	215	1'566
- extraction	250	2'221

4.2. Ventilation during normal and maintenance operation and in case of an event

4.2.1. Operation of tunnel ventilation in normal mode

The ventilation during normal operation is ensured by the natural air exchange due to the piston effect of the trains running in both railway tubes. In case of an insufficient natural ventilation (i.e. the ventilation objectives specified in Section 3.2 are not satisfied) fresh air can be supplied in the railway tubes and warm and humid air can be extracted from the railway tube using the ventilation equipments located in the multifunctional stations, Figure 3.

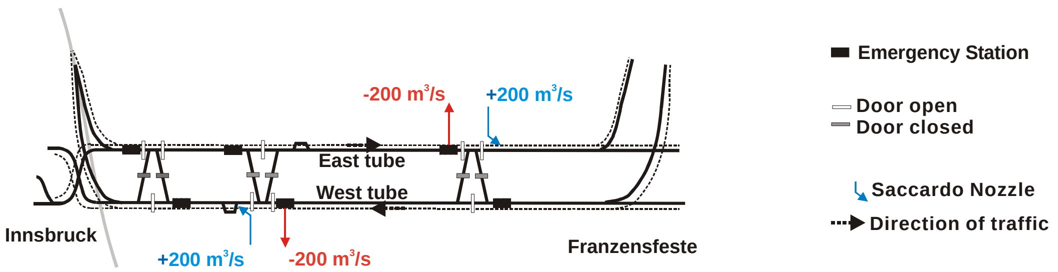


Figure 3: Schematic of ventilation in normal mode with forced air exchange for cooling the railway tunnel.

4.2.2. Operation of tunnel ventilation during maintenance work

Maintenance work in a complete tube

The traffic takes place in the opposite tube in both directions. In the maintenance tube diesel emissions are assumed. The doors of the cross-overs are closed so that the two tubes are aerodynamically connected only via the branching tunnels in Innsbruck and in Franzensfeste. The ventilation is characterized by (see
Figure **4** l.h.s):

- Supply or extraction in the emergency station and air supply through the supply points or Saccardo nozzle in the MFS Steinach and Wiesen in order to create a longitudinal airflow in all the tunnel sections
- Separation of the airflow in the tunnel sections by means of the tunnel doors

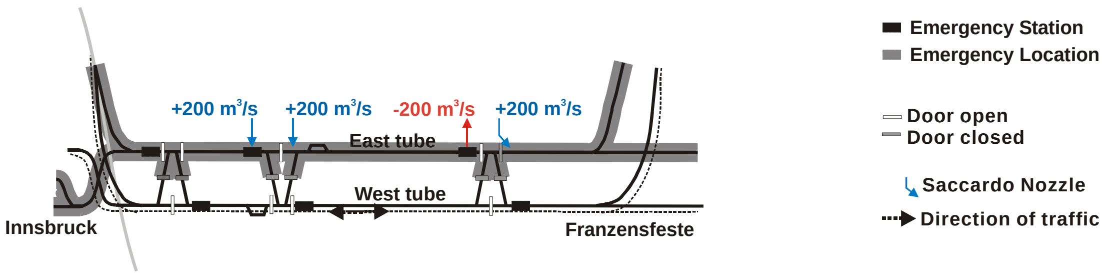


Figure 4: Example of ventilation during maintenance work in tube east and train traffic in tube west.

Maintenance work in one tube section

The trains from the maintenance tube are redirected to the opposite tube through the cross-overs. In the maintenance section diesel emissions are assumed. The doors of the cross-over galleries are open where required. The ventilation is characterized by (see Figure 11):

- Air supply through the supply point, saccardo nozzle or open escape doors in the MFS Steinach and Wiesen in order to create a longitudinal airflow in maintenance section.
- Separation of the airflow in the tunnel sections by means of the tunnel doors

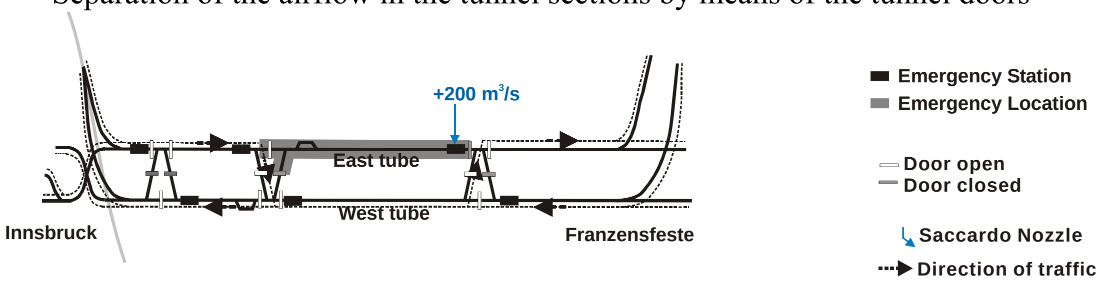


Figure 5: Example of ventilation during maintenance work in the middle section.

4.2.3. Operation of tunnel ventilation in case of an incident (train fire)

Event inside an emergency station

The burning train stops in one of the 6 emergency stations of the base tunnel. The emergency ventilation is characterized by (see Figure 7):

- In the emergency station with the burning train fresh air is supplied though the open escape doors and smoke is exhausted from the air extraction point.
- The passengers escape from the emergency platform over the open escape doors in the protected area of the MFS. The passengers walk in the safe area to the emergency station in the opposite tube from where they are evacuated by a regular empty passenger train.
- In the 2 other multifunctional stations fresh air is supplied in the non-incident tube to produce there an overpressure.
- The ventilation openings in the cross-passages are open in order to allow an airflow directed from the opposite tube to the incident tube stimulated by the overpressure in the opposite tube (to prevent smoke propagation in the cross-passages with the technical equipment).

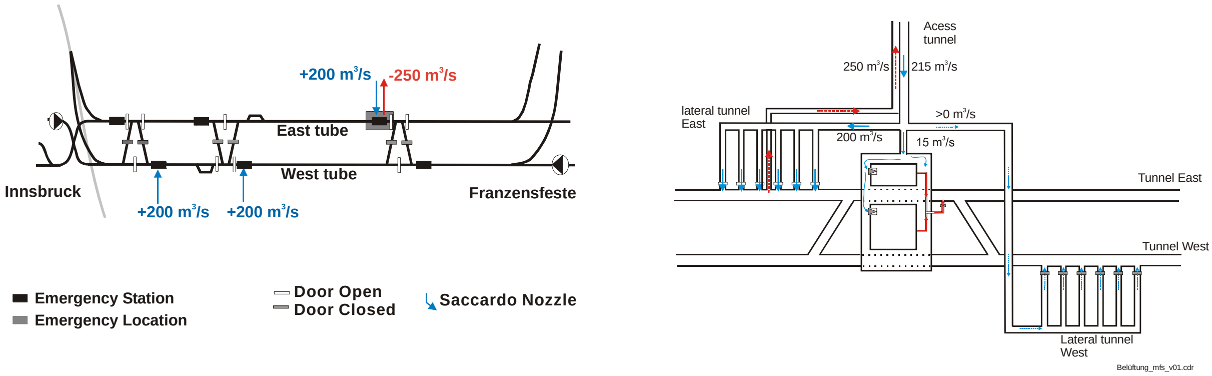


Figure 6: Example of ventilation in case of event in an emergency station in tube east (MFS Wiesen). l.h.s: overall view, r.h.s: details of the emergency station.

Event outside the emergency stations

The burning train stops somewhere outside the emergency stations. The emergency ventilation is characterized by (see Figure 7):

- Over the MFS Steinach and Wiesen fresh air is supplied in the non-incident tube to produce an overpressure.
- The ventilation openings in the cross-passages are open in order to allow an airflow directed from the opposite tube to the incident tube stimulated by the overpressure in the opposite tube (to prevent smoke propagation in the cross-passages with the technical equipment).
- Activation of jet fans at the portals of the opposite tube to assist the emergency ventilation for a fire near the portals.
- The passengers escape through the cross-passages in the opposite tube, which is free from smoke and heat. The evacuation of the passengers takes place in the opposite tube by means of a regular empty passenger train.

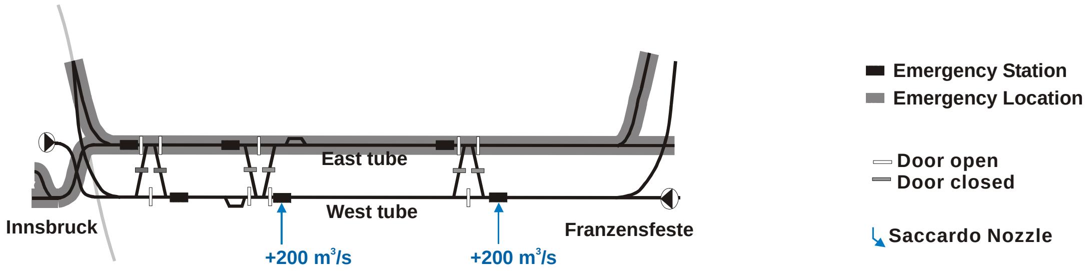


Figure 7: Example of ventilation in case of event outside the emergency stations in tunnel east.

5. RESULTS OF THE INVESTIGATION

5.1. Aerodynamic Issues

Several aerodynamic investigations have been performed in order to determine the aerodynamic key parameters for which the different civil construction elements should be designed (tunnel cross section, tunnel gradient, portal area). A selection of these investigations and their results and implications for the tunnel design is presented here.

5.1.1. Investigation of the pressure comfort on a passenger train

Aerodynamic calculations were performed to check whether the medical pressure limit value (TSI criterion: max. 10 kPa during tunnel passage) and the pressure comfort (UIC criteria: max. pressure fluctuations of 0.5 kPa in 1s, 0.8 kPa in 3s, 1 kPa in 10s and 2 kPa in 60s) on a passenger train are satisfied for the planned high speed traffic. The influencing parameters, i.e. tunnel cross-section, decompression measures at the portals and operational measures (adapted train driving speeds near the portal), were examined.
Figure 8 shows the calculated pressure inside an unsealed passenger train during the passage through the tunnel with a train speed of 250 km/h and for different tunnel cross-sections. Figure 9 shows the transient pressure variations for a train speed of 250 km/h in a well sealed passenger train during the passage through the tunnel also for different tunnel cross-sections.

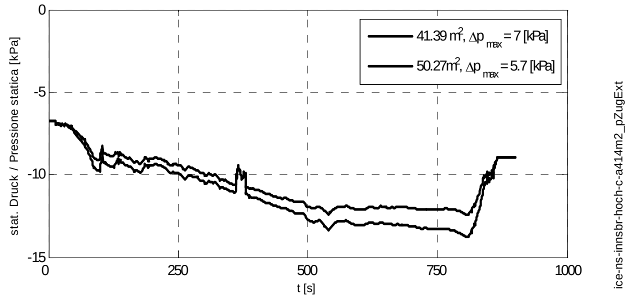


Figure 8: Calculated pressure variations in an unsealed passenger train (at 250 km/h) during passage through the tunnel for determining compliance with medical pressure limit

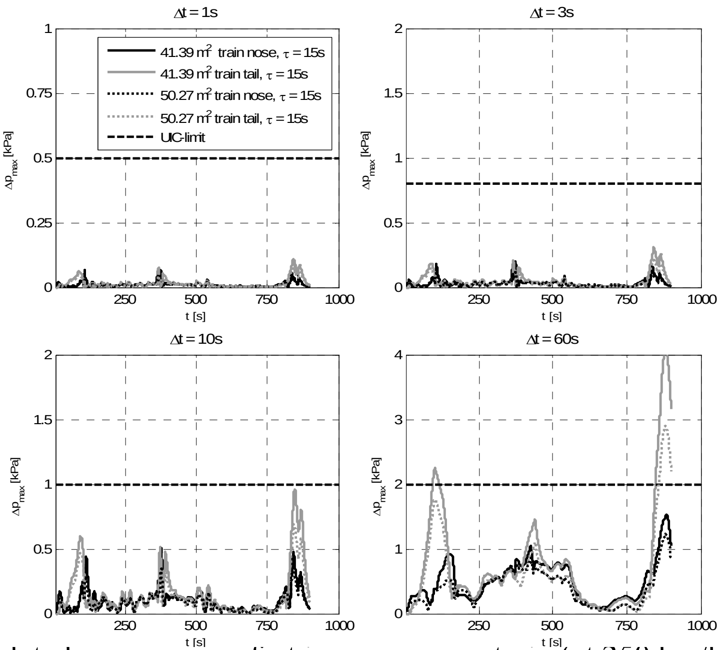


Figure 9: Calculated pressure comfort in a passenger train (at 250 km/h) during passage through the tunnel for determining compliance with UIC criteria

The result of the performed calculations shows that the TSI criterion can be fulfilled for the investigated range of tunnel cross sections and the planned speed of a passenger train of 250 km/h. On the other hand the results of the calculations for the pressure comfort show that the most restrictive criterion is the one for the longest time interval (max. pressure fluctuations of 2 kPa in 60s). This limit is generally not satisfied by any of the investigated tunnel cross sections and the investigated decompression measures at the portal (decompression shaft, enlarged cross section at the portal). The long time criterion can be satisfied with the following train operational restrictions: early deceleration at tunnel, reduced acceleration at tunnel entrance and tunnel exit deceleration and reduction of the tunnel exit velocity.

5.1.2. Investigation of the traction power of a freight train

The operation concept for the Brenner Base Tunnel incorporates freight trains as well as passenger trains. The necessary traction power of the train for travelling through the tunnel is mainly determined by the tunnel inclination and the aerodynamic resistance of the tunnel. The available traction power of a train is limited by the number of locomotives and the power of the locomotives.
In figure 10 the required traction power for a heavy freight train is represented for a tunnel inclination of 8.3‰ and tunnel cross-section of 43.42 m^2. The calculations show that the available traction power of the fright train is sufficient in order to run at 120 km/h through the tunnel.

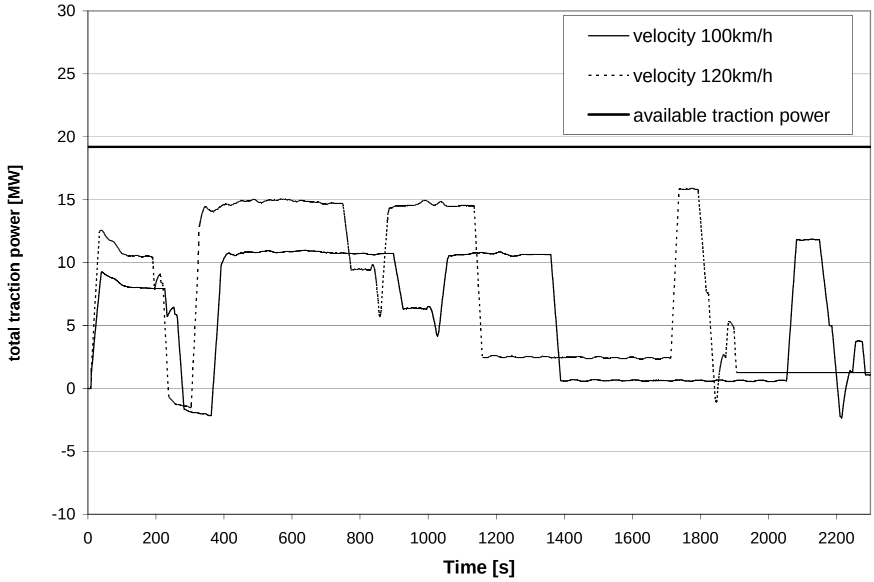


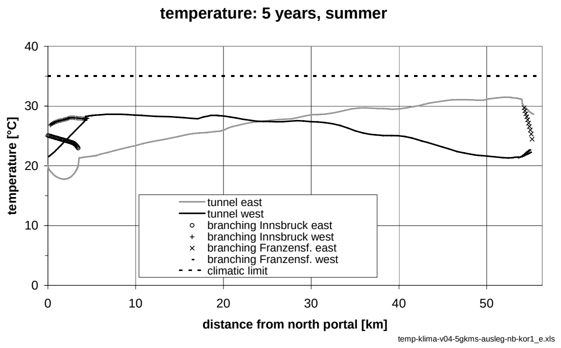
Figure 10: Required traction power for a heavy freight trian travelling at 100 km/h and 120 km/h with a tunnel inclination of 8.3‰ and a tunnel cross-section of 43.42 m^2.

5.2. Thermodynamical Issues

Thermodynamic simulations were performed in order to find out if the limiting criteria for the tunnel climate are maintained in the tunnel system (see Section 3.2).
The thermodynamic conditions were calculated for normal operating conditions with trains running north-south in the eastern tube and trains running south-north in the western tube. The following list summarizes the major influencing parameters:

- time table of train travelling through the tunnel (mix of different types of trains)
- rock temperatures along the tunnel tubes
- water seepage through tunnel lining
- emitted heat by catenary and technical equipment in the tunnel

The results of the simulation are shown in Figure 11.



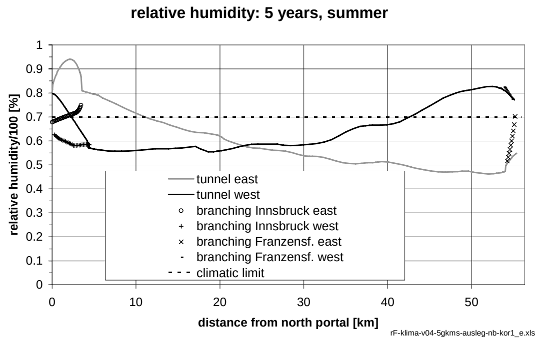


Figure 11: Temperature and relative humidity in the base tunnel in summer after 5 years.

The temperature profiles exhibit that the temperature increases along the tunnel in the direction of the running trains and then decreases towards the exit portal. The temperature increase is mainly due to the heat transfer to the air from the different heat sources (rock, trains, catenary, cross-passages). The flow in the tunnel tubes generated by the running trains avoids a local accumulation of the heat in the tunnel.

The relative humidity is linked with the temperature profile. At a constant absolute humidity the relative humidity (in %, where 100% mean saturated air) is correlated negatively with temperature. Thus, an increase of the temperature leads to a decrease of the relative humidity and vice versa. Therefore, the relative humidity is lower in the middle of the tunnel, where the temperature is higher and it becomes larger towards the portals. The increase of the relative humidity towards the portals is therefore mainly a result of the lower temperatures and not an indication of a higher level of the absolute humidity.

Overall, the predictions show that the limiting criteria are satisfied for the major parts of the tunnel. The following main conclusions can be derived from the simulations:

- Limiting the seepage through the tunnel lining depends on the degree of sealing of the tunnel lining. The simulations have demonstrated the requirement that seepage is kept at a low level. Finding measures to reduce seepage is a task for civil engineering.
- One parameter with a major influence on the tunnel climate is the rock temperature. The data available so far results from preliminary sample measurements in the geologic surroundings of the future tunnel. In order to reduce the uncertainties of the climate predictions it will be important to monitor the rock temperature and other relevant climatic parameters (such as seepage) while works on the tunnel shell progress. Reducing the uncertainties of these parameters will greatly help to reduce the uncertainties underlying the climate predictions performed so far.

5.3. Safety Issues

The essential ventilation objective in case of a train fire in the tunnel is to guarantee a safe place, i.e. an area protected from smoke and heat for the passengers. With the aid of the tunnel ventilation these safe areas are ventilated so that an entry of smoke is avoided. In the event of a train fire in the rescue station the protected area of the MFS will be supplied with air to produce an overpressure against the rescue platform. In the event of a train fire outside the MFS the opposite tube is supplied with air to produce an overpressure against the incident tube. The compliance with ventilation objectives is essentially influenced by the piston effect of the trains leaving the tunnel and the incoming rescue train during the self rescue phase. The ventilation goals were checked using realistic emergency scenarios (train movements, fire load). Based on the simulation the train speed was optimised with regard to the emergency ventilation.

Figure 12 shows the results of a simulation of the air flow in the open doors of two adjacent cross-passages used by the passengers in an event outside the MFS during the phase of the self and external rescue. The figure shows that the longitudinal air flow is influenced by the train movements in the incident tube and the non-incident tube.
Investigations of various scenarios showed that with the emergency ventilation system and with optimised train operation procedures the ventilation objectives are satisfied in the event of a train fire independently of the stopping location of the train. In the simulations also the smoke propagation in the incident tube was examined (based on a 20 MW design fire for the burning train).

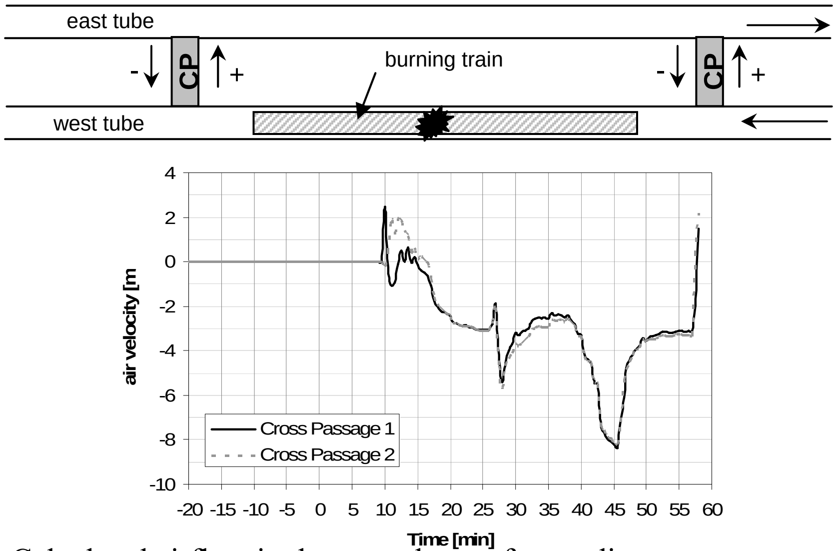


Figure 12: Calculated airflow in the open doors of two adjacent cross-passages used to escape in the opposite tube in case of an incident ousitde a rescue station.

6. CONCLUSION

Within the framework of the UVE project and the technical project preparation a suitable tunnel ventilation concept was developed for the Brenner Base Tunnel by the planning group of the BBT (PGBBT). The ventilation concept guarantees in the normal operation, during maintenance work and in the case of an incident (train fire) that the ventilation objectives can be satisfied in most situations. With the aid of extensive aerodynamic and thermodynamic calculations the effect of the tunnel ventilation could be proved.
The concept represented in this article and the results of the calculations show the current state of the planning. It can not be excluded that within the framework of the finishing of the project in the course of 2006 adaptations of the tunnel ventilation concept will be required due to changes of the boundary conditions in the areas of civil engineering design, equipment, tunnel operation, etc.

7. REFERENCES

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[2] EN 14067-5 (European Comittee for Standardisation), "Bahnanwendungen – Aerodynamik – Teil 5: Anforderungen und Prüfverfahren für Aerodynamik im Tunnel", 2003

CONSIDERATION OF DENSITY VARIATIONS IN THE DESIGN OF A VENTILATION SYSTEM FOR ROAD TUNNELS

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ABSTRACT

This article investigates the effects of varying density on the design of a ventilation system. In particular the effect of strong local heat sources (e.g. fires) on the system behaviour will be discussed. Changes in density have different effects. If a given flow rate has to be achieved at a certain point in a tunnel system the density at this very point might be different from the density at a ventilator station. Hence, if the density at the ventilator station is higher, the volumetric flow rate achieved by the fan can be lower than the required flow rate at a particular point in the tunnel. Since the volumetric flow rate is directly related to the size of a turbo-machine, it can be an important reduction in investment costs. Another important effect is buoyancy. Temperature changes can lead to strong flows induced by the natural buoyancy of the air. The intention of this article is to highlight a few impacts these effects might have on the design of a ventilation system.

1. INTRODUCTION

1.1. Symbols

The following symbols have been used in this article:

p	pressure	[Pa]
h	elevation	[m]
T	temperature	[K or °C]
R	individual gas constant of air	[J $kg^{-1}K^{-1}$]
Re	Reynolds number	[1]
Pr	Prandtl number	[1]
Nu	Nusselt number	[1]
g	acceleration due to gravity	[m s^{-2}]
ρ	density	[kg m^{-3}]
c	specific heat	[J $kg^{-1}K^{-1}$]
k	heat conductivity	[W $K^{-1}m^{-1}$]
$\dot{V}$	volumetric flow rate	[m^3s^{-1}]
$\dot{Q}$	heat flux	[W]

1.2. Density Changes in Air Flow

In the scope of this article air is considered to be a perfect gas. The relation between pressure, density and temperature is given by the ideal gas law

$$p = \rho RT \quad \Leftrightarrow \quad \rho = \frac{p}{RT}. \tag{1}$$

For flow problems in tunnels, the influence of the temperature in (1) is more important than the pressure dependency of the density. Figure 1 shows the relation between pressure and density for a constant temperature of 20°C, as well as the temperature dependency for a constant pressure of 1013.25 mbar.

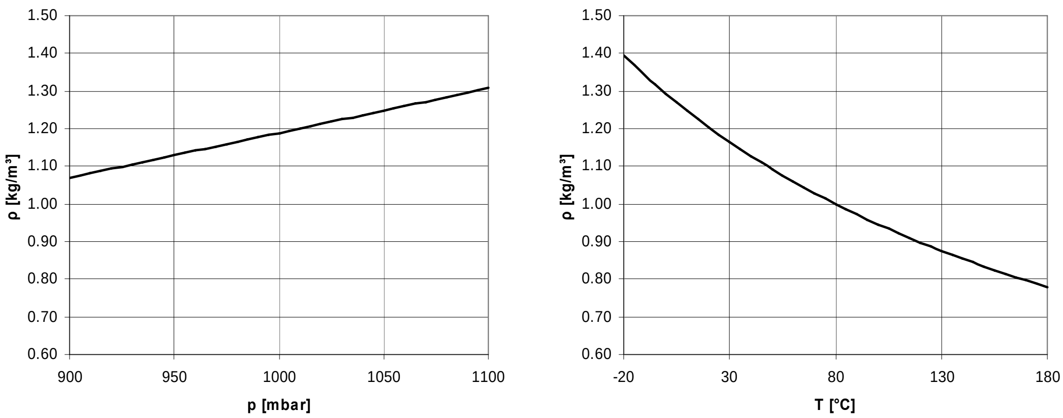

Figure 1: Temperature and pressure dependency of air density

While pressure fluctuations of 100 mbar or more are a rare exception in tunnel aerodynamics, temperature variations of 200°C and more are very common design cases in case of emergencies. Because of the strong influence of the temperature great care has to be taken to model heat exchanges correctly. Pressure, density and temperature also vary with altitude. All computations in this article have used the following equation to determine the atmospheric conditions at a given elevation

$$p = p_{sea} \cdot \exp\left(-\frac{gh}{RT}\right), \qquad (2)$$

where p_{sea} is the pressure at sea level. Under normal conditions a gradient of -6.5 Kkm^{-1} can be assumed for the temperature distribution. Figure 2 shows the density variations depending on the elevation.

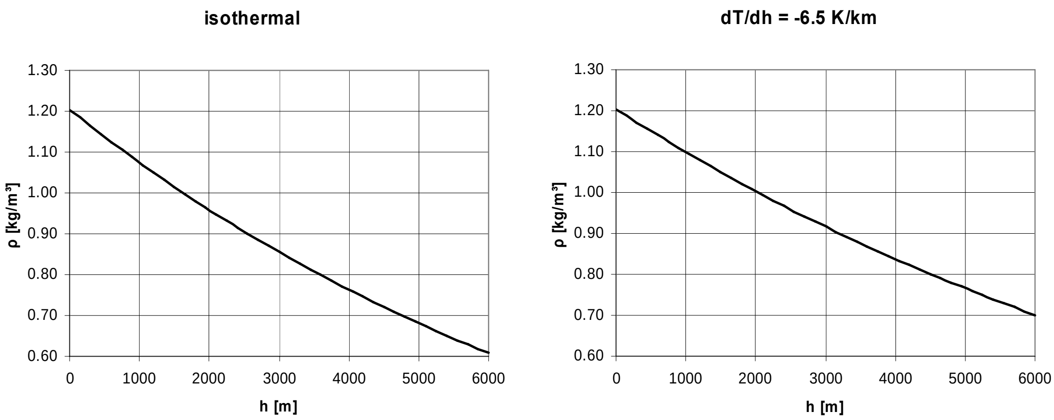

Figure 2: Density variations with altitude

2. BUOYANCY EFFECTS

This section shows what happens if a ventilation system is designed without buoyancy considerations and then is exposed to temperature differences between inside and outside. A computer model of a simple road tunnel has been created to show the effects of buoyancy. It is a fairly standard road tunnel with a cross section of 50 m^2 and a length of 2 kilometres. To illustrate buoyancy effects, it has an uphill grade of 2% and hence the difference in elevation between the two ends is 40 metres. The tunnel and the exhaust air channel are connected by three vents which split the tunnel in an upper and a lower half. Figure 3 shows a sketch of the model with the arrows indicating the airflow. The exhaust channel has a cross sectional area of 20 m^2 and is extended 100 metres sideways on either end (see also Figure 4). An axial fan is situated on both ends of the exhaust channel. Two additional jet fans are placed in the tunnel at 500 and 1500 metres. These jet fans will only be used if the flow velocities in the two branches of the main tunnel differ significantly.

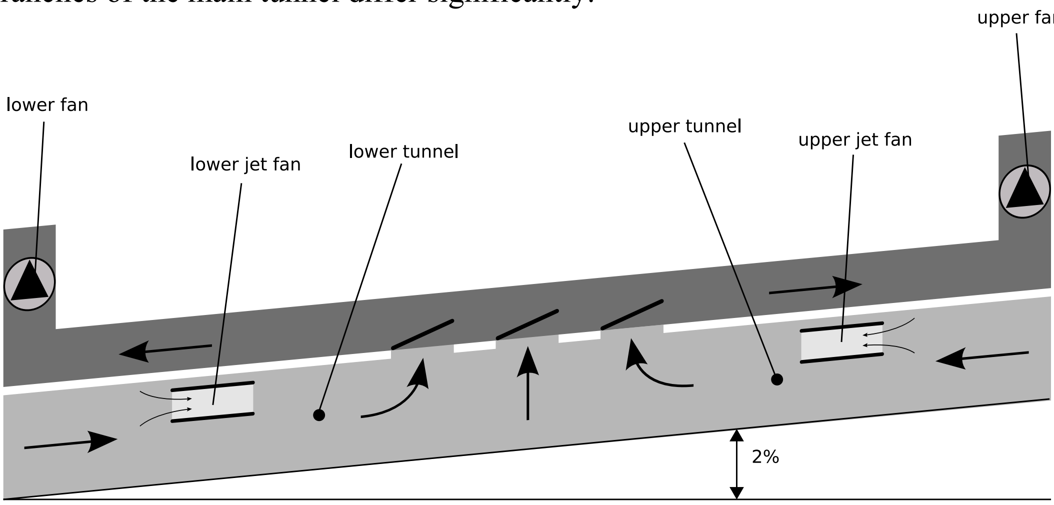

Figure 3: Schematic sketch of model tunnel

Figure 4: Computer model of a generic road tunnel

Both axial fans deliver a volumetric flow rate of 75 m^3s^{-1}. In absence of buoyancy this leads to an air velocity of 1.5 ms^{-1} in both branches towards the extraction point. A first simulation has been made with the design conditions (i.e. no temperature variations considered). This is mainly a check for the computational setup. As can be seen in Table 1 (scenario A), the velocities in the upper and lower half of the tunnel are almost equal. The yet existing small differences are caused by tiny density differences in the ambient conditions at the tunnel ends (see Figure 2). Density variations due to altitude differences can be neglected for most road tunnel applications. Only in nearly vertical shafts, they may have a significant influence.

To show the impact of temperature differences between tunnel walls and ambient air, the tunnel wall temperature has now been set above (scenarios B, C and D), or below the ambient temperature (scenarios E, F and G). Table 1 gives an overview of the computed results. The average velocity varies significantly between the upper and lower branch. In the scenarios B and E, the velocity distribution is particularly asymmetric. Only if additional measures are taken (i.e. using the jet fans) a better flow can be achieved (scenarios C and F). An interesting alternative can also be to let buoyancy be the only driving force (i.e. all fans switched off). In the scenarios D and G it shows that a velocity above 1.5 ms^{-1} can be achieved by this strategy.

This little example shows that natural buoyancy cannot be neglected for the design of a ventilation system. Please refer to Table 1 for a detailed summary of the results. The scenarios B, C and D represent conditions as they might be found in winter, and the scenarios E, F and G represent typical summer conditions.

Table 1: Overview of different scenarios

	scenario		A	B	C	D	E	F	G
	T_{wall}	$°C$	10.0	10.0	10.0	10.0	15.0	15.0	15.0
	$T_{ambient}$	$°C$	10.0	0.0	0.0	0.0	25.0	25.0	25.0
lower jet fan	d_{jet}	m	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	v_{jet}	ms^{-1}	0.0	0.0	0.0	0.0	0.0	15.0	0.0
upper jet fan	d_{jet}	m	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	v_{jet}	ms^{-1}	0.0	0.0	-15.0	0.0	0.0	0.0	0.0
lower fan	Δp	Pa	35.8	37.7	35.6	0.0	34.1	32.1	0.0
	$\dot{V}$	m^3s^{-1}	75.0	75.0	75.0	0.0	75.0	75.0	0.0
upper fan	Δp	Pa	35.6	27.5	25.2	0.0	42.7	40.9	0.0
	$\dot{V}$	m^3s^{-1}	75.0	75.0	75.0	0.0	75.0	75.0	0.0
lower half	v	ms^{-1}	1.50	2.10	1.58	1.70	0.96	1.46	-1.68
upper half	v	ms^{-1}	-1.50	-0.83	-1.35	1.73	-2.09	-1.60	-1.71

3. INFLUENCE OF DENSITY VARIATIONS FOR EMERGENCIES

The position of a ventilator station with respect to the position of a strong heat source (i.e. a fire) can have a strong influence on the design choices. If the fan is positioned close to a fire, it has to be capable of withstanding the hot gases from the fire. Also, due to the higher temperature, the density is significantly lower than in other areas. Thus, a machine which needs to deliver a given mass flow rate at one particular point in a tunnel system, can be smaller if it is placed where the density is expected to be higher.

To illustrate this behaviour, a single gallery with a cross section of 20 m^2 and a length of 1000 metres shall be used. A computer simulation of this simplified example demonstrates the effects. The main relevant effects (i.e. convective heat transfer and heat conduction into the rock) shall be considered. On one side air with a temperature of 400°C enters the gallery. A flow rate of 200 m^3s^{-1} has to be achieved. The difference between placing a fan 50 metres from the entrance or 50 metres from the exit is investigated. Operation of this exhaust fan shall be computed for two hours after the event. During this time, heat exchange between the hot air and the tunnel walls plays a decisive roll. Unlike real tunnel fires, this test case assumes a constant feed of air with a temperature of 400°C. This simplified example considers a homogeneous rock and air temperature of 20°C at the beginning of the test, i.e. the tunnel walls, as well as the rock behind them, initially have the same temperature. With time the heat penetrates into the rock. This penetration is governed by the equation for radial heat conduction.

$$\frac{\partial T}{\partial t}=\frac{k}{\rho_{rock}c_{rock}}\left(\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}\right). \tag{3}$$

For $r \rightarrow \infty$ the temperature remains constant, but the wall temperature and the temperature distribution inside the rock is left free to change. The heat exchange between the tunnel walls and the air flow has been modelled using the following empirical expression for the turbulent Nusselt number

$$Nu=\frac{RePr(0.78\ln Re-1.5)^{-2}}{8\left(1+12.7\sqrt{\frac{(0.78\ln Re-1.5)^{-2}}{8}}\left(Pr^{2/3}\right)\right)}. \tag{4}$$

The Nusselt number depends on the Reynolds and on the Prandtl number. The latter has been assumed to be 0.7 throughout this article.

3.1. Ventilator Operating in Hot Air

A first case shall be simulated where the ventilator operates in hot air (50 metres from the entry). Figure 5 illustrates this setup.

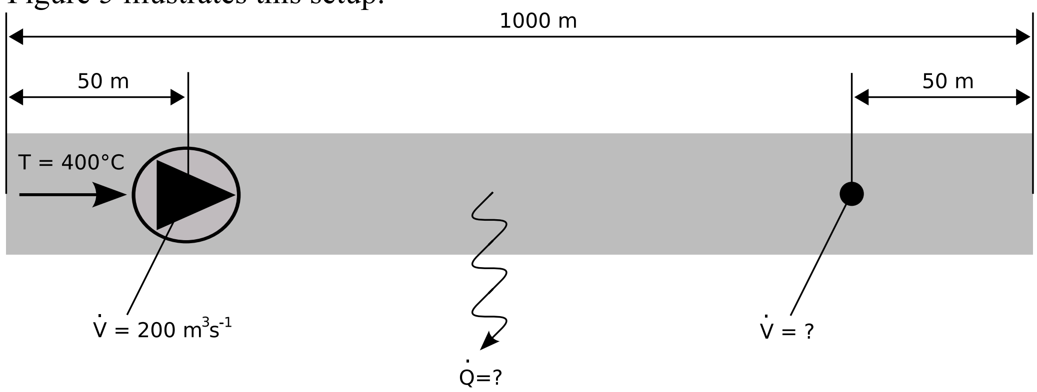

Figure 5: Fan operating in hot air

The flow through this model gallery will be simulated for two hours of physical time. In Figure 5 the other possible position for the fan is indicated (50 metres from the exit). Probably a lower volumetric flow rate will be required at this point in order to achieve the same flow rate at the entry. The required flow rate will change over time. As the tunnel walls warm up the heat exchange between air and rock decreases. This heat exchange, however, is the reason for the higher density at the end of the gallery. If the conditions are kept up for an infinite time, the whole rock and the air will have the same temperature. In this case the difference in density is minor, because it is only related to the pressure drop along the tunnel. This difference can be neglected safely. In this example a maximal power of 15 kW is required to operate the fan. This maximal value occurs at the end of the two hour period.

3.2. Ventilator Operating in Colder Air

To show the difference between operating a fan in cold or in hot air, the fan will now be placed closer to the exit. Figure 6 shows the new setup. The required volumetric flow rate can be extracted from the previous simulation ($\dot{V}$ =160 m^{3}s^{-1}). For this setup a maximal power of 13 kW at the beginning of the two hour period is required.

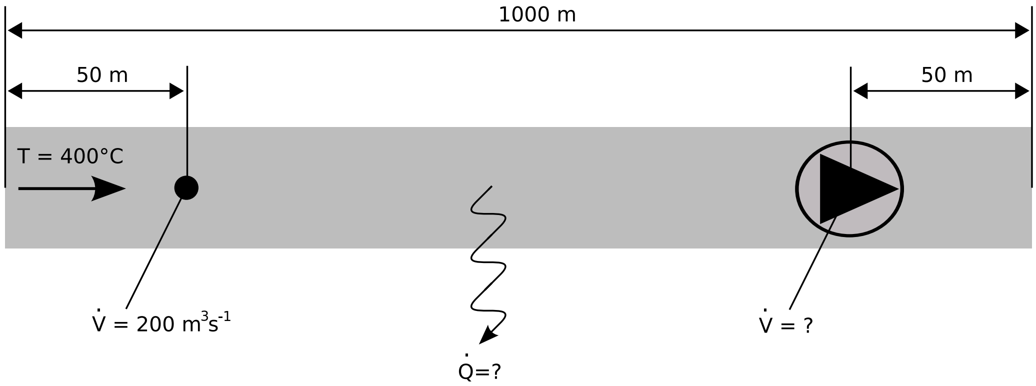

Figure 6: Fan operating in colder air

3.3. Comparison Between Hot and Cold Operation

The power requirement for the ventilator close to the exit is significantly lower. Figure 8 shows the evolution of the power consumption over time for both ventilator positions. In Figure 7 the volumetric flow rate at the position 50 metres from the entry can be viewed. It can be observed that for the two hours of operation the flow rate is higher if the fan is placed close to the exit. This could potentially give more security, while still requiring a smaller investment. The size of the machine, the maximal power requirement and the resistance to heat are all in favour of a position close to the exit.

Figure 10 and Figure 11 show the evolution of air and wall temperature along the gallery. The lines represent different points in time (t = 20 min, 40 min, 60 min, 80 min, 100 min and 120 min). With increasing time the temperature increases as well.

Initially both setups require the same power. As the tunnel heats up, the required power for the fan on the entry side increases. For the alternative fan position, on the other hand, the power decreases. Most of the time, the volumetric flow rate is significantly higher than for the hot fan position.

Note has to be taken that the transient behaviour of the fans has not been modelled correctly. Thus the first fifteen minutes are left out of Figure 7 and **Figure 8** due to the strong transient effects in this period. The volumetric flow rate has been enforced in the computer model. This can lead to unrealistically high forces. To model this phase accurately, the detailed fan behaviour (i.e. the compressor map) needs to be put into the computer model. It is, however, believed that the general trend and the maximal and minimal values are represented correctly.

4. CONCLUSIONS

Density variations in tunnel systems can lead to strong effects. These effects cannot be neglected during the design phase of such a system. The comparison between a hot and a cold position for a ventilator station highlights a few important facts.

- The “cold” fan saves about 13% for the installed power requirement
- A “cold” fan could have a roughly 10% smaller diameter
  (based on the lower volumetric flow rate)
- A fan in a “cold” area experiences lower temperatures (see **Fehler! Verweisquelle konnte nicht gefunden werden.**)

All these points could cut investment costs, if axial smoke extraction fans are positioned as far away from potential fires as possible.

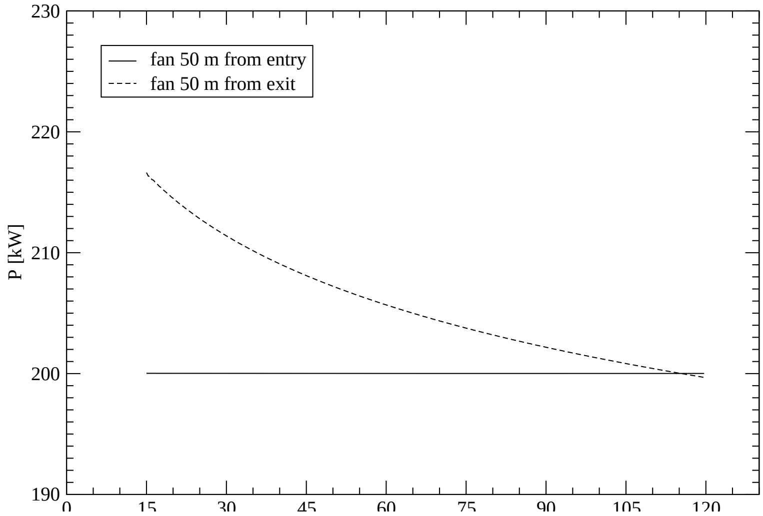

Figure 7: Volumetric flow rate 50 metres from the entry

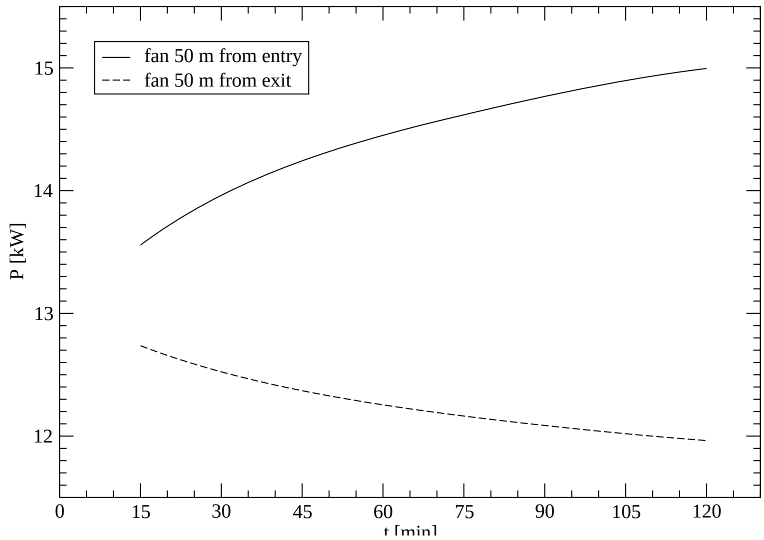

Figure 8: Power consumption of the two different ventilator stations

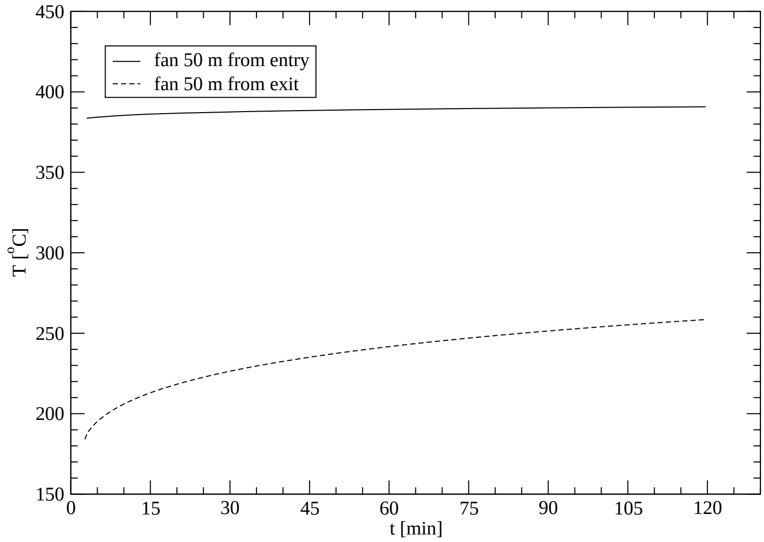

Figure 9: Temperature at ventilator stations

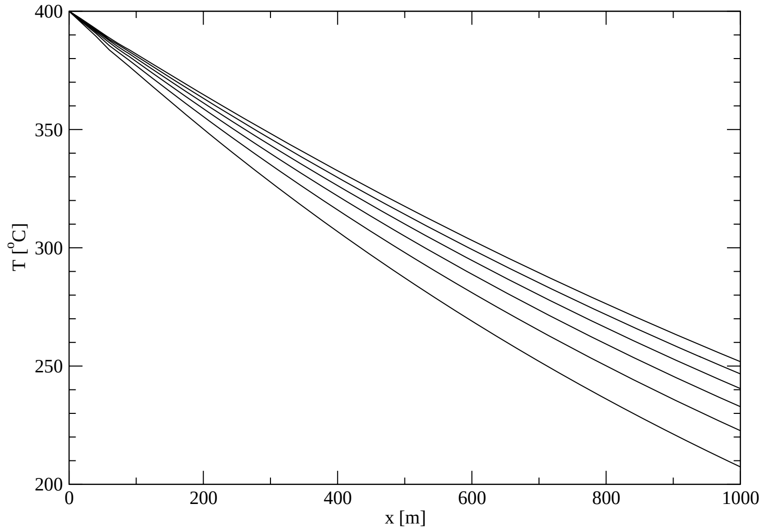

Figure 10: Air temperature evolution

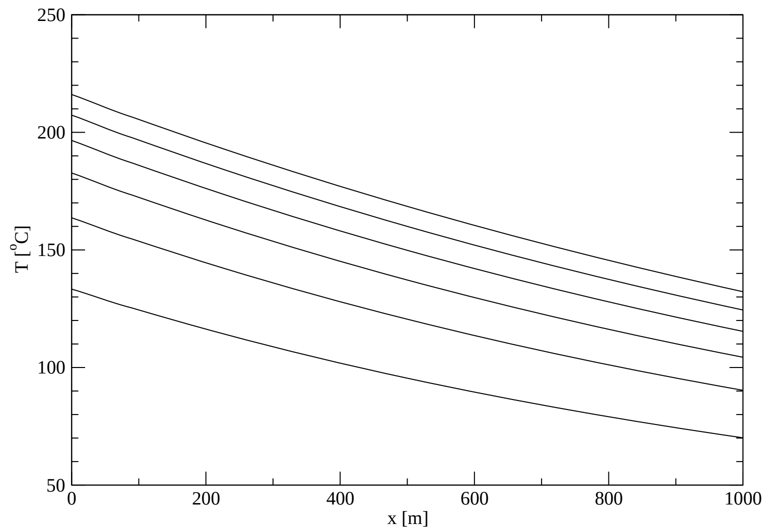

Figure 11: Wall temperature evolution

TECHNICAL EQUIPMENT OF TUNNELS FOR DRAINAGE AND FIRE PREVENTION DEMONSTRATED BY THE EXAMPLE "EISENBAHNACHSE BRENNER, ZULAUFSTRECKE NORD"

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ABSTRACT

At present the „Eisenbahnachse Brenner“ from Munich to Verona is partly re-designed. One section is an about 40 km long line in the Inntal north of the Brenner. This line mainly follows the existing double-tracked location line from Kufstein to Innsbruck. However, on account of the fact that the area is densely populated it must switch to tunnel lines and covered troughs. Therefore a high percentage of tunnel constructions is planned. The necessary safety facilities like emergency routes and location line draw downs into the groundwater area require a great deal of technical expenditure compared to designs of the first generation in railroad tunnel construction.

This is why the lecture will deal with design principles of pumping stations, maintenance basins, safety facilities for tunnels and life-saving tunnels in case of fire.

Keywords: pumping stations, life-saving elevators, backlayering, aeration, fire protection sluices

1. PUMPING STATIONS

1.1. Waters and liquids to be pumped off

1.1.1. Groundwater

Tunnels and groundwater troughs of railroad constructions are made in a leak proof way or leak proof to a high extent. According to water right law this is an indispensable general demand. Otherwise there will be an important interference with groundwater balance. Hence, the greatest part of groundwater is mountain water provided that a drainage in the mountains does not have any detrimental effect on the general water balance.

Therefore the amount of water of such origin can be regarded as negligible

1.1.2. Rain-water

Contrary to groundwater, rain-water in open troughs and rain-water on trains in portal areas of tunnels are an important source. The amount depends on the respective local peak rain loads and on the size of the trough area/catchment area. In alpine regions a rain load of more than 15 minutes with an intensity of 300 to 330 l/s. hectare is to be expected.

1.1.3. Liquids due to accidents and leakages

The compounds of such liquids and the resulting hazardous potential can vary tremendously. Therefore increased precautions have to be taken in order to avoid explosions or other dangers to health. The amount resulting from one single accident at least corresponds with the volume of a big tanker or 108 m³. Even pumping stations for rainwater may be affected by such an accident. Therefore the necessary precautions also have to be taken with such pumping stations.

1.2. Pumping stations for rain-water

When dimensioning and designing the pumping stations it is not the economic aspect that should dominate the design, because the running time of the pumping station will be very short except when mountain water is pumped off. The aspects that should mainly be considered are safety in operation and low maintenance costs.

For safety in case of accident a big open ball passage, the bilateral power supply, the redundant design of the control system and a 100% reserve of the pump efficiency are absolutely indispensable. As for short pressure pipelines, a separated realisation for each pump as far as the gravitational flow into receiving body of water is suggested because therewith the wear and tear of fittings, reflux valves, slide gates and pipe fittings is avoided. Frequency converters for adapting pump efficiency to influent amount can and shall be dispensed with. Instead of that the volume of the suction well shall be set to a maximum switch. This is different when mountain water is pumped off because its constant yield necessitates an economic pump capacity.

The dimensioning of the suction well volume is based on the simple function. It may also be shown in a diagram. For the switch frequencies n = 8 times per hour the functions are marked.

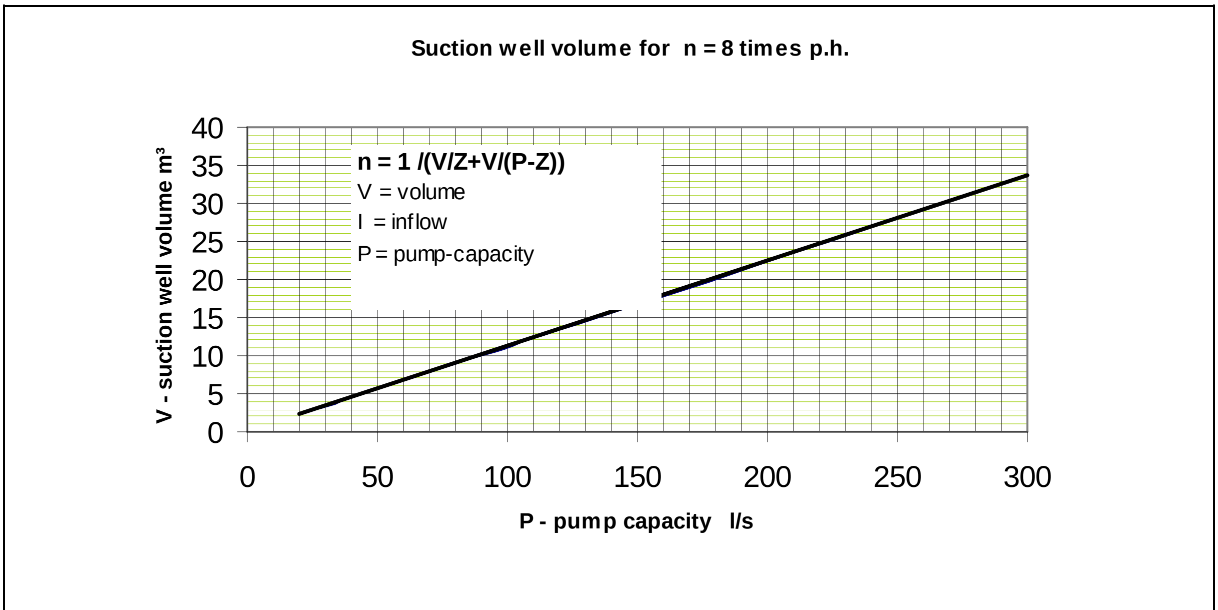


Figure 1: Suction well volume:

In case of accident suction wells may be regarded as high explosive areas because easily inflammable liquids may also flow into the suction well. Due to the possibility that the liquids may contain concrete corroding substances suction wells have to be protected by an acid proof and alkali proof surface cover. As for pumping stations in buildings e.g. in life-saving stairwells, a separation of suction well and pump room is suggested because therewith the pumps may be maintained in a dry room and there is no contact with the medium during maintenance. It is suggested that these pumps are submerged pumps as well in order to have additional safety in case of flood.

Preferably, pumping stations which may be maintained from site should also be submerged pumps with duck feet and draw down facility.

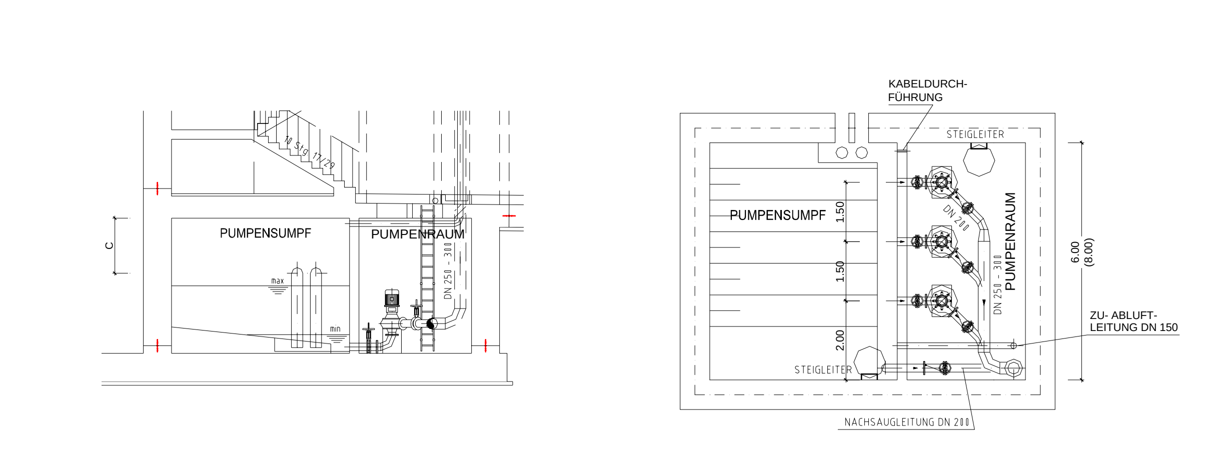


Figure 2: Example of a pumping station in a life-saving stairwell

1.3. Maintenance basin

In case of accident in a tunnel the liquids from tankers are directed to the maintenance basins, which are situated at the lowest point of tunnel constructions. In some cases such basins are included in the plan (underneath the life-saving tunnels). These basins with about 108 m³ of effective volume are explosive areas. They are not equipped with stationary pumps. Via sluice pipes probes may be taken, chemicals for precipitation, neutralisation or prevention of explosive atmosphere may be added. After definition or neutralisation of the liquid the liquids shall be disposed via the stationary installed suck and pressure pipes by means of portable chemistry pumps. In order to protect buildings against explosion, explosion relief shafts with large cross-sections reaching beyond the ground surface are planned.

2. SAFETY FACILITIES

2.1. Definition of safety standard

The kind and scope of architectural and operational precautions for the self-rescue of travellers and railroad staff as well as the action of assistants and rescue parties are defined in the guideline on “Construction and Operation of New Railroad Tunnels Concerning Main and Side Lines” of the Austrian Professional Fire Brigade Union (ÖBFV-RL A –12). More or less these guidelines define the state of the art in technology and have to be regarded as the basis for the authorization procedure of railroad constructions.

As for road tunnels these guidelines correspond with the guide line for safety in traffic RVS 9.261.

In the ÖBFV – RL a safety concept is demanded as a presupposition for any authorization. This concept defines the qualifications of the rescue party; the presupposition for self-rescue and rescue of others in the area of the tunnel, for the safe areas – emergency stairwells, life-saving tunnels, sluices etc. In the following the required freight elevators and the standards of escape route sluices as well as their aeration and the foundations will be dealt with.

2.2. Freight elevators

According to the ÖBFV-RL emergency stairwells with a difference in altitude of up to 30 m have to be equipped with a loading rack with a mobile electric elevator for the transport of heavy equipment and injured persons. The authorization basis to be applied for the transport of injured persons as well as the rescue party is the working device decree (BGBl. II Nr. 164/2000) because the elevator will only be operated under supervision and/or instruction. In this specific case the size of the elevator cage has to be 1,50 x 2,00 m.

Among other things the decree mentioned above provides that elevator cages are compact, doors are locked automatically, and that the transport area is compact in order to prevent injuries in the stairwell.

2.3. Rescue and aeration concept in case of fire in a tunnel

As for the railroad tunnel with on-coming traffic the rescue or aeration concept respectively differs very much from that of a motorway. In a long motorway tunnel with on-coming traffic it is tried to suck off the fumes in the traffic area and therewith keep this area as a non-toxic escape route. In contrast to that a railroad tunnel is not aerated.

It must be possible to reach safe areas in the railroad tunnel within a distance of about 250 m. These safe areas are either life-saving tunnels or sluiceways to emergency stairwells. The sluiceways must be at least 12 m long.

In case of fire sluices have to be aerated in a way that even if both sluice gates are open, an excess pressure of such power is produced that an intrusion of fumes into the safe area is prevented.

Adjacent to the sluices an area of at least 25 m² has to be provided as an intermediate place to stay.

This area can be dispensed with when even physically handicapped people are able to exit into the open without difficulties.

Life-saving tunnels may be 150 m at the very most if they do not lead directly into the open but only do so via emergency stairwells. Life-saving tunnels which are longer than 150 m must be passable by road or rail vehicles.

When designing emergency stairwells the limited physical ability of infirm or physically handicapped people have been taken into account adequately.

2.4. Aeration facilities

2.4.1. Necessary fresh-air volume in case of fire

The aeration of sluiceways is only intended for the case that fire breaks out and the train cannot leave the tunnel for technical reasons any more. The people escaping from the traffic tunnel should be safe when they reach the aerated sluice.

While the calculation of the necessary fresh-air volume in a road tunnel is based on the exhaust fumes and the pollutant concentration limit in the tunnel, the fresh-air volume in railroad tunnel cannot be calculated in that way because in train traffic there are no dangerous exhaust fumes.

When calculating the necessary fresh-air volume for escape routes it has to be assumed that both sluice gates are opened when a great number of people try to escape. In order to protect escape routes from even partly thickening with smoke (e.g. backlayering) air with the so-called critical velocity has to be blown against them. This critical velocity was calculated dependent of the fire size. Figure 3 shows the results of this calculation.

Taking a fire size of about 60 MW in consideration, the critical velocity u/m/s is defined as 3 m/s. With that the necessary fresh-air volume V (m³/s) can be calculated from the equation $V = A.\ u$ when the escape tunnel cross section A (m²) is given.

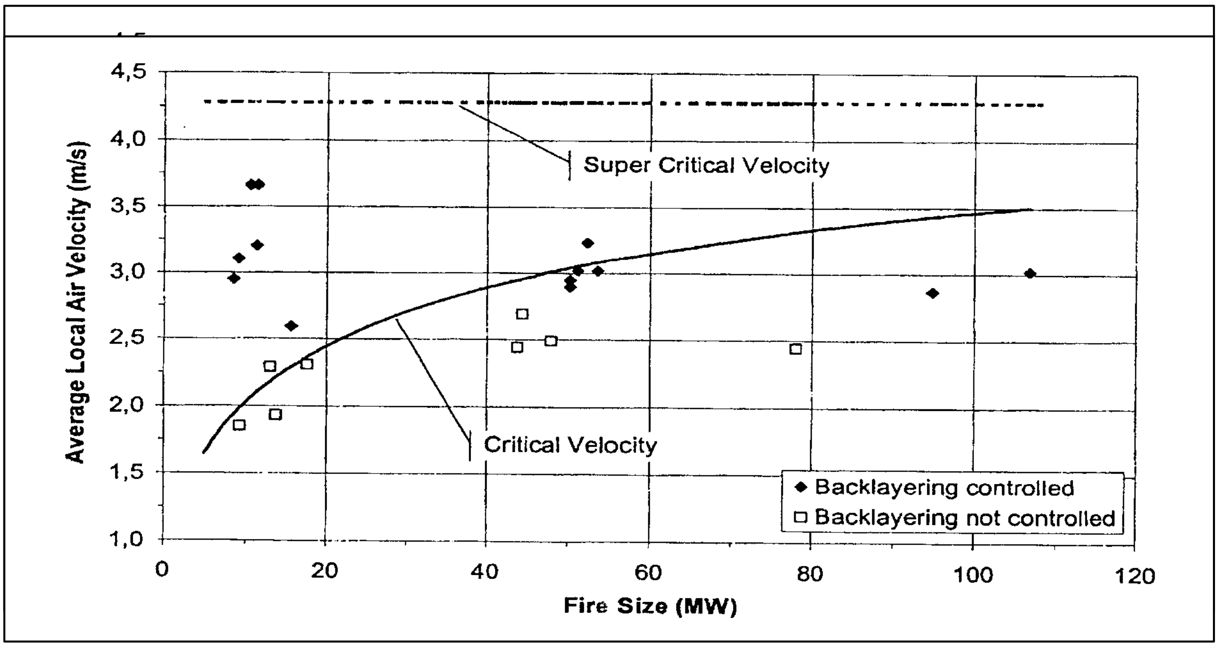


Figure 3: Air velocity for the prevention of backlayering

2.4.2. Pressure ratios in railroad transport

When a train enters the main tunnel an overpressure is produced in front of the engine whereas a negative pressure is produced at the rear of the train. The train works like a piston in a cylinder, however it is not a very tight piston. The longitudinal velocity which is produced by the traffic in the main tunnel can be calculated according to the following equation:

$$\begin{aligned} \frac{du_v}{dt} &= -\frac{1}{2}\left(\frac{\lambda}{D}+\frac{1+\zeta}{L}\right)u_v{}^2 sign.(u_v)+\frac{P_1(t)-P_2(t)}{\rho(t).L}+ \\ &+\frac{A_1.c_w.N_1}{2.L.A_V}[v_1(t)-u_v]^2 sign.[v_1(t)-u_v]+ \\ &+\frac{A_2.c_w.N_2}{2.L.A_V}[v_2(t)-u_v]^2 sign.[v_2(t)-u_v]+\frac{S(t)}{\rho(t).L.A} \end{aligned} \qquad (2.2)$$

Legend:

	s	*time*
λ		*pipe friction correction value in the main tunnel*
D	*m*	*hydraulic diameter of main tunnel*
ζ		*entry loss correction value in main tunnel*
L	*m*	*length of main tunnel*
u_v	*m/s*	*air velocity in main tunnel*
P_1	N/m^2	*meteorological und thermostatic pressure at gate 1*
P_2	N/m^2	*meteorological und thermostatic pressure at gate 2*
ρ	kg/m^3	*density of air in tunnel*
$A_1.c_w$	m^2	*mean resistance area of trains in the main tunnel that move from gate 1 to gate 2*
$A_2.c_w$	m^2	*mean resistance area of trains in the main tunnel that move from gate 2 to gate 1*
N_1		*number of trains in the main tunnel that move from gate 1 to gate 2*

N_2		*number of trains in the main tunnel that move from gate 2 to gate 1*
	m/s	*mean velocity of trains in the main tunnel that move from gate 1 to gate 2*
v_2	*m/s*	*mean velocity of trains in the main tunnel that move from gate 2 to gate 1*
A_v	m^2	*area of main tunnel*
S	*N*	*thrust in main tunnel*

For the calculation of longitudinal velocities the resistance area of the trains must be given. This can be calculated according to /3/ by means of the values given in /4/. For further calculation it is supposed that A1 . cw = A2 . cw = A cw. In the given case this results in a value of Axcw 120 m^2.

With the given equation the velocity as well as the pressure course can be calculated.

Figure 4 shows the velocity course in the 10,470 m long VOMP tunnel based on the supposition that there is no effective pressure difference between the 2 tunnel portals. The train enters the tunnel with a velocity of 250 km/h (69.45 m/s) at a time s = 100 sec. It is also supposed that the total resistance area (Axcw) gets fully effective as early as the engine enters the tunnel. The total length of the train is reduced to zero in this calculation.

You can see that the longitudinal velocity of the air in the tunnel quickly rises to about 13.7 m/s. For an unhindered passage through the tunnel the train takes about 150 sec. After this the train leaves the tunnel again. When the engine leaves the tunnel it is assumed that the total resistance area immediately lapses. When the train has left the tunnel, the moving air gets slowed down by wall friction - at first very quickly, later more slowly. Only after about 10 min. the longitudinal velocity has slowed down to about 1 m/s.

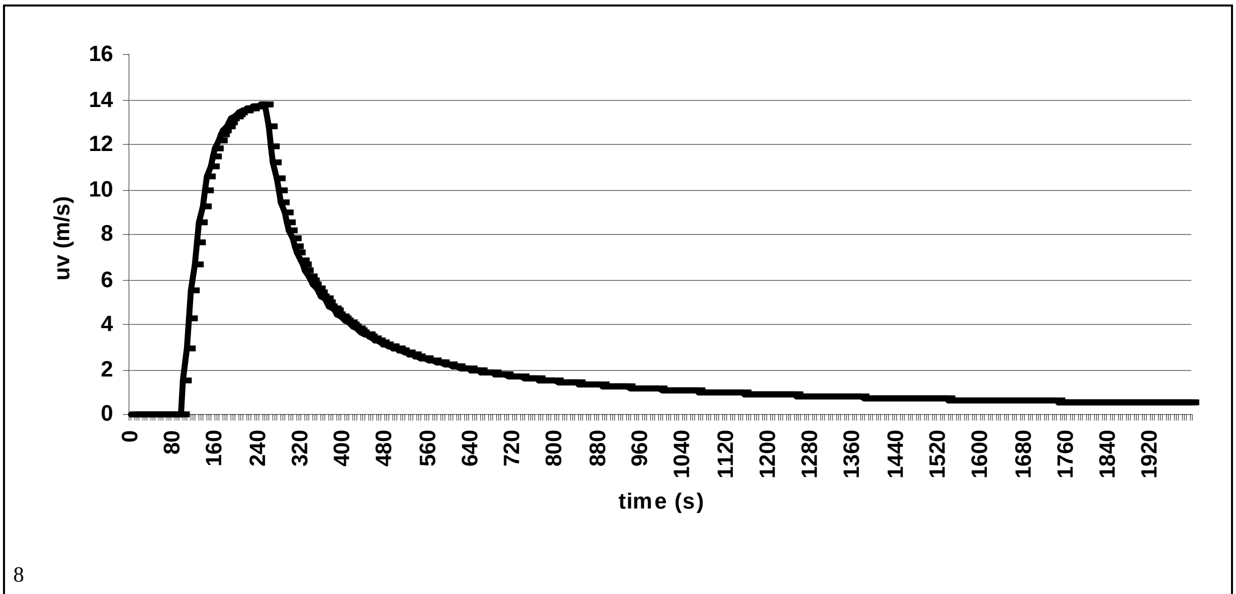


Figure 4: Distribution of velocity in the main tunnel VOMP (A *cw = 120m*m, train passes, pressure difference p1-p2 = 0 N/m*m)

Figure 5 shows the static changes in pressure to be expected at a travel velocity of 250 km/h in the Vomp tunnel provided that there are no effective pressure differences between the 2 portals and that the engine has just passed 3,000 m in the tunnel. In front of the engine a strong overpressure is produced, at its rear an under-pressure is produced. The total pressure difference is about 3,000 N/m³. In case that there are effective pressure differences, the final points of the diagram have different levels. However, this does not change anything in the principal pressure course.

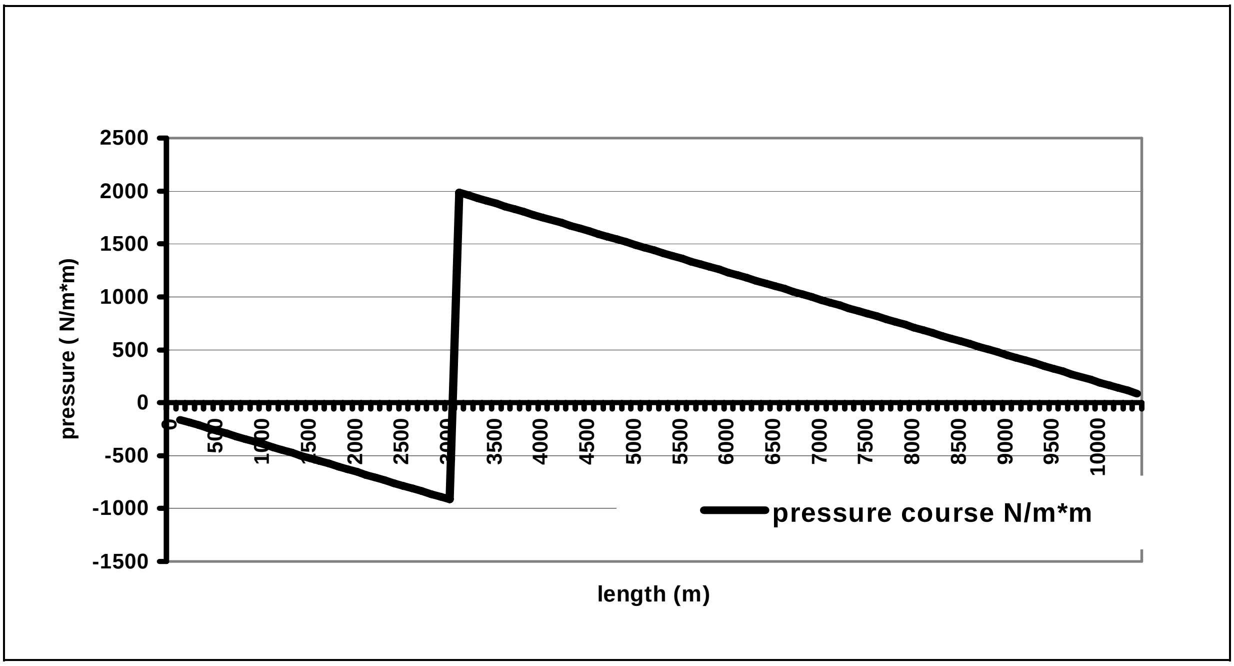


Figure 5: Pressure course in the main tunnel VOMP during passage of a train (the train has just passed 3,000 m in the main tunnel)

Figure 6 shows the march of the calculated longitudinal velocity uv in the tunnel when a train moves through the tunnel from the left at a speed of 250 km/h. After 150" the train leaves the tunnel through the right gate. One minute later an oncoming train enters the right gate, moves through the train at constant velocity and also reaches the left gate after 150". First the longitudinal velocity uv in the tunnel increases and then reaches its highest value i.e. ca. 13 m/s just before the train leaves the tunnel. After this the longitudinal velocity decreases slowly. However, it is reversed when the oncoming train enters from the opposite direction and then it gets accelerated to ca. 13 m/s. After the exit through the left gate the longitudinal velocity decreases slowly and gets back to zero provided that there is no thermic-meteorological pressure difference between the gates.

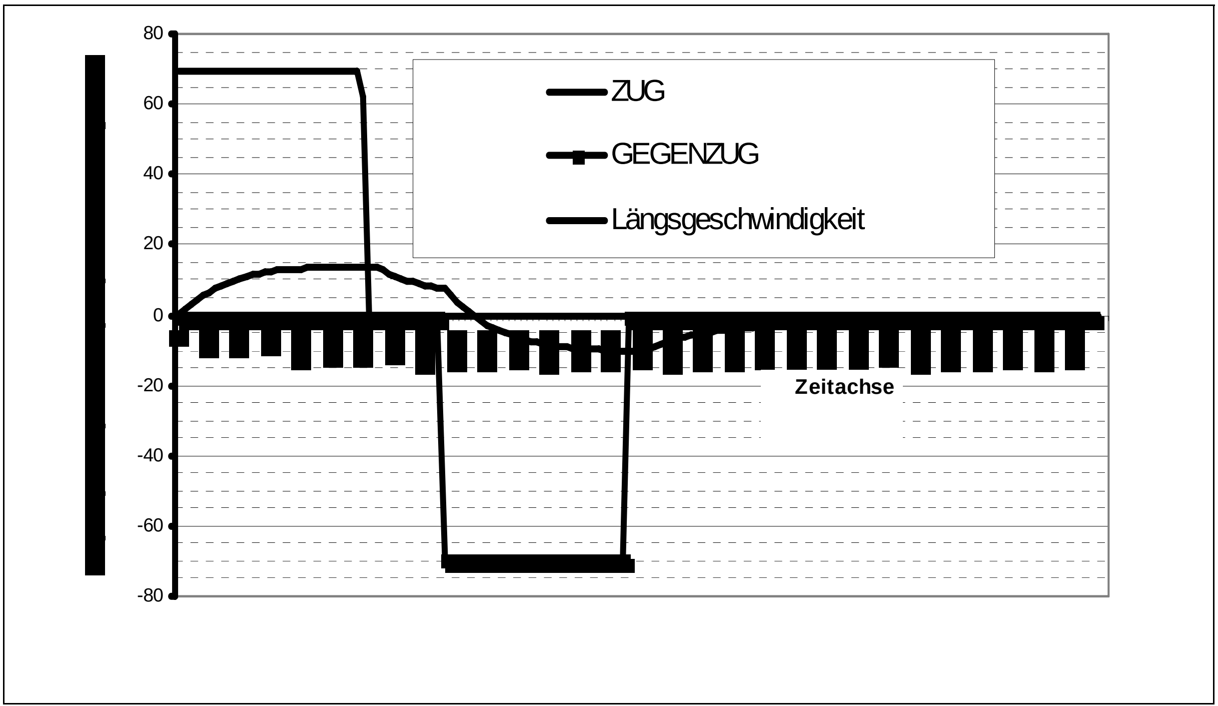


Figure 6: March of pressure with oncoming train

The situation is similar when a train at high speed enters the tunnel through the left portal (km 0) and then slows down. 15 seconds after this an oncoming train reaches the right portal and enters the tunnel. Only in the tunnel the emergency brake is applied. On account of the oncoming train the longitudinal flow is turned around. When the oncoming train has stopped there is a longitudinal velocity ranging from about 4 m/s to 5 m/s in the tunnel.

The approximate pressure ratios in the tunnel for a longitudinal velocity of –4.5 m/s are shown in Figure 7. You can see that there may be an overpressure of about 250 N/m² at the rear of the oncoming train.

It is true that this value is high. However, it cannot be excluded completely that there is an overpressure in the main tunnel – even if only for a short time – when the fire alarm is released. Therefore this overpressure was also taken into account as a possible inflow pressure from the main tunnel when designing the axial blowers.

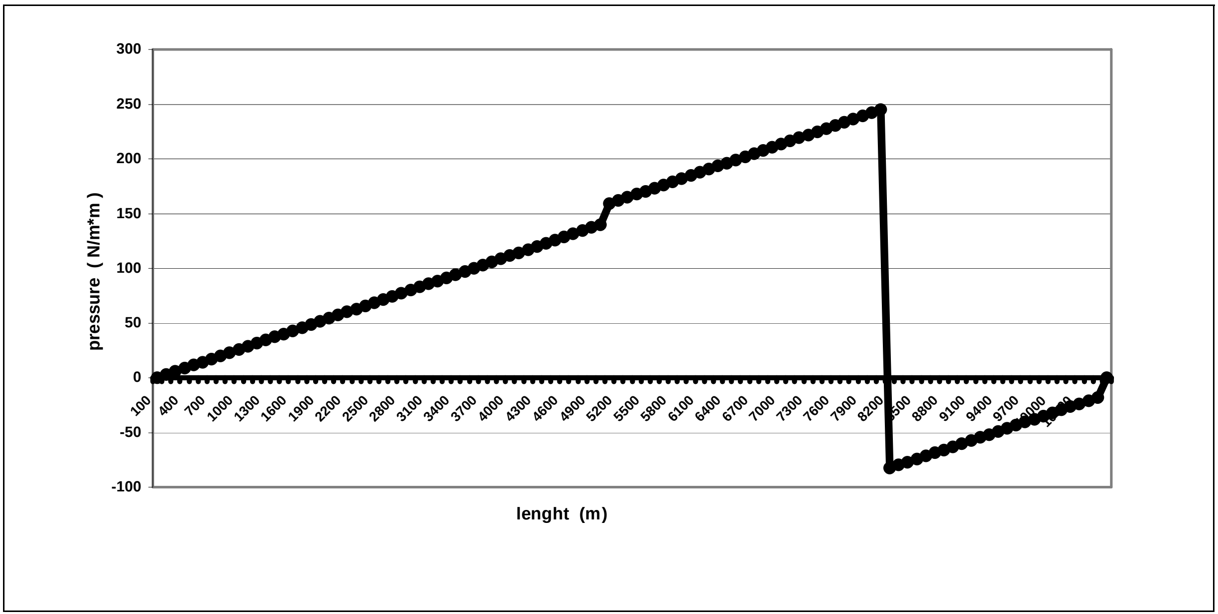


Figure 7: Pressure course in the main tunnel VOMP when a train stops at m 4900 and an oncoming train stops at m 8000 (A*cw = 120m*m, pressure difference p1-p2 = 0 N/m*m)

2.5. Dimensioning of blowers

The necessary pressure increase diff.p, which is to be supplied by the respective axial blower, mainly consists of 3 parts:

diff.p_{FD} (losses by friction, diversion etc.)
diff.p_{Th} (thermic influences)
diff.p_{TM} (influences by train movements in the main tunnel)

The efficiency of the blowers results from the equation:

$$P = V \,.\, \text{diff.}p_T \,/\, \eta_v \qquad 2.5.1$$

V is the required air volume and diff.pT the required total pressure increase.

$$\text{diff.}p_T = \text{diff.}p_{FD} + \text{diff.}p_{Th} + \text{diff.}p_{TM} \qquad 2.5.2$$

Normally, the efficiency of the blower total unit (BTU) is expected to be v 0.7

For stand-by reasons it is advantageous to use one or two blower sizes and to make the adjustments to the respective pressure ratios by different rotation speeds. As the blowers are only applied in an emergency, the reduction of efficiency does not play an important role

2.6. Design of aeration facilities

2.6.1. Life-saving wells and life-saving tunnels

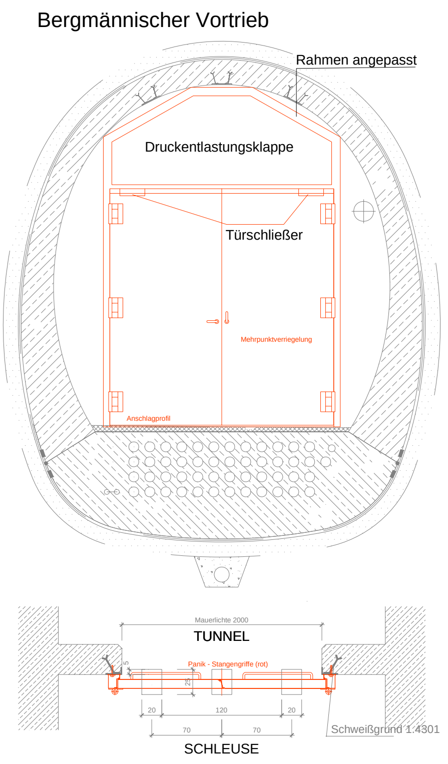
The demand to aerate the sluiceways in front of the safe areas can only be met when fresh air is blown into the sluice via an air feed pipe. However, when both gates are closed an overpressure is produced in the sluice area so that the blower gets into an unstable operation condition (“pumping”). Therefore there has to be a flap above the fire prevention gate on the tunnel side, which opens when a certain overpressure is reached in order to relieve the pressure. The inside pressure shall be set to about 75 PA because when opening a gate pressure is transformed into velocity so that there is already an air velocity of about 11 m/s at the mere opening. This inside pressure effects one sluice gate with a pressure of about 172 kN so that an electro-mechanical or equivalent opening facility is required in order to open the gate for an adolescent or a handicapped person.

Vehicle movements in the main tunnel with pressure and sucking forces of more than 2,000 kN/m² can destroy gates when the lock is non-secured so that an unlocked gate must cause a fault report. The blowers are mostly installed in the basins of the life-saving tunnels.

In passable life-saving tunnels the axial blowers are installed in niches or portals and the whole tunnel is put under pressure. Hereby, a “pumping” of the blower is also prevented by relief valves. The exact overpressure for the opening of the relief valve depends on the respective access tunnel and can only be defined during test operation.

2.6.2. Sluice doors and sluice gates; Pressure relief

According to ÖBFV-RL A –12 both slice gates have to be fire resistant, T 90. It must be possible to open them into escape direction and they must be protected against unintended slam shut.



Their construction must be in a way that it can be charged with a load of ± 4000 N.

As the number of sluice gates is an important cost factor, it is intended to produce them in series and make a door stop on one side of the openings so that constructional deviations of the light opening do not influence the production.

Just like the doors the pressure relief flaps also have to be made according to the fire protection regulations because a failure of the aeration system may always be possible. They have to be kept shut except in an emergency because otherwise the smooth operation of the railroad traffic might get interrupted.

2.6.3. Air feed duct

In life-saving wells air feed ducts on the pit wall of the downward tunnel lead into the sluices and then join the air pipelines planned on the sluice ceiling. Their cross-section is designed to be about 1,50 m² in order to keep the resistance and especially the noise level within limits. Sluices with a cross-section 2,50 / 2,50 m require an air volume of 18,80 m³ / h. In order to avoid fumigating of the escape routes in the stairways, a ventilation flap built in after the inner sluiceway gates shall provide for aeration in escape direction when fume is detected in the sluiceway itself.

In life-saving tunnels the tunnels to the sluiceways function as air feed ducts. From the tunnels the air enters the sluiceways via adjustable flaps. Even here, the pressure is actually relieved via the valve above the sluice gate on the side of the main tunnel.

2.6.4. Control and supervision of blowers

A most decisive aspect for keeping escape routes free from fumes is the punctual start of the blowers in order to produce an overpressure in the sluiceways of the life-saving wells and life-saving tunnels. If the blowers are only switched on when the first sluice gate is opened, a thickening with smoke of the escape routes cannot be excluded because the acceleration of air masses takes time.

Therefore, it is intended to immediately switch on the blowers in the area of an accident via the central monitoring system in case an emergency is reported. If this does not happen, the blower gets automatically switched on when the panic handle of the outer sluiceway gate is opened whereupon the emergency gets reported.

3. SUMMARY

Beside the by-pass of Innsbruck the design and the execution of the Inntal line marks an essential part of the Brenner basis project.

The basics for the design, especially concerning the safety facilities for self-rescue – safe areas, sluiceways and aeration of sluiceways just as lifting systems for people – could partly not be defined properly due to missing concrete directives.

The design process laid the basis for further building projects.

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DESIGN OF THE INCIDENT VENTILATION FOR THE VIENNA SUBWAY

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ABSTRACT

The Vienna subway system was opened in 1976. Since that time requirements have changed and due to some accidents in other subway systems new concepts for the passenger safety have been designed. Lines are extended new stations are under construction and new railcars have been ordered. At the beginning the focus of the ventilation design was to fit comfort criterions (splash reduction), heat control and air exchange in the stations to reach an acceptable air quality. A design for train fire aspects have been no issue neither on the amount of air extraction nor on the heat resistance of the equipment.
The design of the new stations take all these aspects into account, the concepts of the ventilation system have been changed. Existing stations are adapted little by little, as far as the boundary conditions of the structure admit changes.
Before opening a new station smoke tests are executed to validate the ventilation layout and consequently guarantee smoke free escape ways.

Key words: Ventilation design, ventilation simulation, ventilation control, ventilation test

1. VIENNA´S SUBWAY SYSTEM

The Vienna subway system is developed in several extension phases. Up to now 2 phases are finished (phase 1 from 1969 – 1982, phase 2 from 1982 – 2000), currently phase 3 (2000 – 2010) is running. Phase 1 includes the lines U1, U2 and U4 with a total length of 32 km.

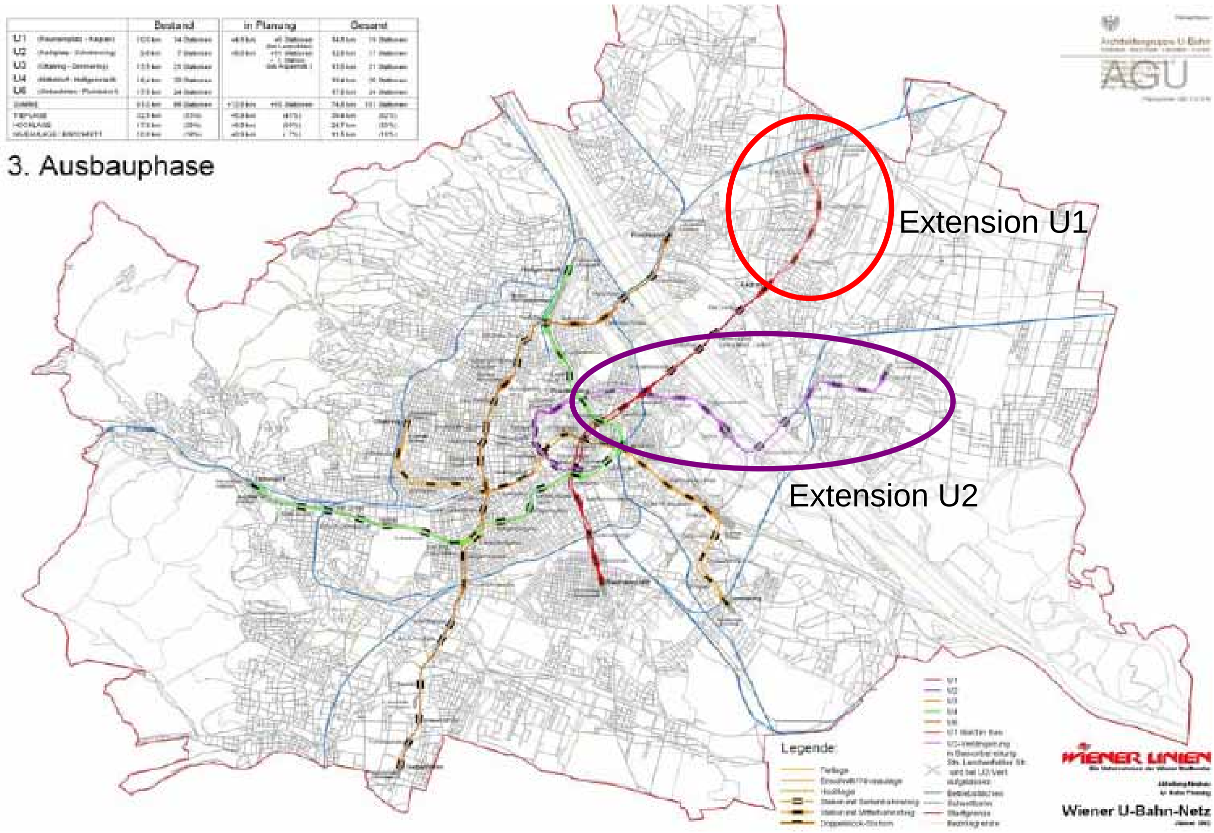


Fig. 1: Overview of the Vienna subway system (phase 3)

During phase 2 the lines U3 and U6 have been constructed and extended the system length up to 61 km. The actual phase 3 is the extension of the lines U1 and U2, the system length will rise up to 75 km.

At present 85 stations are in operation, The actual extension of the lines 1 and 2 will enhance the number of stations to 97.

1.1. Historical development

The first ventilation concept for the stations of the line U1 constructed during the years 1978 till 1982 had extraction buildings between two adjacent stations. Thus smoke was sucked into the tunnel, away from the station. Fresh air could enter the station through the exits and should guarantee a smoke free escape for the passenger.

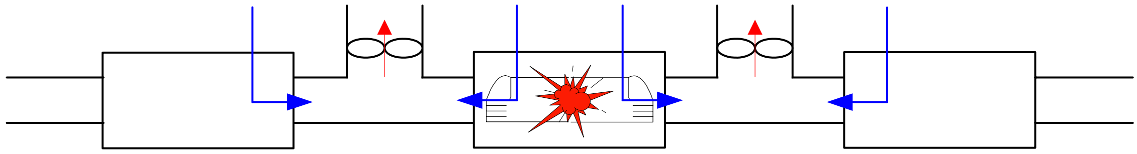


Fig. 2: First ventilation concept in case of fire (1978 –1982)

The layout of the ventilation concept was done in principal for keeping the air quality (temperature, humidity) inside the station within the given boundaries. So the main operation task was to push fresh air into the tunnel system. Fans have been installed with two speeds with a capacity of 20 to 40 m³/s, with no specification on temperature resistance or emergency power supply. In case of a fire, the fans have been reversed for extraction and operated under full load. As the ventilation buildings have been 300 m away from the station, the smoke extraction efficiency was not ideal. Tests done by us of smoke shells showed that escape ways could be kept smoke free, but smoke in the middle of the station was not sucked out.
This experience changed the ventilation concept for the next projects. Ventilation buildings have been located close to the stations, the air volume was raised to 50 m³/s.

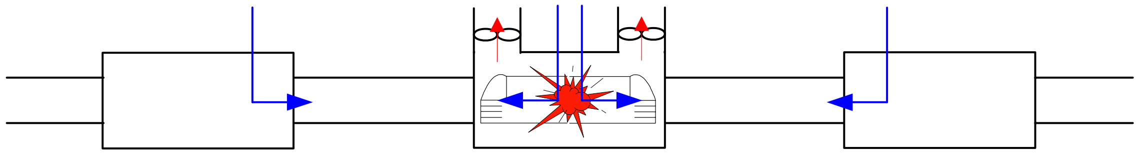


Fig. 3: Ventilation concept till 1991

At this time too fans have been installed with a temperature resistance of 250 °C for a duration of 90 minutes, based on authority demands.
Still the concept was not ideal why the extraction openings have been located in the middle of the stations. So the extraction volume of 50 m³/s could be used for each station, the volume of air sucked through the tunnels was reduced.

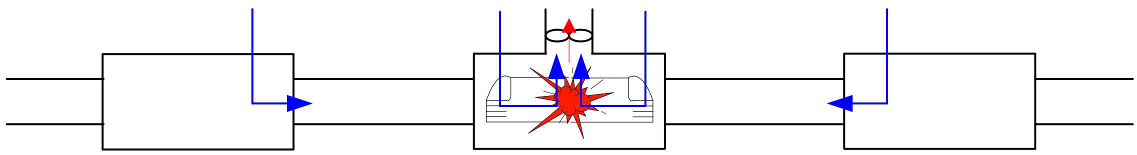


Fig. 4: Ventilation concept with extraction in the middle of the station

Fans have been equipped with frequency converters and emergency power supply. In addition to that smoke barriers have been installed inside the stations at the escape stairs entrance.
In the year 1996 the air volume was raised up to 100 m³/s which brought almost ideal results during the smoke test. But still air has been sucked out of the tunnel tubes, which leads to the installation of jet fans inside the escape ways. Those should reduce the resistance of the escape ways, therefore kept the power consumption of the fans on an reasonable amount. Besides the safety aspect was raised, as the brake down of an exhaust fans could not fail the whole concept.

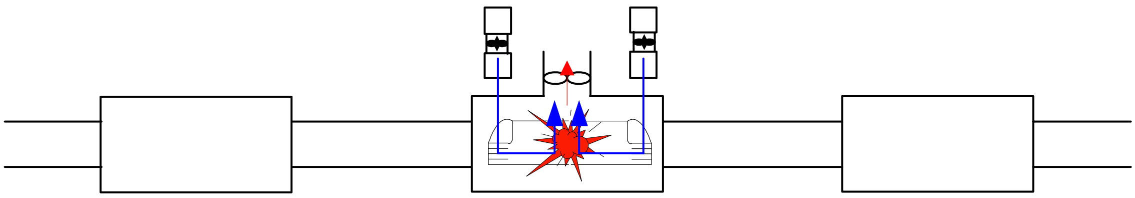


Fig. 5: Ventilation concept with additional jet fans

1.2. Rolling stock

On the Vienna subway network two different types of stocks are operated, the U (117 units) and the V stock (.
The U stock, are coupled in units of two that cannot be operated alone. Aluminium was used for the car body, which reduced the weight by about 50% compared to a steel body.

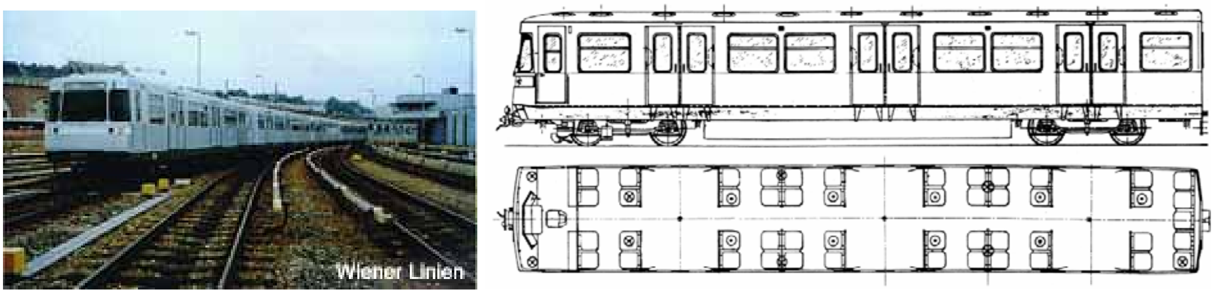


Fig. 6: U stock

When additional trains were needed for the opening of line U3 in 1991, the modified U11 stock, was created. As of December 1999, there are 117 units (234 cars) of U1/U11 stock in service on the Vienna metro.
From 1991 onwards, U stock was slightly modified to meet new safety regulations; at the same time the plastic seats were replaced with the fire-proof cloth ones used in U11 stock.
Currently, trains from the second batch of U stock (numbers 2063/3063-2136/3136) are being fitted with new AC motors and new electronic equipment as part of a refurbishment programme. The refurbished units are referred to as U2 stock and are stationed at Erdberg depot for use on line U3.
The standard formation consists of 3 units or 6 cars; only generic trains are formed: U-U-U or U11-U11-U11. Only U2 stock units are often coupled with U stock. After 8 pm and on Sundays 4-car trains are used: U-U or U11-U11.
In the year 2001 the heat release rate of the U and V stock has been calculated by the Technical University of Vienna. The result for the U stock is shown in figure 7.

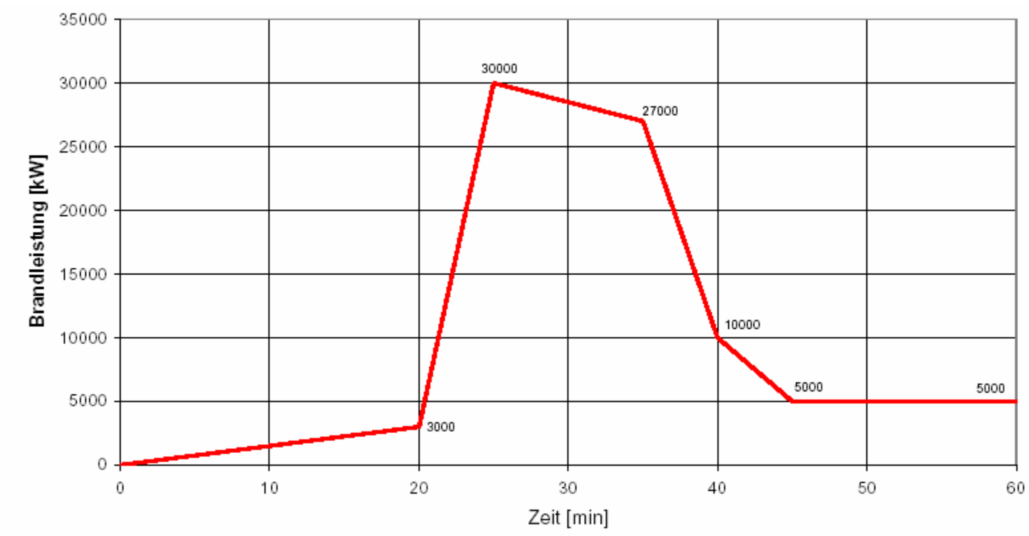


Fig. 7: Heat release rate U stock

The V stock consists of six interlinked coaches, two driving trailers and four non-driving motor cars. At present one prototype is operated at the U3 line, 25 trains are already ordered.

Fig. 8: V stock

2. DESIGN CRITERION

The design of the incident ventilation system should comply with the following requirements:

- The escape ways should be free of smoke for a duration of at least 30 minutes, to guarantee a self rescue of the passengers and the access of the rescue services
- Smoke have to be exhaust close to the fire location to minimize the station area filled with smoke, especially the platform
- The temperature resistance of the exhaust fans is at least 250 °C, depending on the location it could raise to 400 °C for a duration of 90 minutes
- Heat release rate of 24 MW (80 % convective part of 30 MW)
- Minimum fresh air velocity in the cross section of the escape ways at least 2.2 m/s
- The smoke free layer at the platform and the escape ways has to be at least 2.2 m high
- The smoke movement is only allowed half of the platform length

3. ACTUAL INCIDENT CONCEPT

Based upon the heat release calculations the old stations of the U2 line have been adapted. The stations on the extension of lines U1 and U2 got a new concept, using jet fans in the entrances and in the tunnels. The layout of the jet fans inside the adjacent tunnels is done in a way that the air speed is almost zero. Herewith the air flows in the station only via the entrances. The exhaust volume is calculated to reduce the exhaust temperature for the design criterion of the fans, which leads to volumes of about 100 m³/s.

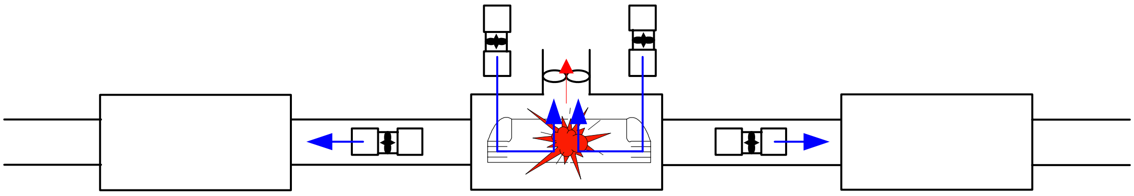


Fig. 9: Ventilation concept with additional jet fans

As some of the new stations are build in cut and cover sections, they get high halls. For these types of station smoke management is used for the incident ventilation. The building volume is used for smoke storage, and at the top of the hall the smoke is sucked out via a duct with distributed openings.
In some of the new stations exhaust openings in the middle of the station could not be constructed. So they got a suspended ceiling with dampers, similar to road tunnels. For the extraction on both sides of the duct fans are installed (see figure 10)

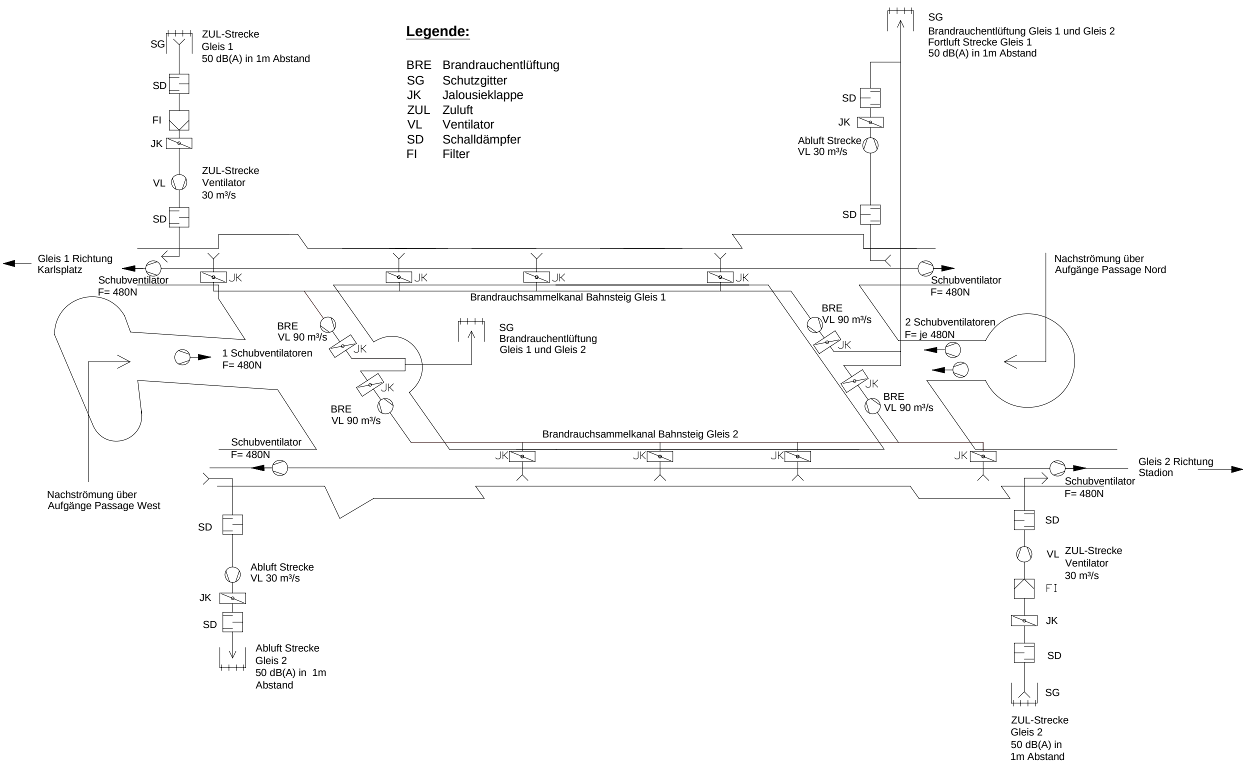


Fig. 10: Flow scheme for the U2 station Schottenring

The installation of the dampers is just above the rail axis. Therefore the volume of air extracted and the air temperature will be very high, which leads to an exhaust volume of 180 m³/s on each track.

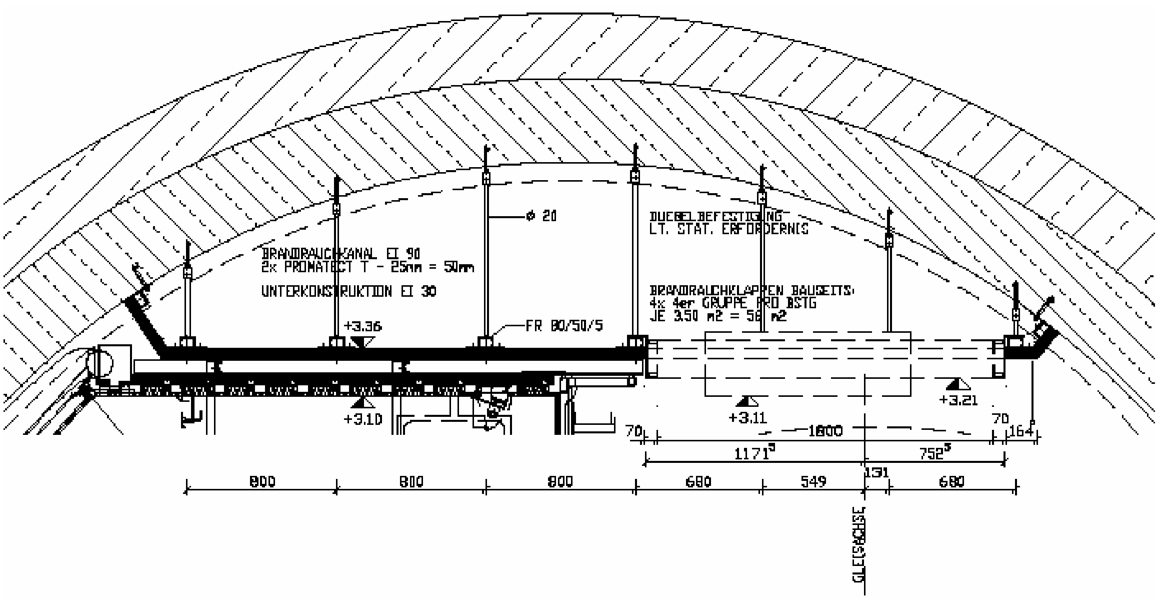


Fig. 11: Section through the suspended ceiling

In case of an incident inside the station the closest damper to the fire location will be opened. The location of the fire is detected by a linear fire detection system.
In case of an incident the safety concept pretend that the train have to stop in stations or outside tunnels. The stock drivers or the station supervision will inform the network control station. The alert of the rescue services, the shut down of the third rail and the start of the ventilation system is also handled by the network control station. Passengers are informed by loudspeakers, elevators are automatically stopped and operated to rescue levels the doors will be kept open.

4. DESIGN VERIFICATION

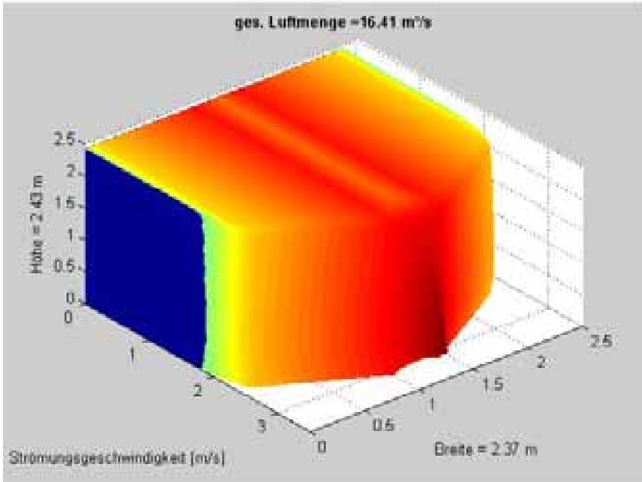
Before opening a station or after an existing station has been reconstructed, a smoke test has to be performed. During these tests the air velocities in the entrances have to be recorded. Therefore online measuring of all entrances has to be done at the same time.

Fig. 12: Measurement arrangement entrance (left) tunnel (right)

Anemometers are used in each entrance and in the tunnel tubes. To get the average air velocity inside the cross section, a grid measurement is done to calibrate the arrangement.

Fig. 13: Grid measurement results

	0.10	1.00	1.20	1.40	2.27	
2.33	2.5	3.2	3.1	3.2	2.5	H = 2.43
1.00	2.5	3.2	4.0	3.2	2.5	
0.50	2.5	3.2	3.5	3.2	2.5	
0.10	2.5	3.2	3.2	3.2	2.5	
	B = 2.37					



The measurement results are evaluated using the trapezoid formula.

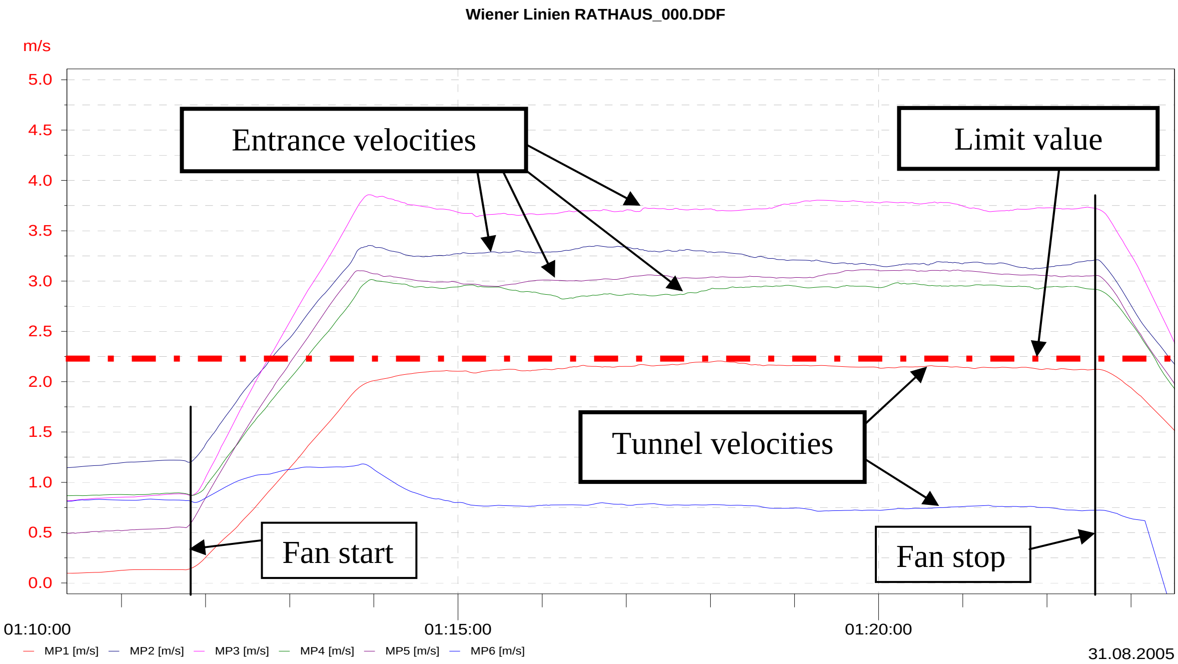


Fig. 14: Measurement record

5. CONCLUSION

The new layout, the additional rescue guidelines and the tests done guarantee for a state of the art design of the new stations for the Vienna subway system. Constant inspection of the routines and simple actions are the bases for a safe operation.

IMPROVING ROAD AND TUNNEL SAFETY VIA INCIDENT MANAGEMENT: IMPLEMENTING A VIDEO IMAGE PROCESSING SYSTEM

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ABSTRACT

Today, increasing traffic volume and complexity has created a need for more optimised & improved ITS technology, highly automatic incident management systems in particular.

Facts & figures such as ‘more than 200.000 people killed each year in traffic’, ‘At least 10 people have been killed and several others injured by a fire in the Gotthard Tunnel’, … and also the need for more security result in more investments into safer roads and better control of the traffic on highways in general. Traffic managers are looking for effective incident management because this can save countless commuter hours, hectolitres of fuel, and thousands of euros. Effective incident management completely depends on fast incident detection and fast incident verification. While video detection handles both traffic data collection and automatic incident detection, its incident detection shows a high detection rate, a short time to detect, a fast incident verification and a low false alarm rate. These characteristics make video extremely useful for reaching incident management goals such as fast & effective intervention or secondary incident prevention.

This paper discusses the wide range of capabilities and some of the limitations of video image processing for incident detection as Traficon have experienced it over the past 20 years. A basic methodology will be discussed highlighting the key parameters for implementing a video image processing system. This paper also will give you a head start on what video detection, as ITS technology, will bring in the next decade. Detailed case studies of AID systems in the tunnels of Slovenia, Austria, Germany serve as an illustration of these features.

INTRODUCTION

Traffic Managers worldwide are faced with an increasing demand for state-of-the-art intelligent traffic systems: both for statistics purposes as for safety issues. Fast-developing urban regions have a need for information on traffic streams, to take well-founded decisions regarding new road infrastructure and changes to the existing infrastructure. Traffic congestion and secondary accidents are now costing thousands of lives and billions of euros every year. Therefore, traffic managers need an effective incident management system. The **time delay to detect and verify an incident** seems to be the crucial factor for effective incident management. Every minute lost heightens the risk of having another accident and drastically increases the time to clear the accident.
Traditionally, loops and CCTV cameras provide ample information to direct traffic flows and assemble statistics. But their information is limited, and increasing traffic volume and complexity has created a need for more optimised systems; highly automatic incident management systems in particular.

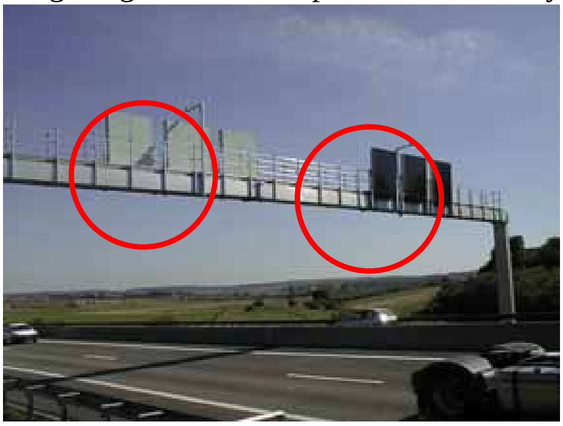
We believe that improved ITS technology such as incident detection systems could lead to a significant reduction in both frequency and cost of accidents. Some observations gathered from several studies support this point of view. First, between 20% and 30% of all accidents on freeways are caused by preceding (primary) incidents. Secondly, far more than 50% of the secondary accidents occur within 10 min of the first incident. In many cases, they are caused by minor primary accidents and could have been avoided if unprepared approaching drivers could be warned in time. Third, studies show that more vehicle hours of delay result from traffic jams caused by accidents rather than from regular daily traffic jams. While video detection handles both traffic data collection and automatic incident detection, its incident detection shows a high detection rate, a short time to detect, a fast incident verification and a low false alarm rate. These characteristics make video extremely useful for reaching incident management goals such as fast & effective intervention or secondary incident prevention.

Basic functions of incident management

The basic functions of Advanced Transportation Management Systems (ATMS) are traffic monitoring, incident detection, incident verification, driver information and incident clearing. Traffic monitoring, setting appropriate speeds and ramp metering can keep the traffic rolling at a level close to or even above the maximum capacity. This will avoid or delay the recurring congestion and its potential secondary effects. The time needed to detect an incident is of utmost importance. It is only starting from this moment that other activities such as incident verification, driver information, alternative routings and removal activities can start. Incident verification is necessary to decide upon the appropriate corrective actions and on the ways to inform the driver. The fast and efficient information of drivers approaching an accident zone will decrease the number of secondary accidents and also decrease the traffic load in this zone. This can be done by VMS panels, radio, Internet, etc. Finally the necessary manpower and material must be available on the spot as soon as possible to clear the accident and to restore normal flow. These five factors are the key elements for efficient incident handling.

Traffic monitoring, Prevention (1)

By setting appropriate speeds and a good controlled ramp metering, one can keep the traffic flow at a level close to or even above the maximum capacity. This will avoid or delay the recurring congestion and its potential secondary effects.




Figures 1 & 2: The installation on the Luxembourg highways with video traffic monitoring connected with Variable Message Signs every 1.5 km has proven to be very effective.

Incident detection, time to detect (2)

Incident detection can be seen as a crucial component of the overall incident management process. It is clear that an incident has to be detected and verified before any other incident management actions can be taken (such as incident verification, driver information, alternative routings and removal activities). To guarantee the success of any incident management process, it is critical that incidents are detected as soon as they have occurred. Timely and accurate incident management becomes more important when we consider the negative effects of not clearing an incident as quickly as possible. A delay in detecting an incident can cause long queues and traffic congestion, which, in turn, are the primary cause of secondary accidents.

Incident verification (3)

When an incident is detected, it is necessary to decide upon the appropriate corrective actions and on the ways to inform the driver. The use of video cameras is normally the fastest way to see what must be done. One can use a specific CCTV system combined with Automatic Incident Detection using the video of these cameras.

Driver information (4)

The fast and efficient information that drivers approaching an accident zone receive, will decrease the number of secondary accidents and also decrease the traffic load in this zone. This can be done by VMS panels, radio, Internet, etc.

Incident clearing (5)

Finally the necessary manpower and material must be available on the spot as soon as possible to clear the accident and to restore normal flow.

These five factors are the key elements for efficient incident handling. **Video detection** is by far the best method to perform the three first tasks so that the full incident management can be executed at best.

WIDE AREA VIDEO CONTROL: AUTOMATIC INCIDENT DETECTION

Video detection has now been available commercially for several years and is gaining acceptance as a more effective technology than conventional inductive loop-based technology. Why?

BASIC FACTS

Incident detection **using video image processing** has several distinct advantages over inductive loop-based technology (Blosseville, Morin, and Locegnies 1993). Inductive loops only are capable of gathering traffic flow data at a point. Video image technology can provide this as well as information about traffic flow at a higher level. It can measure travel times, average speed, and detect stalled or stopped vehicles within the detection zone. It has been successfully used to accurately detect shoulder incidents (Blosseville, Morin, Locegnies 1993).

Wide area video detection for direct automatic incident detection is based on real time analysis of the images of cameras that cover the whole road that has to be monitored. This analysis will detect all abnormalities of the traffic such as stopped vehicles, inverse direction drivers, slow vehicles, fallen objects, traffic jams, etc. An average installation will have cameras installed along the road at distances between 250 and 400m, for tunnels best results are obtained with distances between 70 and 100m. Since there is full coverage, all incidents can be verified immediately. This detection method is mostly used in tunnels, on bridges and on roads with heavy traffic and regular traffic jams and accidents. Figure 3 illustrates a real life, video detection example.

Figure 3: Wide Area Video Detection for Direct Automatic Incident Detection.

When direct video detection is not possible due to budgetary restrictions, a good compromise is to use indirect incident detection based on wide area zone monitoring. The indirect approach covers zones up to 100 metres. Cameras are mounted every 500 to 1.000 metres. The parameters monitored are the average space speed, the variations of these speeds and the zone occupancy. These data can be used to calculate the expected travel time and its evolution. Tests performed with systems based on the space speed show a fast detection of incidents between cameras (less than 2 minutes) and a high detection rate (more than 90%). Typical installations have cameras at a distance of 500 to 1.000 metres and visually cover most of the highway that has to be monitored. An important side feature of this detection method is the good performance of the time to destination or travel time measurement both in normal traffic and congestion situations. Indirect video incident detection can also be used as a stand-alone installation that will directly activate VMS panels to warn the drivers of upcoming traffic jams. This method already showed very good results for mobile installations that have to guard road works informing the drivers in real time about the situation of the road ahead (See figure 8).
Another advantage of this method is that it can be combined with CCTV systems with pan-tilt and zoom that have a good homing system. The automatic incident detection will detect the incident and automatically show the image of the camera concerned to the operator, who can then verify the incident and start the appropriate actions.

USE OF CLOSED CIRCUIT TELEVISION CAMERAS (CCTV)

The NTCIP proposed standard for center-to-center communication describes the function of cameras as a help for the traffic management system

- Verify the existence of traffic congestion reports
- Determine what assistance may be needed by the incident
- Monitor the progress of incidents, construction and special events
- Determine when the residual congestion from an incident is cleared
- Provide visual images to the public as to the state of the highway
- Determine what type of Emergency Services are needed to be dispatched

All these functions can be combined with an **Automatic Incident Detection** system. This will result in an integrated video traffic monitoring system with optimal results for safety.

WHAT IS THE CRUCIAL FACTOR FOR EFFECTIVE INCIDENT MANAGEMENT?

An effective incident management completely depends on **fast incident detection and fast incident verification**! Every minute lost heightens the risk of having another accident and drastically increases the time to clear the accident.

Classic incident detection systems based on loop data and incident detection algorithms have normally a time to detect of 5 minutes or more with a detection rate of about 85%. After this detection one still has to verify what has happened. These delays will greatly influence the impact of the incident. Out of incident simulation models, we can see that the impact of detection and verification time of incidents during heavy traffic has a strong influence on the amount of vehicles involved and the time to clear the traffic jam. The following calculations and accompanying figures are partly based on data from the ARRB Research Report 327 'Effective Incident Detection and Management on Freeways' by Chung, E. and Rosalion, N. (1999).

Table 1: Summary of the waiting and clearing time of an incident with or without a fast incident detection & verification system

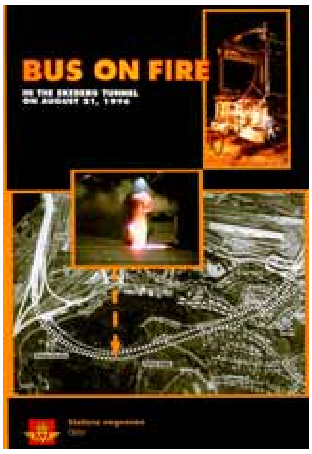
Traffic restart at	**Without fast system (16min)**		**With fast system (2 min)**	
	Clearing time	Waiting time	Clearing time	Waiting time
100% of full cap.	**77 min** to clear	**1505** hours	**34 min** to clear	**289** hours
90% of full cap.	**93 min** to clear	**1676** hours	**40.5 min** to clear	**331** hours

This means that in this example without looking at shock waves and other effects, the direct impact of 14 minutes delay in verifying will multiply the number of involved vehicles by factor 4 and thus also multiply by 4 the risk of secondary accidents. The economic impact (total time lost due to the accident) is even five times larger. All these effects will grow practically exponentially if the road is nearing saturation when the accident occurs.

Figure 4: Incident Clearance with/without a fast incident detection & verification system.

Video detection is a direct wide area detection method. ‘Direct’ means that it is not a question of calculating if an incident could have occurred, but a direct detection on the image of any abnormality in the traffic situation. As such, the VIP/I or Traficon’s incident detection module is able to detect all major incidents within seconds: stopped vehicles, wrong way drivers, queues, slow moving vehicles, fallen objects, … This short time to detect and fast incident verification can seriously reduce the impact of the incident and prevent secondary accidents.

An example of how an AID system helped preventing a major disaster is the bus accident in the Ekeberg tunnel (Oslo, Norway). In 1995, Traficon equipped this tunnel with 63 cameras. The Ekeberg Tunnel is about 1500 metres long, has three lanes in each of the two tubes, and the amount of traffic on a weekday is 76.000 vehicles a day. Although it is fairly unusual for a bus to catch fire inside a tunnel, this happened in the Ekeberg Tunnel in August 1996. Because the driver had difficulty opening the front door, as the emergency exit did not function, he was not able to get out of the bus immediately. Luckily the video based incident detection system had already given a ‘stopped vehicle’ alarm three minutes before the bus driver was able to activate the local push button alarm himself. The tunnel was already closed and the alarm lights were flashing informing the drivers concerning this incident.



Figures 5 & 6: The video based incident detection system gave the alarm 3 minutes before the bus driver had activated the local push button alarm. The tunnel was already closed, the alarm lights were flashing and no other cars were involved.

Another example is the **Tunnel de Foix** in France

Figure 7: Since the beginning of February 2001, the tunnel of Foix (Ariège - France) is open. With its 2160 metres it constitutes one of the longest tunnels on the French national road network. Right from the beginning, at the time of the risk survey, the commission of security asked for the installation of an incident detection system because of the passage of vehicles transporting dangerous goods.

OTHER VIDEO IMAGE PROCESSING FUNCTIONS

Besides monitoring stopped vehicles, there are lots of other events that should be monitored and informed to the traffic managers.

1. Queue monitoring

The early detection of queues is very important because this will allow the traffic manager to inform the road user of upcoming traffic jams in time, this to prevent queue tail accidents.

2. Road works monitoring

Road works can lead to very dangerous situations because the traffic jams they generate are not expected by regular road users, as a consequence resulting in many accidents.
Using video detection and VMS panels that can be mounted on a temporary basis have proven to lower the accident rate by more than 70 %!

Figure 8: Road works along the E313, Belgium.

3. Inverse direction

Another important application that can be performed by video is the monitoring of roads and tunnels for inverse direction. This application is especially useful at the entrances and exits of highways.

4. Fallen objects

Wide area automatic video monitoring allows the detection of fallen objects (e.g. something that comes down from a trailer), this information can be used to warn the driver in the area and to program the removal within the shortest time possible.

5. Pedestrians

Recently the city of Los Angeles installed 35 Smart pedestrian warnings based on video detection.
The system was developed by the Los Angeles Department of Transportation and tested over more than one year. It uses a video camera to detect pedestrians entering the crosswalk. A controller then activates a flashing light on a mast arm above the crossing. The effect was that 72 % of the warned motorists stopped when the light flashed, whereas without the system only 25% did. In L.A. only 7% of the incidents involve pedestrians but they account for 40% of the traffic fatalities.

Figure 9: In L.A., a video camera is used to detect pedestrians crossing the street. Approaching motorists are then warned by a flashing light.

6. Fire and smoke

It is also possible to detect other effects of incidents such as smoke and fire. This approach is mainly used inside tunnels. The main problems with this kind of measurements are that they also need full coverage, they nearly always come with an important delay and that they are subject to a higher degree of false alarms. The following table illustrates how long it takes before smoke or flames become visible after a vehicle has stopped in a tunnel. It is clear that if the stopped vehicle can be directly detected in 12 seconds and verified in a few seconds, this will have superior results.

Evolution of Fires of Vehicles in and around Tunnels:

Table 2: Evolution of Fires of Vehicles in and around Tunnels (Data are from Escota, France).

Type of vehicle	Stopped Vehicle	Visible Smoke	First Visible Flames	Global Fire
Car	0 min	3 min	5 min	8 min
Van	0 min	5 min	8 min	15 min
Lorries engine fire (2%)	0 min	Fast	fast	fast
Lorries Brake fire (98%)	0 min	10 min	12 min	20 min

Even if most fire and smoke is detected first by detecting the stopped vehicle it is also possible to detect direct smoke and even flames using video detection.

7. Stopping vehicles or left objects (Homeland Security)

The immediate detection and monitoring of vehicles stopping in suspect zones such as bridges can be a major source of information for detecting dangerous situations, similar for the detection of fallen or left objects on roads and bridges.

IMPORTANT CONSIDERATIONS

Detection rate

The detection rate and the time to detect are generally considered the most important factors in an incident detection system. But besides these it is very important to consider also the false detections and the overall life reliability of the system.

False detections

The number of false detections must be limited in order to avoid that the system will become fully useless. Many people still use the false detection rate (number of false detections over the number of real detections). This factor is dependent on the number of real incidents.
We feel a better definition for an incident detection system should be based on the number of false detections per Km lane per day. This can also be split up over different types of events one wants to be informed of.

False detection cost

Using video detection an eventual false detection can be cleared instantly by the informed traffic manager. This is a major saving of costs over other systems where one either has to go on site or has to use a pan and tilt camera to search, locate and verify the incident.

Reliability

In general all of the road detection systems have a much higher reliability than in road systems, they normally have also a much shorter time to repair.
Some customers have also preferred to install fully **redundant systems** such as the Öresund tunnel between Sweden and Denmark.
In this tunnel the cameras are at a distance of 60 meter when testing the system we found out that all stopped vehicles were detected by 3 cameras. Since they had also split up the system between pair and impair cameras, this resulted in a system with nearly 100% on time

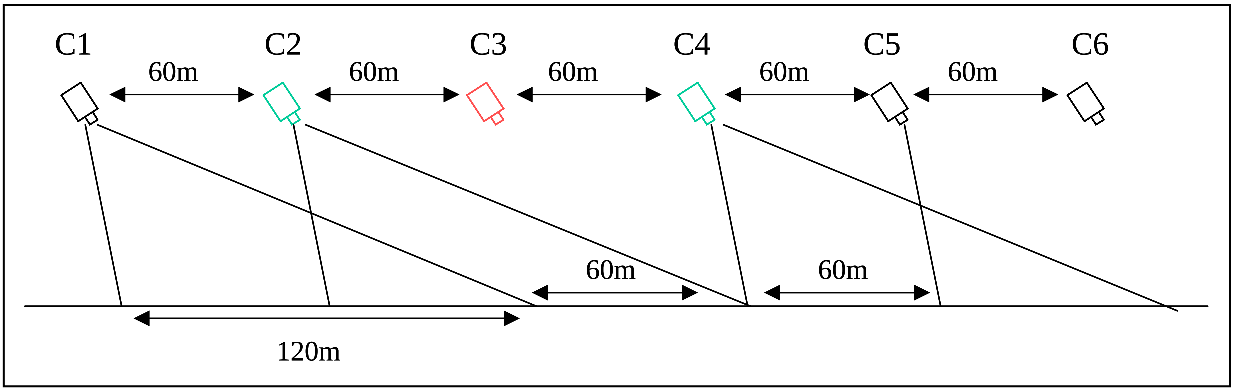


Figure 10: Fully redundant system in the Öresund Tunnel

CONCLUSIONS

The actual state of the art makes it now possible to have fully automatic video based incident detection covering both the main road and the hard shoulder. The direct incident detection systems based on video images cover the entire highway and will provide the fastest way (10 seconds) to detect the incidents. They show the highest detection rate with the lowest false alarm rate and also the lowest false alarm cost.
Available data support our claim that using video signals for detecting traffic data and incidents is the most reliable and cost-effective solution currently available. A full coverage, video incident detection system on a busy highway has an economic payback period of less than 6 months, this even without taking into account the number of lives saved or the ecological impact.

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VITUS: VIDEO IMAGE ANALYSIS FOR TUNNEL SAFETY

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ABSTRACT

This paper summarises work undertaken on the VITUS project. The main aim of VITUS project is to build and implement a prototype for an automatic video image analysis system in order to increase safety in tunnel roads. A feasibility study about video image analysis in tunnels was carried out, and the implementation of the prototype and evaluation of the system is work on going. Experiments on real sequences using innovative image processing algorithms display promising results.

Keywords: Tunnel safety, video image analysis and vision enhancement systems, traffic surveillance, traffic control systems, real world applications.

1. INTRODUCTION

This paper describes work undertaken on the VITUS (**V**ideo **I**mage analysis for **TU**nnel **S**afety) project. The main aim of this project is to build and implement a prototype for an automatic video image analysis system in order to increase safety in tunnel roads.

Tunnels play a crucial role in the importance of the transport sector for Europe’s economy. Austria is one of the leading countries in Europe when it comes to the total number and length of street and motorways tunnels. Controlling traffic tunnels is a complex task which imposes serious requirements. When an incident is detected by the tunnel operator, the tunnel operator has to proceed to the incident verification including the notification to the proper personal (e.g. roadway authorities, hospital, police). Examples of incident verification are crashes between vehicles, lost cargo, objects on the road, and fire among many others. Thus, it is required that operators pay careful attention during the monitoring task, and tunnel monitoring has to be resolved by them within a very tight timeframe.
Besides, the tunnel control centre has to coordinate the incident detection and verification, utilization of emergency response actors and on-scene actions, traffic management, and evacuation. As consequence, tunnel operators have a high degree of responsibility on tunnel monitoring and emergency management, and effective incident management completely depends on fast incident detection and fast incident verification. Many road tunnels are already equipped with video systems, mostly analogue CCTV-Systems. Such systems allow operators the supervision of tunnel activities and the guidance of emergency activities. However, these video systems generate a huge amount of information, which clearly can not be completely supervised by tunnel operators the whole time.

On the other hand, after the fire disasters occurred in the “Mont Blanc” tunnel located at the frontier between France and Italy (1999, 39 died), “Tauern” tunnel in Austria (1999, 12 died), and the “Gotthard” tunnel located in Switzerland (2001, 11 died) the European authorities reviewed the safety standards for tunnel operation. Such tragedies have provided the impetus for a major re-appraisal of fire safety in European road and rail tunnels. In 2001, the European Union launched the White Paper [Commission European Communities, 2001], which proposes 60 specific measures to be taken at Community level under the transport policy, including, among others, a directive on safety standards in tunnels. The EU Directive launched in 2004 provides institutional, organizational, operational and technical measures addressing tunnel safety. This directive determines the major stakeholders that are involved in the Tunnel Safety Management and their objectives and responsibilities. The Transport Committee of the Economic Commission for Europe formed a multidisciplinary group of experts on safety in tunnels [UNECE].

As a consequence, development and implementation of automatic or semi-automatic interpretation tools to aid human operators (not to replace them) to detect unexpected events, and abnormal behaviour is desirable and necessary. Implementation of advanced applications might increase safety, and it may play an important role in the performance of economy. ASFiNAG, as road authority of the motorways and fast-highways in Austria, is interested in offering safety, and highly efficient ways of transport in an enlarged Europe [ASFiNAG, 2004].

Over the last decade, increasing interest in the field of visual surveillance has led to the design of a plethora of systems for automated visual video surveillance systems. Considerable efforts have been spent on the computer vision area to develop algorithms for detecting and tracking moving objects in the image, for object classification and detection of unexpected events and abnormal behaviour. Recent advances in hardware and computing power helps in the development of visual surveillance applications. A combination of computer vision methods with video technology is able to detect all major incidents: stopped vehicles, slow moving traffic, and statistical information such as speed, and vehicle classification. Different models and techniques to detect moving objects, follow trajectories and extract statistical information have been proposed by different authors [Boyd et al., 1999], [Buzan et al., 2004], [Coifman et al., 1998], [Cucchiara et al., 1999], [Remagnino, 1997], [Viola, 2001]. Commercial systems like ABT2000 [Artibrain], INVIS [Ascom], MediaRoad [Citylog], Traffic Analysis System [Crs], Autoscope [Image Sensing Systems], Vantage [Iteris], Mavis [Mavix], Video Trak 910 [Peek Traffic], SiADS – SITRAFFIC [Siemens], and Traficam [Traficon] demonstrate these abilities. Certainly, this list is not complete.

However, to the best of our knowledge, no work has been reported on digital image video analysis and pilot projects in tunnels. VITUS (Video Image analysis for TUnnel Safety) project aims at building and implementing a prototype for an automatic video image analysis system for tunnel safety. To achieve their objectives, VITUS is divided into two subprojects called VITUS-1, and VITUS-2 respectively, and partners coming from diverse areas such as road authority (ASFiNAG), industry (ETM and PTV), government (ASTL and BMVIT), academic (ICG), and research (ARC Seibersdorf and ACV) are involved in the project.

The remainder of this paper is as follows: Section 2 summarises the tasks carried out among VITUS-1 project. Section 3 is the main core of the paper describing VITUS-2 project in detail and its current status. Conclusions and future work are drawn in Section 4.

2. VITUS-1: THE FEASIBILITY STUDY

The feasibility study VITUS-1 defines a concept mainly based on automatic incident management based on digital video image analysis. During this feasibility study, a concept that enables (1) automatic recognition of dangerous situations through video sequence analysis, (2) warning of tunnel operators, (3) warning of road users upon necessity through the tunnel control system, and (4) the automatic archiving of the relevant video sequences has been defined. Among VITUS-1, following tasks were carried out:

1. user requirements and models of tunnel scenarios have been defined,
2. a revision and evaluation of video sensor technologies,
3. a market study about current products,
4. a revision and evaluation of image processing algorithms and the possible computer vision techniques to be applied,
5. a compilation of the state-of-the-art algorithms (both areas, scientific and commercial),
6. recording of test sequences considering different situations and events, and
7. a specification of system's architecture, and a design of the prototype.

More information about VITUS-1 can be found in [Schwabach et al., 2005].

3. VITUS-2: A PILOT PROJECT

The demonstration project VITUS-2 implements a prototype based on the user requirements, including a description of the tunnel activities while considering the tunnel's infrastructure and it also addresses the evaluation of the system. Results of VITUS-1 provide an assessment of the pilot and demonstration project VITUS-2 with regard to its feasibility, the necessary system resources and the expected effort under the defined conditions. To achieve VITUS-2's objectives, seven work packages (WP) have been defined. Figure 1 summarises each work package and the topics related to.

Work packages and related activities are:

1. Installation of test-site: This WP covers the necessary hardware, mechanical and electronic components for the acquisition, transmission, and storage of the data. Electronic components, dedicated recorder equipment and the sensor network for intelligent surveillance will be installed in the Plabutsch tunnel in near future. Analogue cameras were installed during 2004 when the tunnel was closed for maintenance purposes. Figure 2 depicts the system architecture.

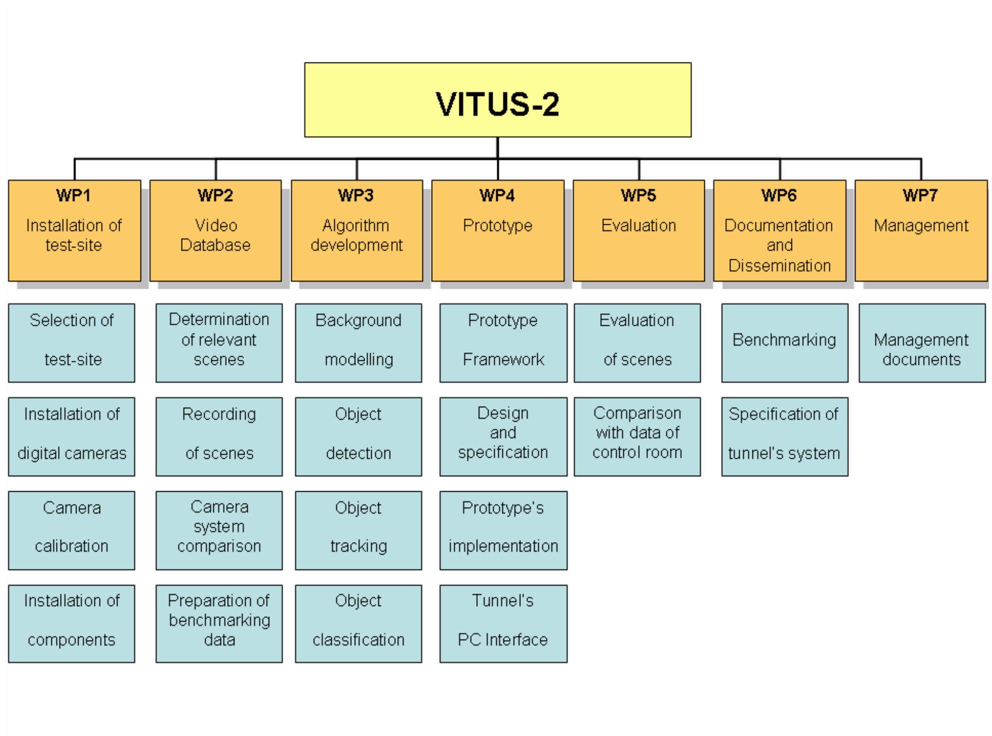

Figure 1: VITUS-2: Work packages and their responsibilities.

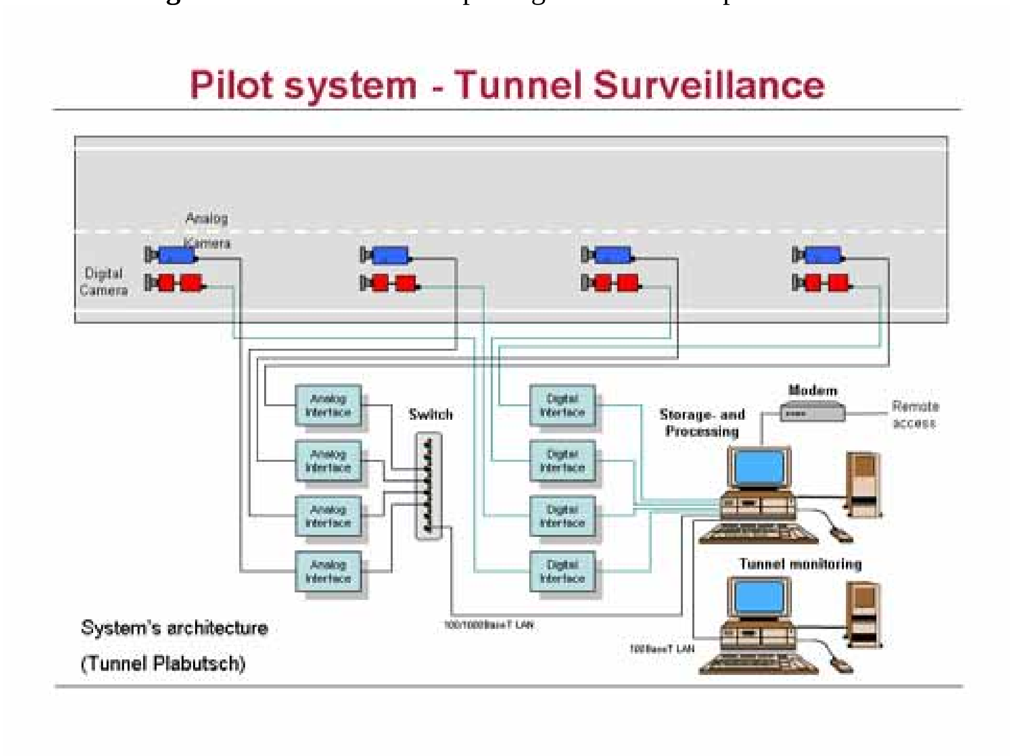

Figure 2: VITUS-2: System architecture.

2. Video database: Along the whole project, representative scenes were defined and recorded. As result a representative database was built. Current database consists of almost 10 hours of video material distributed into 176 scenes covering various possible scenarios, (normal traffic, presence of persons), different environment conditions (normal illumination in tunnel, emergency illumination in tunnel, dry floor, wet floor), and abnormal and dangerous situations (traffic in wrong direction, fire and smoke, lost cargo).

Table 1: Recorded situations.

Situation	Illumination	Roadway
Normal traffic	Normal, low	Dry, wet
Traffic in wrong direction	Normal, low	Dry, wet
Presence of people	Normal, low	Dry, wet
Lost cargo	Normal, low	Dry, wet
Fire and smoke	Normal	Normal

Table **1** shows which situations were recorded, and Figure 3 depicts some representative scenes taken from this video material.

Building this database is not an easy task. Normal traffic situations are relatively easy to record, but consider traffic in wrong direction or presence of fire. It might be possible to obtain such scenes in normal operation of the tunnel. However, these situations are very dangerous. In this case, the scenes were simulated which has many and not trivial implications: The tunnel has to be closed, people have to take part of the simulation (drivers, police, firemen, etc.) and a coordination task with tunnel operators has to be done. Almost 20 people were involved during each test (in case of presence of fire and smoke more people like policemen and firemen were necessary), and people acting as drivers drive more than 1200 km.

3. Algorithm development: This WP concerns the development of image processing algorithms and the analysis and understanding of the data. Along VITUS-1 three main topics were identified as the most relevant: Object detection and object tracking (recognition of stopped objects; detection of persons at unauthorized places; detection, recognition of lost objects, etc.), detection and management of several traffic situations (normal traffic, recognition of traffic jam; classification of objects, statistical analysis), and detection and management of dangerous traffic events (detection of vehicles in wrong direction, fire and smoke detection). The algorithms have to process the video data to achieve an automatic understanding of current situation in tunnel to comply with the users' needs. Results delivered by image processing algorithms provide the information required for event recognition and behaviour analysis in order to interpret current situation. An assessment of the reliability of the image analysis algorithms is of utmost importance. Up to now, image processing algorithms for background modelling, tracking, and classification were developed. The tracking algorithm is based on a statistical analysis of current frame [Alefs et al., 2005], and classification of lost objects is mainly based on feature based methods [Grabner et al., 2005]. These algorithms were evaluated using different sequences of aforementioned database to check their response under tunnel conditions.

Figure 3: Typical tunnel scenes from our test database: (a) Normal traffic behaviour, (b) Traffic in wrong direction, (c) Fire and smoke, (d) Presence of persons, (e) Presence of persons, (f) Lost cargo. (a-d) dry roadway; (e-f) wet roadway.

Ongoing work is concentrated on an increase of robustness in order to reduce false positives and false negatives. While the former is a critical factor for the acceptance of tunnel operators, the latter refers to the misdetection of situations which must to be detected.
Figure 4 depicts some results of image processing algorithms developed up to now. Results of object detection (a), object classification (b), object detection and tracking (c), and trajectory of the objects (d) are depicted. Integration of these algorithms into the prototype is the next step in this WP. Our current database provides important material to check and evaluate the response of the algorithms.

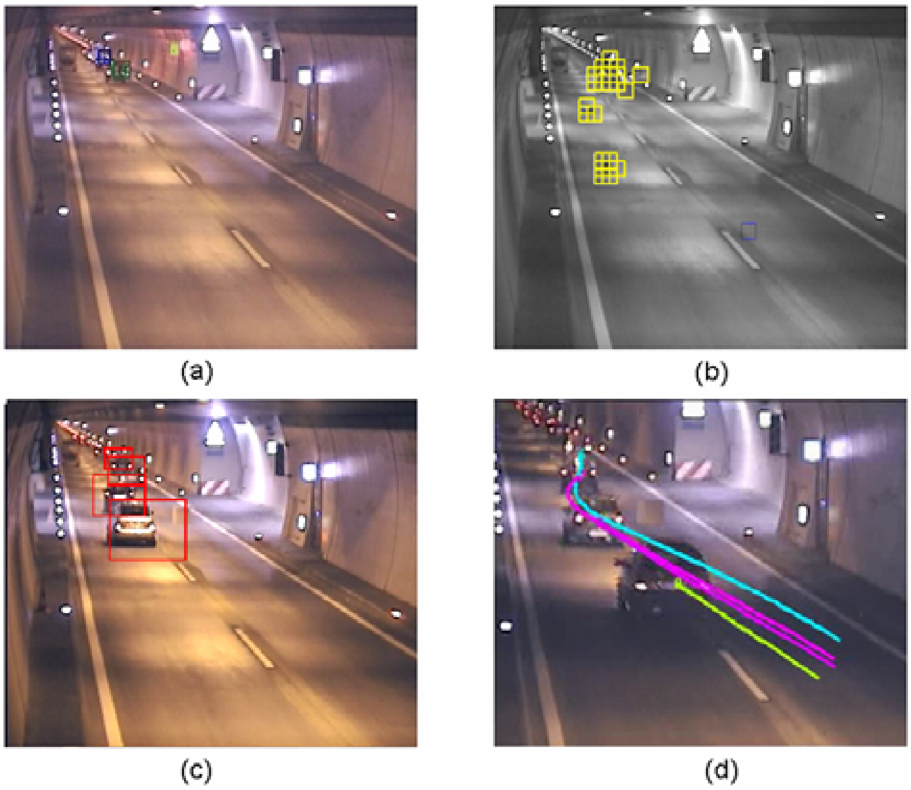

Figure 4: Results of image processing algorithms. (a) Object detection, (b) Object classification, (c) Object detection and object tracking, (d) Trajectory of the objects.

4. Prototype: This work package implements the prototype, i.e. it represents the central point for implementing all produced software and algorithms. This work package covers the software application, the necessary communication between the different modules and the necessary data communication. Figure 5 shows a prototype of the Graphic User Interface (GUI) of the application. It is well known, a clear system design is critical to both its acceptance and use for users. Thus, it is necessary that the GUI has a very simple design to facilitate its use by tunnel operators. We are working on a redesign in order to manage various cameras simultaneously.

By using current GUI, the user can choose the source of data (video stream coming from an analogue input, video stream coming from a digital input, and sequences saved in different formats like RTP stream, MPEG-2, and AVI files), the processing task to be performed (video image analysis, live), and the kind of event to be detected (traffic jam, wrong way driver, lost cargo and strange objects, all of them). Besides, it is possible to restart the application, to load the previous configuration, to store the current configuration, to edit the current configuration and to display the log event file. We are planning to compress the data using MPEG-4 codec and its integration in the application. Ongoing work is concentrated in the development of the necessary modules for data communication and event management.

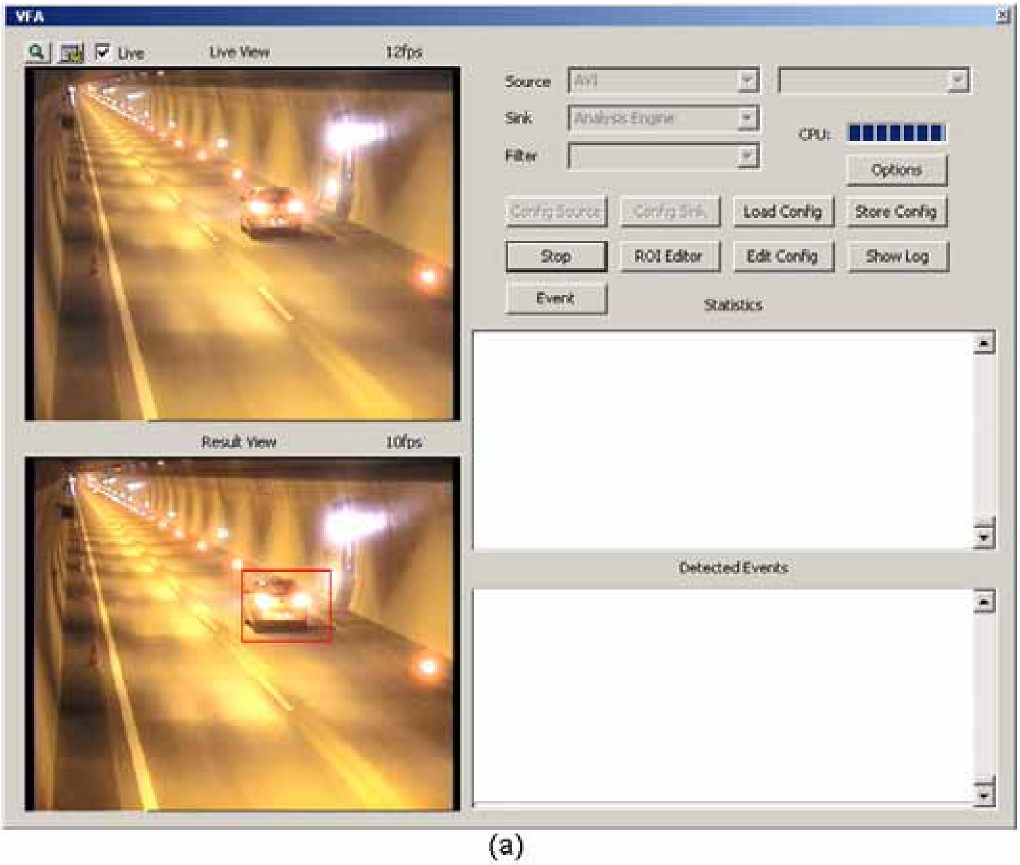

Figure 5: GUI of the application.

5. Evaluation: Current work package is responsible for the evaluation of the prototype in terms of selected scenes and normal operation of the tunnel. The evaluation verifies the achievements of the prototype.

6. Documentation and dissemination: This work package is in charge of the whole documentation and the dissemination of achieved results of the project. To do that, a users group will be formed. The actions to be taken are led along the project in close collaboration with the others partners.

7. Project management: The last package runs during the whole project, and it concerns the complete documentation of the project, meeting's organisation, etc. The project management concerns the administrative and financial review, scientific innovated research and industrial results management.

4. CONCLUSION

Tunnel safety is a challenging task with very serious requirements, due to special tunnel conditions and a tight timeframe for recognition purposes.

This paper has reported work undertaken on VITUS Project. VITUS project aims to build and implement a prototype for an automatic video image analysis system in order to increase safety in tunnel roads. A feasibility study about video image analysis in tunnels was carried out. The system's architecture of the pilot project was determined for the integration of video analysis into the tunnel infrastructure of the tunnel control system, which enables a systematic and comparative evaluation of the video analysis in the pilot project. Experiments on real sequences using innovative image processing algorithms have shown promising results. The installation of the components, the implementation of the prototype and evaluation of the system is work on going.

Future work is mainly concentrated on following tasks:
1. Installation of all the components in the tunnel,
2. integration of the software components in the pilot system,
3. complete testing of the system considering hardware equipment and mechanical components (cameras, PCs, data transmission, integration in the operator's room) and software systems (image processing, compression, module test, integration test),
4. comparison of response of the algorithms using analogue data and digital data,
5. evaluation of the influence of compressed data on the system.

It is expected that VITUS project is aimed at bringing transparency to tunnel operators and helping them to monitor tunnel activities. It is hoped that the results of this research will provide an increase in tunnel safety, and it should help to form the basis for future efforts. The efforts will continue beyond the project period until their final completion during 2006.

ACKNOWLEDGEMENT

This research was carried out under the Program I2 "Intelligente Infrastruktur" supported by the Austrian Federal Ministry of Transport, Innovation and Technology (Bundesministerium für Verkehr, Innovation und Technologie, BMVIT). We are very grateful to ASFiNAG, and ASTL for the support during current study. We also would like to acknowledge tunnel operators of Semmering tunnel, Plabutsch tunnel, and Spital tunnel for their cooperation during recording the sequences of our video database. We extend our gratitude to the students of Institute for Computer Graphics and Vision (TU-Graz); and the students of Institute for Technical Informatics (TU-Graz) for their collaboration during the tests.

Current paper does not constitute a standard, specification, or regulation.

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PHOTOGRAMMETRIC ADVANCED DETECTION SOLUTION INCIDENT DETECTION IN TUNNELS

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ABSTRACT

Use of photogrammetric methods and image analysis for automatic monitoring and measurement systems. Interesting new detection and evaluation possibilities can be developed on the basis of the combination of photogrammetric measurement methods and image analysis. The following will be explained: 1) the functionality of such measurement methods; 2) possibilities in traffic safety; 3) possibilities in traffic monitoring; and 4) the schematic of such a system.

1. THE FUNCTIONALITY OF SUCH MEASUREMENT METHODS

Each single frame of every video stream is handled in the photogrammatic image analysis process.

In the first step, the regions of interest are specified. In the second step, the different detection methods of the image analysis processes are used to filter the image areas. In steps three to five, these areas are calculated using photogrammetric algorithms. The employed cameras, computers and algorithms allow these measurements to be completed in real time.

Dynamic processes can be calculated for the complete area using a timestamp and the scaled positioning of the cameras. The steps of this process are illustrated in Figure 1.

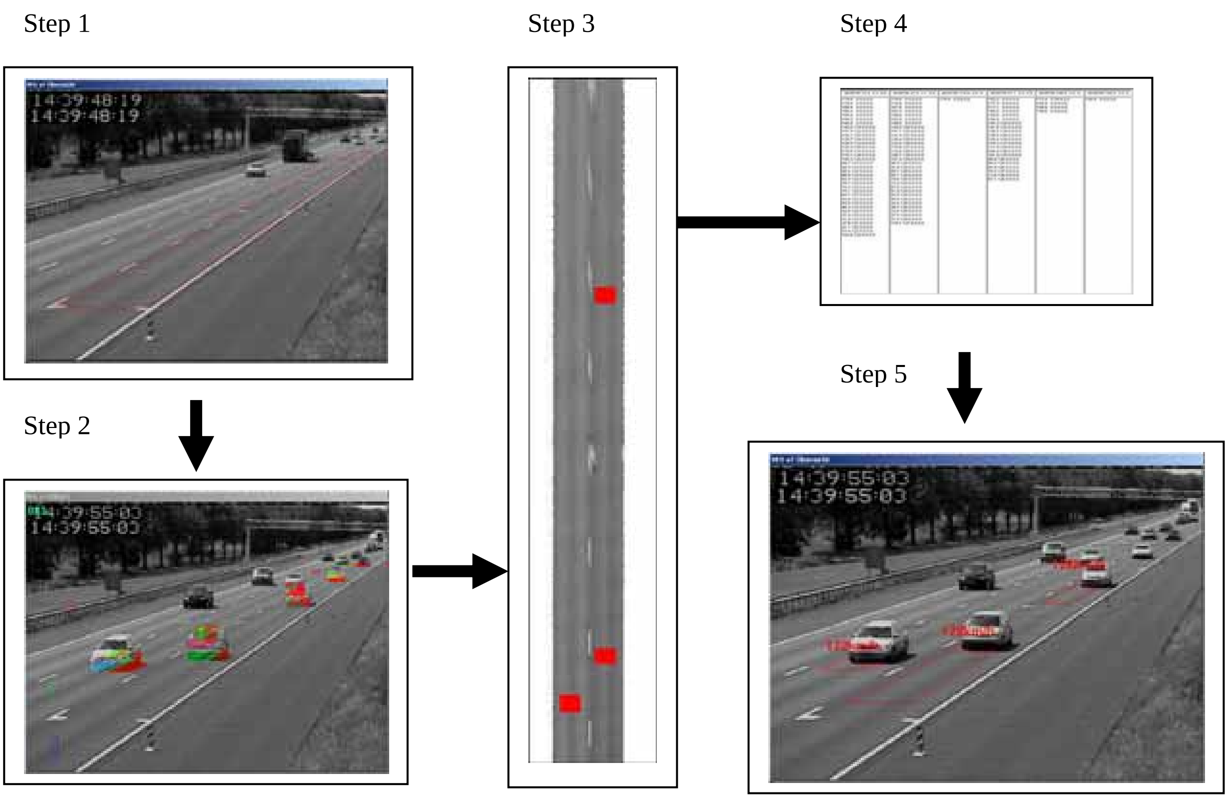

Figure 1: Process steps

2. POSSIBILITIES IN TRAFFIC SAFETY

Calculation and graphical presentation of speed flow and delay detection through the complete tunnel

With the combination of image analysis and photogrammetry, vehicles can be detected, qualified, and their movements exactly calculated. The results can be saved on a time line and graphically displayed for a better understanding.

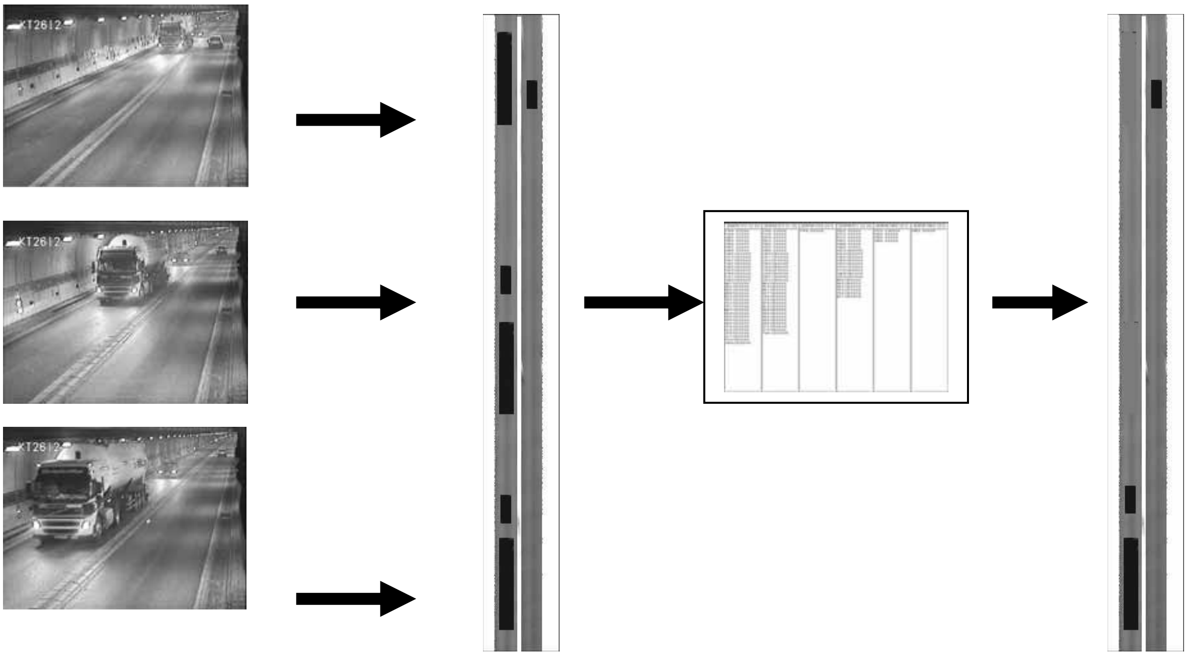

Figure 2

By connecting multiple cameras and their processes, the traffic flow can be calculated, displayed and archived for the complete tunnel area. Every vehicle that drives through the tunnel can be analysed.

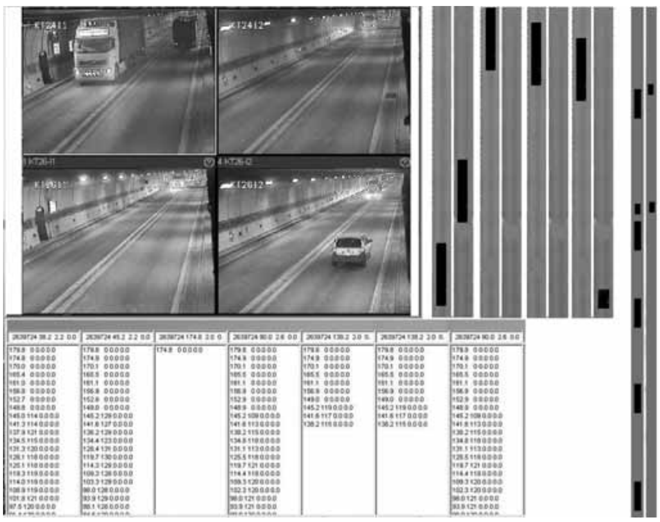

Figure 3

Detection of illegal driving, detection of stopping or slow-driving cars

With the help of the movement and direction calculated for all vehicles, illegal driving can be detected directly and the corresponding risk management measures initiated.

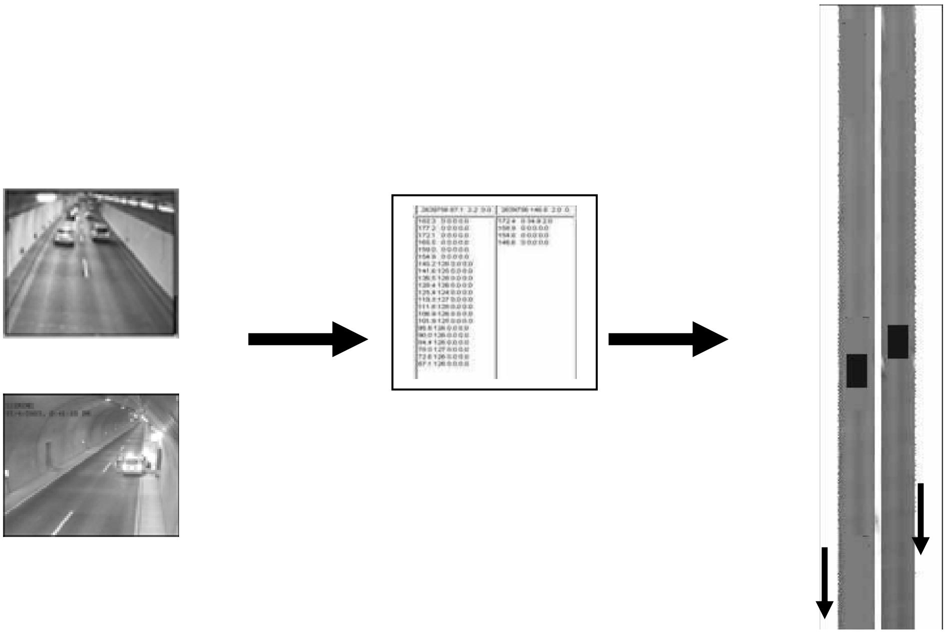

Figure 4

Detection of dangerous objects in the traffic lanes (lost goods, animals, etc)

The video analysis system detects dangerous objects automatically and allows the corresponding risk management measures to be started immediately.

Detection of vehicles with dangerous goods

Using specially equipped cameras, vehicles with dangerous goods can be detected automatically and their passage through the tunnel monitored as explained above.

Classification of vehicles

With the help of photogrammetry, the dimensions of the vehicles can be calculated automatically and classified accordingly.

Smoke detection

The video analysis system detects smoke automatically and allows the corresponding risk management measures to be initiated automatically.

Figure 5

3. POSSIBILITIES IN TRAFFIC MONITORING

Calculation of speed and distances, generation of court-admissible files and documentation

License plate recognition system to search for listed cars and risk management

With the integration of licence plate recognition systems, traffic enforcement cases can be handled fully automatically.

Figure 6

Monitoring of prohibited driving and overtaking incidents and generation of court-admissible files and documentation

Identifying illegal drivers

With the procedure described above and a special time code method, it is possible to produce court-admissible files and documentation. The drivers are recorded with additional cameras and the license plate recognition is completed automatically.

Figure 7

SAMPLE SYSTEM SCHEMATIC

One example of an analytic system is shown in Figure 8.

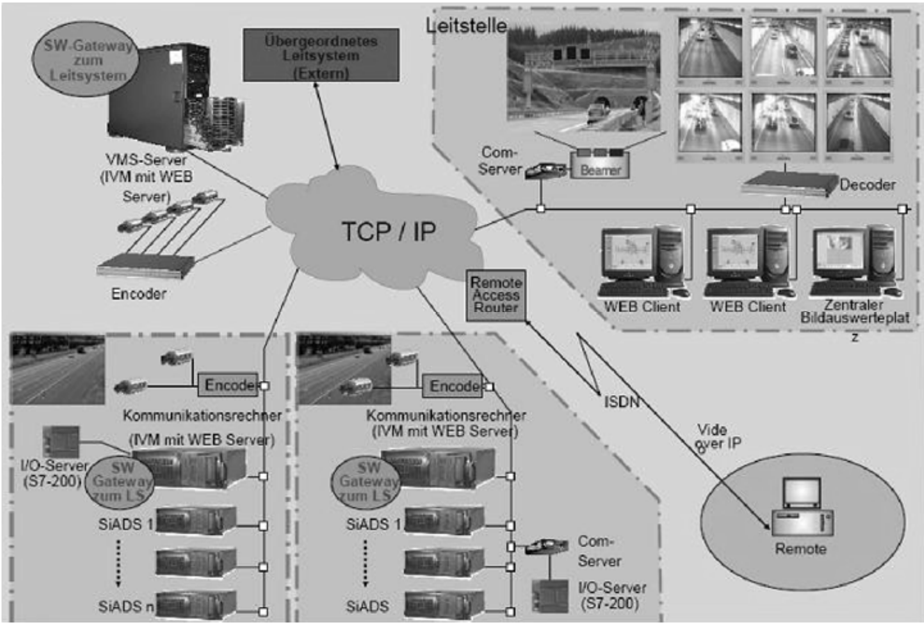

Figure 8: Siemens SiADS**plus** system

A DSS FOR "DYNAMIC TUNNEL" TRAFFIC AND INCIDENT MANAGEMENT

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ABSTRACT

Traffic incidents in tunnels can have dramatic consequences and can prove extremely costly in terms of human lives, increased congestion, pollution and repair costs.

Traffic incident management is the primary tool in minimizing the impact and reducing the probability of secondary incidents. It primarily includes incident detection, verification, response, clearance and recovery operations. Besides these operations, traffic management in the post-incident scenario is a crucial step to minimize the negative consequences on network efficiency and safety. Traffic management includes the dissemination of information to drivers and the activation of proper traffic control measures at the incident site and on the roadway infrastructures affected by the traffic incident.

This paper describes the current development, within the SITI project, of a DSS (TRIM-Traffic and incident management) designed to assist traffic control centre (TCC) operators to effectively and safely mitigate traffic congestion associated with incidents in tunnel and on the surrounding road network.

In particular TRIM is designed to support on-line and off-line tasks of TCC operators required to define, implement and control the appropriate traffic response plans on the basis of the incident severity level, the predicted duration, the estimated delay and extension of the impact area and the current/predicted traffic demand approaching the incident site.

The basic elements of a response plan are the traffic channelling and control schemes to regulate traffic flow past the incident site, the traffic diversion on appropriate routes to relieve traffic demand at the incident site and the dynamic dissemination of information to drivers using various output devices and regarding traffic conditions, changes in roadway geometry, operating traffic speeds and routing.

BACKGROUND

The Italian roadway and motorway network is characterized by a high density of traffic and tunnels. In recent years the risks of incidents have increased as many road infrastructures, including tunnels, were designed several decades ago to carry lower traffic volumes than the current traffic levels and were built with technical requirements that with time have become outdated.

Currently all the main Italian roadway and motorway companies are involved in the process to improve the tunnel safety levels according to the recent EU directive that defines minimum harmonised organisational, structural, technical and operational safety requirements for all tunnels longer than 500 meters in the Trans-European Road Network.

The SITI project co-financed by the MIUR (Ministry of Education, University and Research) aims to study, develop and demonstrate a set of innovative technologies in order to improve the traffic monitoring process and the safety level inside the road tunnels.

SITI introduces a new approach, the "Dynamic Tunnel" vision, which considers the tunnel as a whole with the road network before and after the tunnel itself, like a complex system in continuous evolution.

A SITI objective is the implementation of a DSS for the selection and best implementation of traffic management measures in response to the occurrence of an incident to alleviate serious traffic congestion, minimize substantial queue back-up and reduce potential secondary incidents. The main functions of the DSS are aimed at preventing crisis situations and at making more effective the traffic control operations during the emergency events, both at local and wide area.

POST-INCIDENT TRAFFIC MANAGEMENT STRATEGIES

An incident represents any unpredictable occurrence that disrupts traffic flow for a period that lasts longer than the incident itself and, temporarily, reduces roadway capacity.
An incident can range from disabled vehicles or debris dropped along the side of the roadway up to major collisions involving fatalities, fires or hazardous material spills. Severe incidents involving significantly damage to roadway and structures, such as multi-vehicle collisions, tanker truck explosion and fire in tunnels, can cause severe disruptions in the flow of traffic including even disturbances in the economy of a whole region. However minor incidents, such as disabled vehicles, are responsible for the majority of the total delay caused by incidents.
The occurrence of incidents, besides its direct impacts in terms of property damage, injuries and fatalities, can quickly lead to congestion and associated travel delay, wasted fuel, increased pollutant emissions and higher risk of secondary incidents.
The amount of delay and impacts that results from the incident depends on the duration of the following five distinct phases often overlapping:

1. <u>Detection</u> that determines the occurrence of the incident;
2. <u>Verification</u> that defines the precise location and nature of the incident;
3. <u>Response</u> that concerns the activation and dispatching of personnel and equipment to the incident site;
4. <u>Clearance</u> that includes the removal of vehicles, debris and spilled material from the roadway to restore the complete roadway capacity;
5. <u>Recovery</u> that consists of dissipating the queue at the site of the incident once the roadway is cleared in order to restore as quickly as possible the normal traffic conditions.

Together the first four phases represent the total duration of the incident or the period of time ranging from the occurrence of the incident to the complete restoring of the roadway capacity.
The recovery phase largely depends on the extent of the disruption to traffic flow caused by the incident and on the effectiveness of the traffic management measures implemented soon after the occurrence of the incident.
Traffic management includes the implementation of a range of traffic control measures at the incident site and on the roadway infrastructures affected by the incident aimed at minimizing traffic disruption, reducing the probability of secondary collisions and protecting responders working on the incident.
The control at the incident site is required to facilitate the orderly and safe movement of traffic past the incident by channelling traffic with flares, cones, delineators and warning signs into the lanes that remain open to traffic.
Typical techniques implemented for the on site control are:

1. roadway shoulder utilization to provide additional capacity around the incident scene;
2. ramp diversion from the exit ramp immediately preceding the incident site, to divert traffic temporarily off the roadway onto a nearby parallel street and back onto the affected roadway downstream of the incident scene

3. contra flow lane diversion (for major incidents causing the full closure of the carriageway for several hours) to allow upstream trapped traffic to utilize a travel lane from the opposing roadway direction;
4. alternate one-way movement when two-way traffic is reduced to one-way traffic and traffic in both directions must use a single lane. Alternate one-way traffic control may be affected by means of temporary traffic signal or by flagmen.

Traffic management may also requires the implementation of measures that temporarily limit traffic demand approaching the incident location to prevent congestion or vehicle queuing upstream of the incident. In this context typical traffic control strategies are traffic diversion on alternative routes and ramp metering.

By effectively controlling entering vehicle volumes with traffic signals at the entrance ramps located upstream from the incident site, the ramp metering strategy can help keep the traffic density below the critical level and provide a smooth flow of traffic on the section of roadway immediately upstream of the incident.

The diversion of the traffic flow approaching the incident area on appropriate alternative routes is the only way to alleviate congestion especially in the occurrence of major incident requiring the long-term closure of multiple lanes or full closure of the roadway. However the effectiveness of traffic routing depends on the availability of alternate routes and their level of congestion.

A diversion strategy involves the determination of where and how much traffic should be diverted and the sequence of roads forming the diversion routes that are best suited to handle this increased traffic demand. A diversion strategy may also involve the modification of signal timing and the activation of guide signs along the diversion routes to allow the effective and safe passage of diverted traffic.

A major element of traffic management in post-incident scenario is the dissemination of information to drivers approaching the incident area regarding traffic condition, changes in roadway geometry, operating traffic speeds and routing by deploying various output devices (variable message signs, lane control signals, radio broadcasts, etc). Drivers’ response to the provided incident-related information is crucial for successfully diverting traffic, reducing secondary incidents and improving responders’ safety on the incident scene

In conclusion by reducing the duration of the incident and maximizing the use of the available roadway capacity during incidents, both the economic cost of congestion and the associated aggravation can be reduced. The result is more reliable travel, shorter trips and an ability to accommodate more trips within the existing roadway infrastructures.

BASIC REQUIREMENTS AND FUNCTIONS

In this context a DSS with the capability of storing, analyzing, and displaying geographically referenced information and data on network characteristics, traffic and incidents, predicting incident duration and traffic delay, generating and implementing appropriate traffic response plans to different incident scenarios and controlling their effectiveness in reducing traffic disruption and related impacts, appears to be the perfect tools to greatly increase the efficiency of incident and traffic management.

Particularly the main requirements that TRIM should be able to meet are:

- to integrate and display information flowing from the surveillance and control devices, installed inside the tunnel and on the surrounding road network, to the TCC (i.e.: traffic flow sensors, traffic signs, VMSs, meteo sensors, AVL, etc,);
- to perform traffic simulation studies at macro/micro scale to evaluate feasible traffic response plans under different traffic conditions and incident scenarios;

- to store, query and analyse network characteristics data, incident scenarios and historical traffic data, needed to define possible diversion routes and control strategies and to feed traffic simulation and prediction models;
- to select on the basis of predefined rules the most appropriate traffic plan in response to an incident and suggest to the TCC operators the needed steps for its implementation;
- to provide during the incident management period reliable estimates of the network traffic conditions to verify the effectiveness of the proposed traffic response plan.

Based on these requirements TRIM design is aimed to make available a new software tool suitable to help the TCC operators in their tasks, especially when they face dramatic traffic congestion caused by major incidents inside or in the proximity of a tunnel, involving long duration clearance operations and affecting high traffic volumes.
In particular *TRIM* is designed to help the TCC operators to effectively perform:

- ➢ off-line tasks, concerning the study and design of a set of traffic response plans to face possible incident scenarios through the use of micro/macro traffic simulation and prediction tools;
- ➢ on-line tasks during the incident management process, concerning the selection, implementation and follow-up of the most appropriate traffic response plan, in relation to the incident severity level and the traffic volumes approaching the incident site.

The main off-line and on-line functions of the TRIM system are outlined in the flowchart illustrated in figure 1.

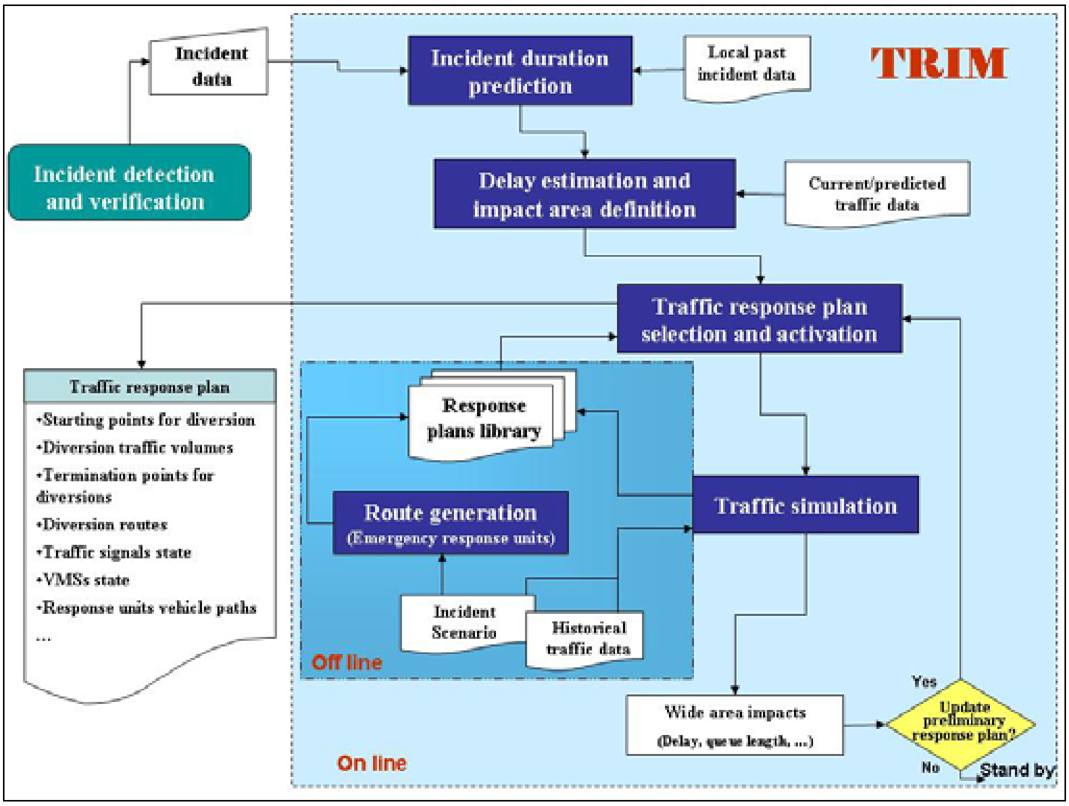

Figure 1: Flowchart of TRIM basic functions

The flowchart shows the different steps followed from the occurrence of the incident to the implementation and control of the traffic response plan.

After an incident has been detected and verified through information coming from the different available sources (traffic sensors, CCTVs, police patrol, etc.), the incident details (i.e.: type, location, time of occurrence, vehicle involved, injuries involved, fatalities involved, etc.) are input by the TCC operator into TRIM through a convenient graphical user interface.
Once TRIM has received the input information describing the incident, the first step is to predict the incident duration on the basis of the incident characteristics and the operational experience accumulated from previous incident management operations. Duration prediction refers to the expected time interval ranging from the incident occurrence to the end of clearance operations.
Starting from the predicted incident duration and taking into consideration the amount of the road capacity reduction and the prevailing traffic conditions, TRIM estimates delays and impact area extent that will be caused by the incident.

These estimates are then used to select a preliminary traffic response plan that includes the set of strategies chosen to manage traffic flow (such as diversion points, diversion volumes, termination points, diversion routes, timing for traffic signals, emergency signals, messages to be displayed on the VMSs etc.). The selection is performed on the basis of rules pre-defined by the traffic experts.
According to the selected traffic response plan, TRIM proposes to the TCC operators, step by step, the predefined traffic management measures to be implemented. The traffic response plan is integrated with information about the best paths to be taken by the involved emergency response vehicles to reach the incident site more quickly and vice versa.
Traffic micro-simulation is then performed starting from the preliminary estimates about the incident duration, the current traffic data received from sensors, the diversion routes and the traffic control measures taken by the TCC operators. Traffic micro-simulation reproduces in a virtual environment the spatial-temporal evolution of the traffic flow on the roadway network affected by the incident with the final aim to offer an immediate, reliable estimate of the effectiveness of the preliminary traffic response plan.
If the simulation results (such as delays and queue lengths) differ significantly from the expected traffic performance, TRIM helps the TCC operator to select and implement a new, more effective traffic response plan.
On-line traffic micro-simulation can be performed again when updated information on the traffic conditions or the clearance operations duration becomes available in order to verify the effectiveness of the current traffic response plan.

The TRIM off line functions are aimed to study and evaluate feasible traffic plans in response to possible incident scenarios through the use of micro and macro scale traffic simulation models.
Micro-simulation, that captures the behaviour of vehicles and drivers in great detail, is performed to evaluate traffic congestion evolution at local scale in the proximity to the incident site due to the complicated structure of the models involved.
On the other hand macro-simulation, due to their more aggregate nature, is performed to evaluate the traffic conditions at a wider scale (i.e.: regional/national network), to choose the best diversion points for the specific incident and to determine the best routes for the chosen diversion points.
Finally an off-line function of TRIM is the generation of shortest paths, so that emergency responders can avoid blocked or slow routes and quickly reach the incident site.

GENERAL ARCHITECTURE AND MODULES

TRIM is designed to work inside a motorway or an urban area or a long tunnel traffic control centre (TCC) able to perform traffic surveillance, traffic control and driver information functions.
Trim, including macro/micro scale traffic simulators, is designed to support on-line and off-line functions such as the incident duration prediction, the traffic delay estimation, the impact area determination, the formulation, selection and control of appropriate traffic response plans. Traffic simulators will enable traffic control operators during the incident management period to perform detailed real-time analysis of the network traffic conditions under the current control strategies.

The general architecture of the TRIM system is illustrated in figure 2.

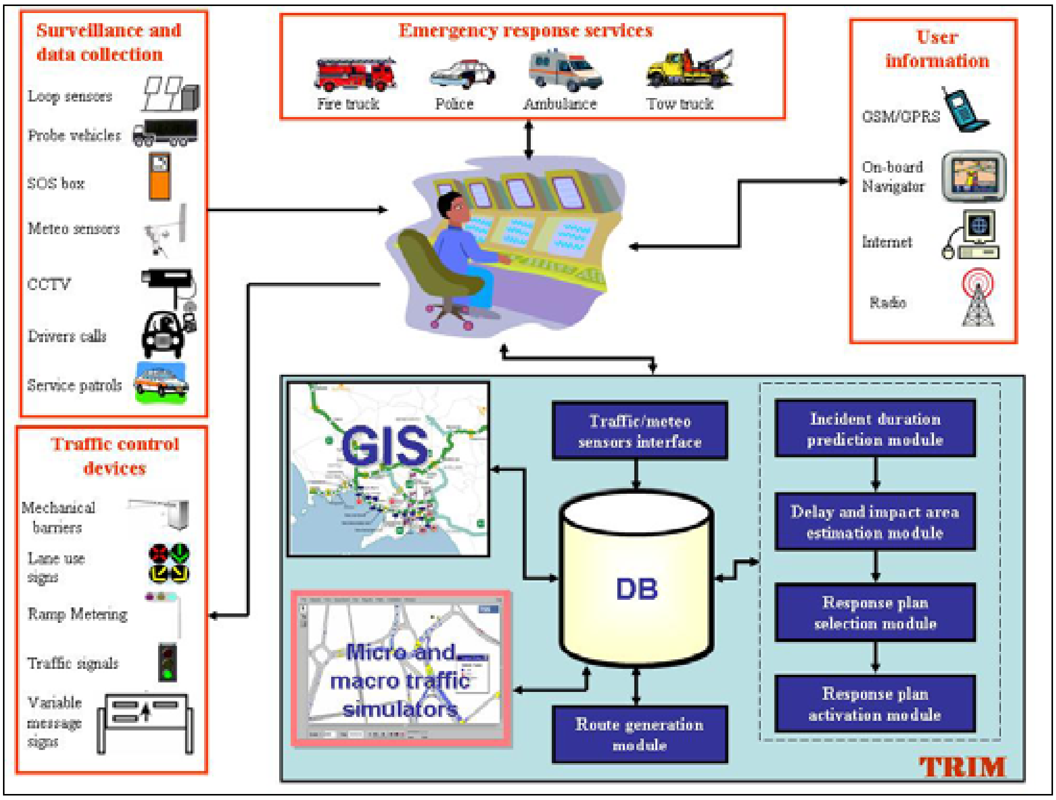

Figure 2: TRIM general architecture

TRIM is composed of the following software modules:

- a relational database (MySQL) designed to store, query and update historical incident and traffic data, traffic network characteristics, data exchanged between the various system modules, simulation results and traffic response plans;
- a GIS-based user interface (ArcView) that enables TCC operator to display the roadway network, the real time traffic data and the status of the control devices on a background map, to run on-line and off-line prediction and simulation procedures, to analyse and display the results in multiple views and tables, to define and implement traffic response measures;
- an interface module to gather on-line traffic/meteo data collected by sensors installed inside the tunnel or on the surrounding roadway network;

- a module to predict the duration of the incident ranging from its occurrence to its complete removal. The module incorporates a statistical model that includes variables related to operational and incident-type factors that can be realistically obtained in real time under incident conditions. The model is tailored on the basis of the time experienced in past incidents occurred in the local area;
- a module to estimate the incident delay suffered by drivers and the impact area extent in case of non-intervention. The module incorporates a model, based on deterministic queuing method that calculates the cumulative vehicles hours of delay and the consequent queue length upstream of the incident site. The incident delay is estimated starting from the estimated incident duration, the prevailing traffic demand and the value of the capacity loss;
- a module to select the most appropriate traffic response plan on the basis of a predefined set of rules. The rules-set is formulated by traffic experts who possess specific knowledge and expertise to solve traffic congestion problems. In the rule-formalising process, traffic simulation tools can provides data for deriving consistent rules for the selection of the best traffic plan in response to an incident;
- a module to help step-by-step the TCC operator through its tasks needed to implement the traffic response plan including the provision of incident-related information to drivers and the application of traffic control measures on the network infrastructures affected by the incident;
- a path generation module to enable the shortest, fastest routing of emergency response vehicles from the various key locations, including hospitals, fire and police stations, to the incident scene;
- traffic simulation tools at micro (AIMSUN) and macro scale (MIAURB) to model and evaluate the evolution of the traffic flows associated to different traffic management strategies and incident scenarios.

CONCLUSIONS

Roadway and tunnel agencies are now more frequently asked to develop and improve incident management to expedite response and clearance processes and to minimize the traffic flow disruption and the potential for secondary incidents.

Traffic management is a key step of the complex incident management process as it can greatly reduce the amount and duration of the resulting congestion. Traffic management embraces the selection of the most appropriate traffic control strategies, such as signal modification and traffic diversion, and the dissemination of incident-related information to drivers to avoid the incident and adjust driving behaviour.

The paper has presented a DSS (TRIM) to assist traffic control centre personnel involved in determining the appropriate strategies to effectively and safely manage traffic in post-incident scenario and support execution of steps required for their implementation and control.

TRIM has the capability to use both historical and real time sensor data, to collect and categorize incident information, to simulate all candidate traffic response plans prior to their implementation, to perform the immediate preliminary estimate of incident impacts in terms of duration, delay and geographic extent, to select and implement the most appropriate response plan and, finally, to model and control real time traffic conditions during incidents.

The proposed DSS will be soon tested under real conditions in the interurban high congested corridor extending from the southern neighbourhoods of Naples to the town of Sorrento. The corridor is defined by the “SS 145” roadway (named Sorrentina) suffering from relatively high incident rates and including a 1400 meters long tunnel.

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CONTROL STRATEGY AND HARDWARE IMPLEMENTATION FOR FLOW MANAGEMENT BY DAMPERS

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ABSTRACT

This paper describes the provisional ventilation system in the Lötschberg tunnel which was implemented during the installation phase. A system was established which uses 1 major fan to ventilate the entire main tunnel system. The flow distribution to the 4 main branches is realized by 4 controllable dampers which induce sufficient pressure loss so that the desired volumetric flow rates in all branches is established.

The following report outlines, a 2-step strategy used to determine the required aperture angle for all dampers with varying boundary conditions.

Results from a field test confirm the viability of the method applied.

Keywords: tunnel ventilation, railway tunnel, base tunnel, flow management, controllable dampers, control, Lotschberg, NEAT

1. INTRODUCTION

The 34.5 km long Lotschberg tunnel connects the Bernese Oberland and the Canton Valais with a continuation through the 100 year old Simplon base tunnel to Italy. It is the first NEAT[1] tunnel about to be completed. It will be open for commissioning tests in 2006 and for regular service in 2007. Excavation was completed in April 2005 and with some final construction works continuing, the project entered the installation phase. During this phase railway technical equipment is installed in the tunnel.

Initially, temporary ventilation equipment was to be used for the installation phase and this system was to be independent from the final equipment. As permanent equipment was not to be used, the initially proposed ventilation system for the installation phase consisted of 4 large temporary and redundant fan stations. Due to political pressure to realize saving potentials in 2004, a new ventilation system was developed by Zschokke Bau AG (now: Implenia Bau AG) and the restriction that hindered the use of permanent equipment was removed.

This system uses one main fan station to supply fresh air for the entire main tunnel system. Smaller stations are added for side branches, i.e. access galleries. In order to distribute the total flow to the 4 main flow paths, a control strategy was implemented ensuring the flow rate to each of the 4 main flow paths could be regulated. This system and the implementation of the hardware involved, along with the measured system response will be discussed in this report.

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[1] The NEAT is a Swiss nationwide program to prepare the railways to accommodate goods trucks to travel across the country on rail instead of on the road and to improve passenger traffic across the Alps. The Gotthard railway base tunnel is the core element of the NEAT program.

2. THE VENTILATION SYSTEM

During construction, the consortia were responsible for the ventilation of their respective areas. The construction works in the northern part were carried out by ARGE Satco, the central part by ARGE Ferden and the southern part by Matrans. The ventilation system for the installation works was put in place by Zschokke Bau AG where the consortium TU ABL was responsible for all installation works in the Lotschberg tunnel. Construction and installation works overlapped.

2.1. System overview

The Lotschberg tunnel consists of a single tube railway tunnel and a second parallel tube with a full cross-section extending almost the entire length of the tunnel (excepting approx. 5 km at the northern end).

The entire length of the east tube is fully equipped with railway technical equipment and is sealed with concrete lining. Only the first 13 kilometres of the south portal of the west tube is sealed with concrete lining and railway technical installations. The remainder of the west tube is designed for the access of rescue personal and as an evacuation route if need be. This section of the west tube is sealed with shotcrete. There are several caverns to accommodate railway technical equipment, i.e. converters, switches and the like.

The north portal lies at altitude of 780 m above sea level and the south portal at 650 m. The culminant point of the base tunnel is at 820 m. The portals at Mitholz and Ferden are located at 980 m and 1214 m above sea level, respectively.

In the final stage, there are 3 ventilation stations: Mitholz (supply), Ferden (supply) and Fystertella (extract). All stations are redundant. Fystertella allows the extraction of hot gases. The stations Mitholz and Ferden are located in access galleries, Fystertella uses a separate extraction gallery with a 400 m long chimney.

An overview over the tunnel system of the Lotschberg tunnel is given in **Figure 1**.

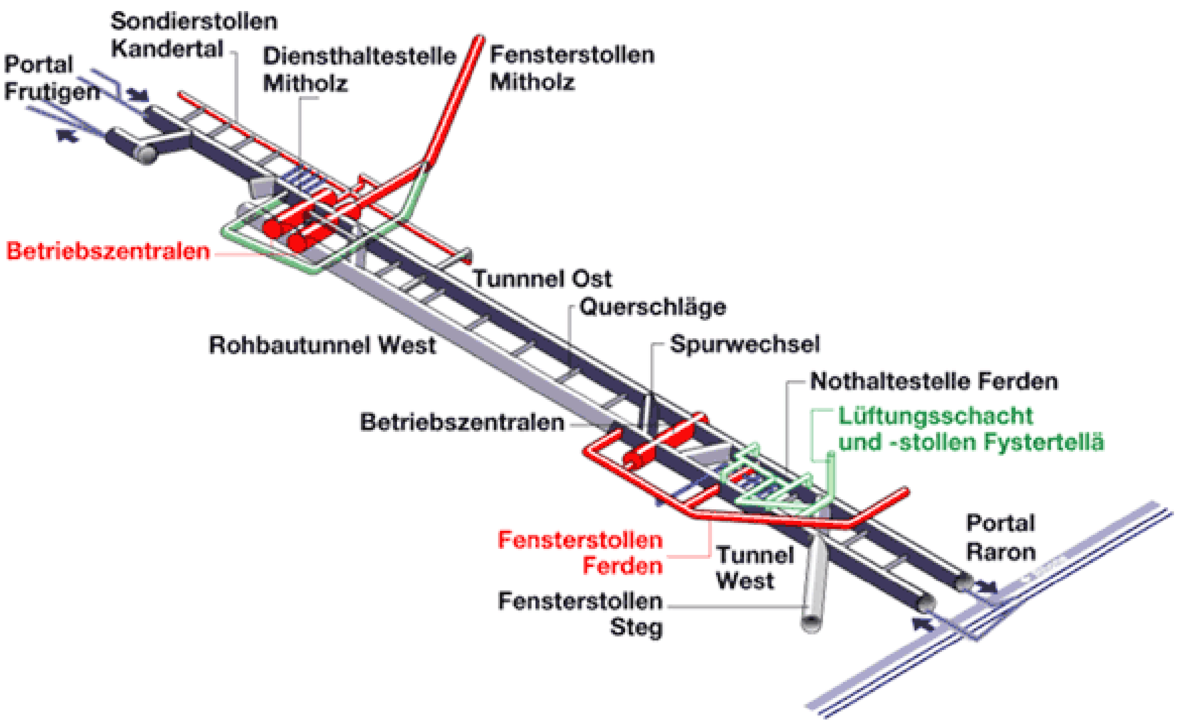

Figure 1: System overview of the Lotschberg Tunnel

2.2. Ventilation phases

The challenge of a ventilation system during the installation phase is that construction works and installation works can not be separated completely, i.e. some final structural works are still continuing while installation of railway technical equipment has commenced. Nonetheless, the different phases require specific ventilation systems to account for the particular needs of the different consortia. During the installation phase, the consortium of the TU ABL has to co-ordinate activities for the installation of tracks, catenary, cables, ventilation, safety installations, mechanical equipment, and telecommunication. The various responsibilities of the installation teams result in a large amount of vehicles with significant emissions of heat and pollutants. Accessibility of the entire tunnel must be ensured. The high standards for comfort and safety at work by the Swiss SUVA are strictly monitored and sanctions are severe. All this results in complex exigencies to the ventilation system.

The different phases for the ventilation systems can be seen in **Figure 2**. It shows the phase 0 where the construction companies are still in charge. The red lines indicate the initiation of the installation works under the existing ventilation regime. In phase 2, Zschokke Bau AG was responsible for ventilation in the southern part and in phase 3, the air locks in the centre were opened and one ventilation regime for the entire tunnel was established. Phase 1 is missing as it was taken over by the construction companies. There is a short transition phase where new requirements to the ventilation system are established to accommodate for commissioning tests towards the end of 2006.

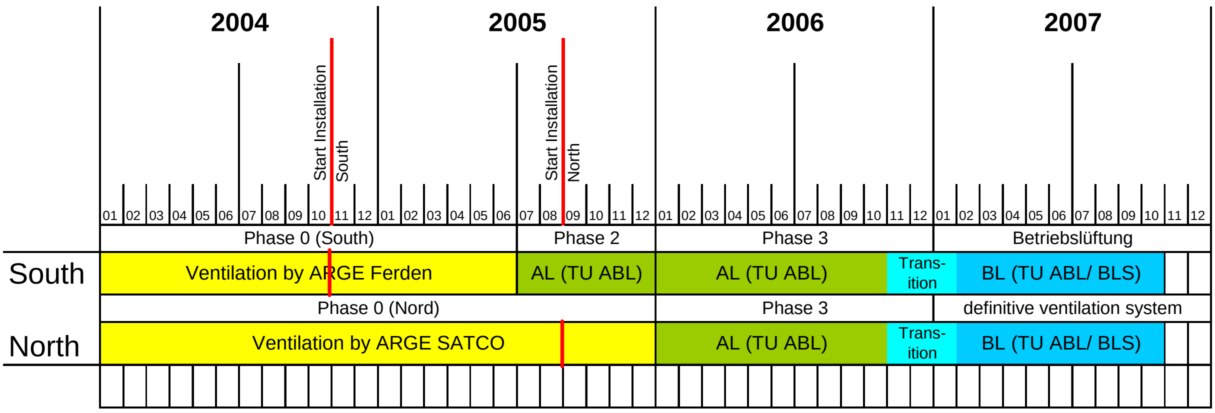

Figure 2: Phases from construction, installation, commissioning to permanent ventilation

2.3. Ventilation concept

There were separate ventilation concepts for phases 2 and 3. For simplicity, only the one for phase 3, which has been in operation since January 2006, will be discussed.

The main idea of the new ventilation system is to use primarily one fan from the powerful smoke extract station Fystertella. Its complete installation could be forwarded with respect to the initial work program for this purpose. All the final equipment is redundant and all scenarios can be run even in case of the failure of one of the fans. This ensures a high level of security for the ongoing works as well as a high availability in case of a failure or during maintenance works. It also allows undertaking the commissioning works for the definitive installations while the main fan used during the installation phase is renewed. Therefore, it must be ensured made sure that only one of the fans is used for normal operation; the other one is thus, if no major problem occurs, almost new at the time of hand-over to the final tunnel operator.

Side branches are ventilated with small additional fan stations. While the central extraction fan operates mainly at a constant flow rate, the distribution of the flow to the 4 main branches varies for the different scenarios.
For this purpose, 4 dampers of the emergency station are used as controllable flow restrictors. In the case of the Lötschberg Tunnel, these louvers have a dimension of 4 m x 5 m. The worm gear drive allows to enforce a fixed but arbitrary position.

Both main tunnel tubes are separated into North and South by strong railway tunnel gates, which open automatically for a train in movement. The east and west tubes are aerodynamically separated as all cross-vents are closed permanently with escape doors.

Figure 3 gives a schematic overview of the ventilation system of Zschokke Bau AG for the installation phase 3 of the Lotschberg tunnel.

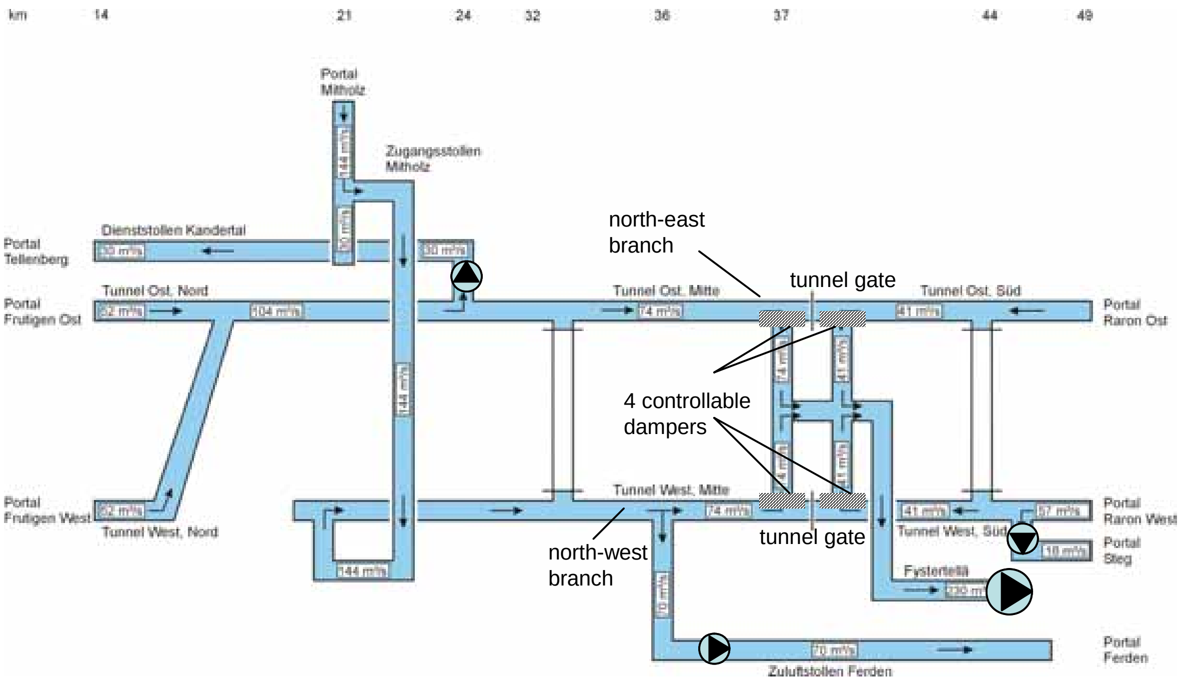

Figure 3: The ventilation Scheme of the Lotschberg tunnel during phase 3 of railway technical installations

3. FLOW MANAGEMENT BY DAMPERS

In most tunnel applications, dampers are used to open or close a flow path. Their use in an active control system invokes additional difficulties and requirements which have been overcome here.

3.1. Principles

In order to manage flow for the 4 branches in the Lotschberg tunnel, one damper in each branch is used to induce a variable pressure loss in all but one branch so that the pressure loss for all flow paths from their inlet to the point of reunion is equal.

With the louvers completely open, one of the flow paths has the largest pressure loss. This flow path is called the principal flow path. In the other flow paths, the louvers need to be partially closed in order to achieve pressure loss as high as the respective volumetric flow rates.

The pressure loss in a branch varies inter alia with the volumetric flow rate, vehicle movements, temporary flow restrictions, the position of doors and the weather. All these factors may vary with time on a short, medium or long scale. Also, if the flow rate in one branch varies with constant flow rate of the man fan, the flow rates in all the other branches are influenced immediately. This highlights the requirement of a continuous control of the damper settings. However, it is crucial not to change damper settings too radically as the system may cause a feed-back reaction which results in alternating over- and undershoots.

3.2. Damper characteristic

In most scenarios, the fan station in Fystertella functions at a constant volumetric flow, the distribution of the total flow is achieved by using the 3 louvers of all flow paths but the principal flow path as throttles. The required throttle action is achieved by the setting of the aperture angle. For this, it is necessary to be given the relation between pressure loss coefficient ζ and aperture angle α. This is usually known to the supplier of the equipment or must be found experimentally for this purpose.

In this case, the damper characteristic has been found experimentally on-site. The principle of the measuring setup is shown in **Figure 4**. The flow rate was measured in the collector corridor in a sufficiently long distance to the damper, where the flow distribution is almost homogeneous and the cross-sectional area is well known. The pressure difference was captured with a Testo 400 data logger using the Testo pressure probe No. 0638 1545. Pairs of flow velocity and pressure difference were continuously logged while the aperture angle of the damper was opened in intervals from 90° to 0°. The results are displayed graphically in **Figure 5** and analytically in the form of eq. (1).

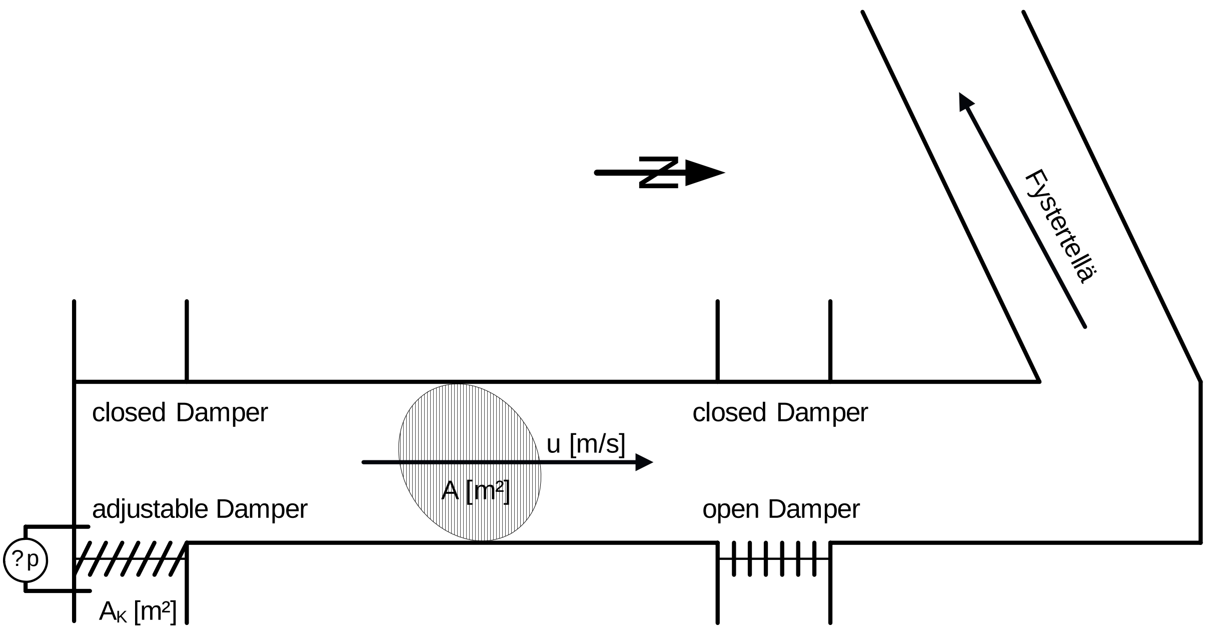

Figure 4: Measurement Setup

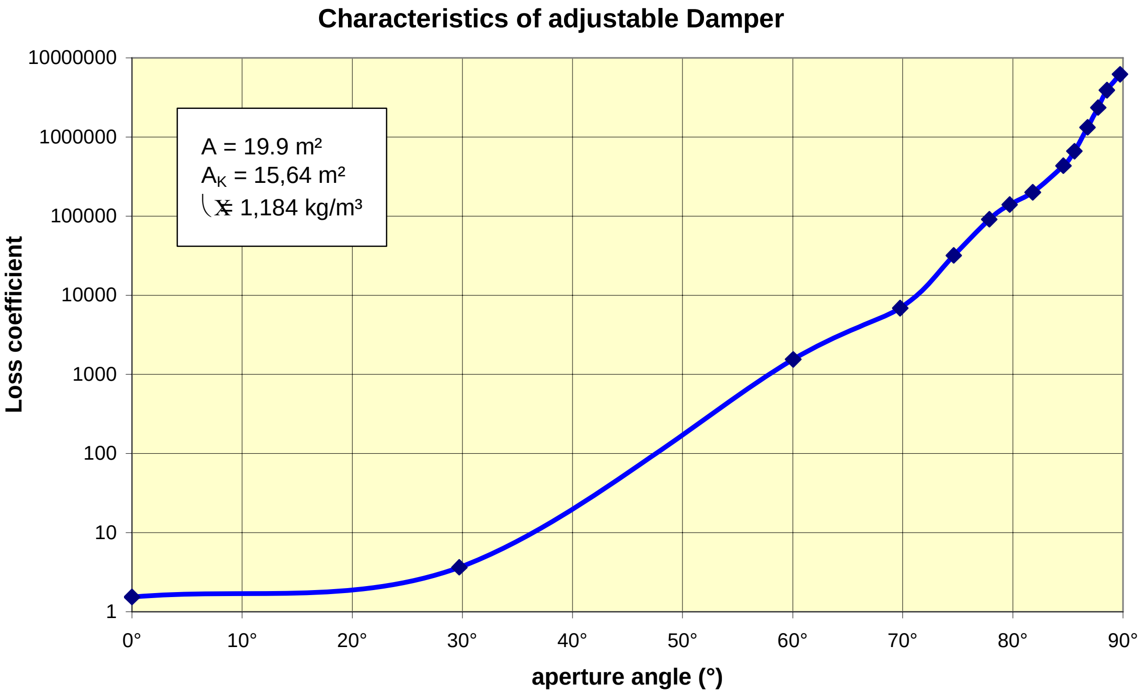

Figure 5: Pressure loss coefficient ζ over aperture angle α of a Sirocco louver used in the Lotschberg tunnel (α=0° --> open, (α=90° --> closed)

$$\zeta_i = f(\alpha) \rightarrow \alpha_i(\zeta_i), \tag{1}$$

where the loss coefficient ζ describes the total pressure loss in comparison to the dynamic pressure of the flow according to $\Delta p = \zeta \frac{\rho}{2} u^2$.

3.3. Required aperture angle

There are 2 ways to determine the required aperture angle α of the louver.

1. Analytical determination by model assumptions
2. Step-wise adaptation by nominal / actual value comparison

3.3.1 Analytical Approach

In modern SPC[2] it is possible to request an implementation of a simplified tunnel model. As the programming language for the SPC is rather complicated, it was decided to implement the tunnel model to the superior control system, where it was possible to use a higher programming language to read actual measurement values and to compute the required aperture angle.

A simplified system consisting of 4 flow paths with one local sink is presented below in **Figure 6**.

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[2] SPC: storage programmable control

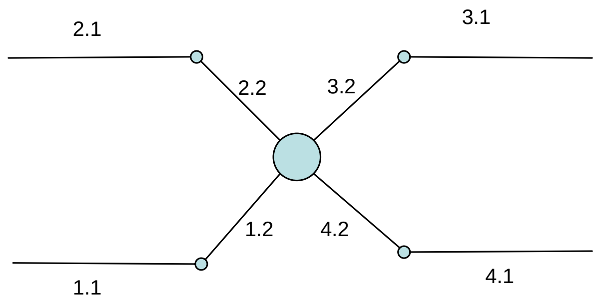

Figure 6: Simple node model with 4 flow paths which are each split into 2 parts

In the first step, the required depression in the sink point is calculated by assuming all dampers are opened (α=0°). The required depression is then the minimum value of the expression in accolades, which is evaluated for each flow path. The sum in eq. (2) is over all sections along the flow path.

As the cross-sections and flow rates along the flow path may vary, especially if there are reunion or split points, it is useful to refer all loss coefficients to an arbitrary reference cross-section. This is why A_0 has been introduced.

$$p_0 = \min\left\{ p_i - \sum\left[\zeta_i \frac{\bar{\rho}}{2}\left(\frac{\dot{V}_i}{A_0}\right)^2 + \zeta_{K,0°}\frac{\rho}{2}\left(\frac{\dot{V}_i}{A_0}\right)^2 + \bar{\rho} g\left(h' - h_I\right)\right]\right\}, \qquad (2)$$

where

i	::	index for any flow path	
I	::	index of the principal flow path	
’	::	indicates value at the sink point	
p_0	::	required depression at the reunion point	Pa
p_I	::	pressure at portal	Pa
A_0	::	reference area for ζ	100 m^2
A_K	::	free area of louver	m^2
$\dot{V}$	::	volumetric flow rate	m^3/s
$\zeta_{K,0°}$	::	pressure loss of completely open louver	
$\bar{T}$	::	average temperature in flow path	K
g	::	gravity	9.81 m/s^2

Eq. (2) thus yields the required pressure level (depression) at the point of reunion. All flow paths must, with the defined flow rates, yield the same pressure. As only the principal flow path I reaches this pressure level with an open damper, all the other dampers must be partially closed. Therefore, eq. (3) needs to be solved for ζ using p_0 from eq. (2).

$$p_0 = p_i - \sum\left[\zeta_i \frac{\overline{\rho}_i}{2}\left(\frac{\dot{V}}{A_0}\right)^2 - \zeta_{K,i}\frac{\rho_i}{2}\left(\frac{\dot{V}}{A_0}\right)^2 - \overline{\rho}_i g\left(h' - h_i\right)\right] \rightarrow \zeta_{K,i} \qquad (3)$$

For the use in the SPC, it is necessary to invert eq. (4).

$$\zeta_i = f(\alpha) \rightarrow \alpha_i(\zeta_i) \qquad (4)$$

which finally gives the required louver setting α_i.

Depending on the actual height differences and the actual variation of density, particular attention must be paid to the evaluation of the average densities along the flow paths. A problem in this analytical approach is also the precise determination of the absolute portal pressure, which, even if the best available equipment is used, can only be precise by 10-50 Pa; and sometimes, this is the pressure loss of an entire flow path. The analytical approach requires therefore a minute calibration after entering into service.

The major advantage of this analytical approach is that the system reaction is not effected by short term changes which may cause an undesirable system reaction.

In the case of the Lotschberg tunnel, the analytical approach is used to determine the initial aperture angle of the 4 controllable dampers after a change in the scenario.

After the initial angle has been reached, it is adjusted by a nominal / actual value comparison which is described in the next section.

3.3.2 Nominal / actual value comparison

If the flow rate in one of the branches leaves the allowed bandwidth, it is necessary to adjust the aperture angle of the dampers.

During normal operation of the Lotschberg tunnel, the trailing average over 5 minutes of the measured instantaneous flow rates is used to determine if there is a deviation. In the emergency scenarios, the reaction needs to be much faster; the average over 30 sec. is then used.

Especially in case of large deviations from the nominal values and in order to avoid long control cycles, it is desired to reach the new required aperture angle in only one step.

In order to achieve this, the assumption is made that the new ζ-value is proportional to the old ζ-value multiplied by the square of the relation of actual to nominal volume flow as given in eq. (5).

$$\zeta_{new} = \zeta_{old}\left(\frac{\dot{V}_{actual}}{\dot{V}_{no\min al}}\right)^2 \qquad (5)$$

It has been found that relation (1) can well be approximated by an exponential function of the form

$$\zeta = a * e^{f\alpha} \qquad (6)$$

with *a* and *f* being empirical coefficients. Combining eq. (6) and eq. (5), the new angle α_{new} is found according to

$$\alpha_{new} = \alpha_{old} + \frac{1}{f}\ln\left(\frac{\dot{V}_{actual}{}^2}{\dot{V}_{no\min al}{}^2}\right) . \qquad (7)$$

3.4. Measured values

Finally, an indication of the system reaction shall be given. For this purpose, the main fan at Fystertella was set to 60 m^3/s. All louvers except for the one in the north-west branch were closed. During the first 30 sec., the north-east damper was opened as well. Then, the north-west damper was gradually closed (see **Figure 8**) and the system reaction observed.

Figure 7 displays the flow rates in both branches. It can be seen that the flow rate in the north-west branch was initially at 60 m^3/s. After opening the neighbouring damper, the total flow rate is split according to the pressure losses in both paths. Due to the increasing pressure loss in the north-west branch caused by closing the damper, the flow rate there decreased, while the flow rate in the north-east branch augmented.

Note that the flow distribution was held within a small range of 5 m^3/s for most of the aperture angles. This rather concise example is representative for the observations made in the first months of operation. Thus, flow management by dampers is technically feasible.

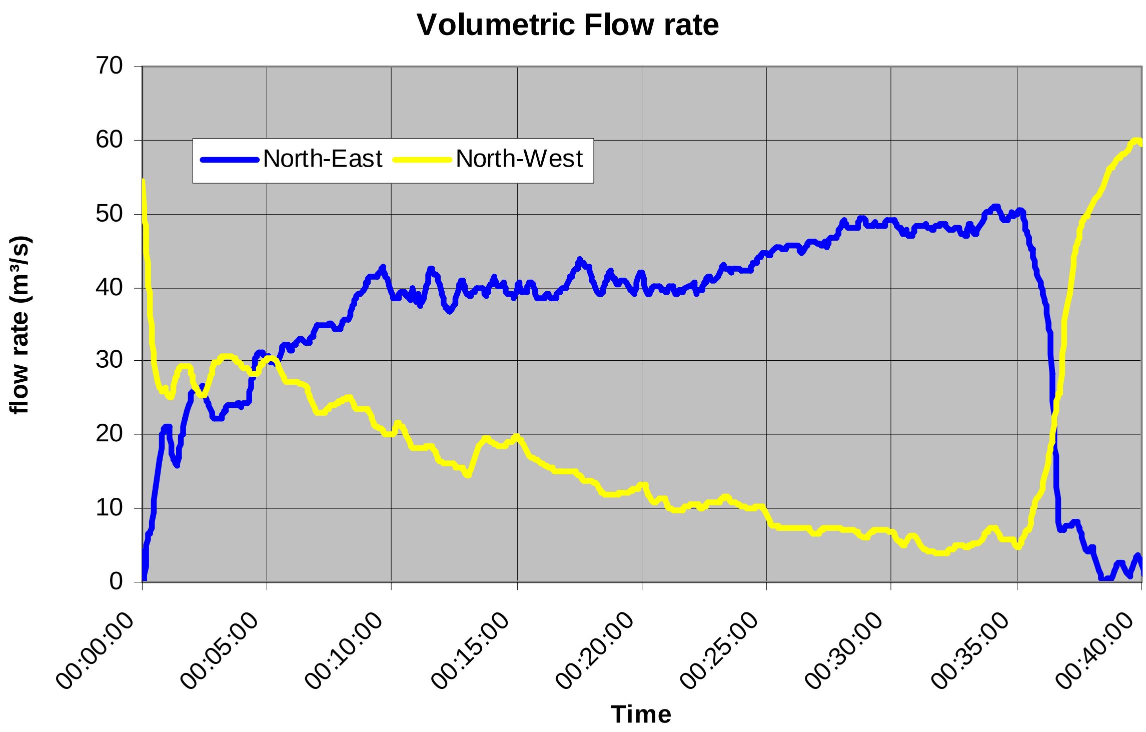

Figure 7: Volumetric flow rate in the north-west and north-east branch with both southern dampers closed all the time

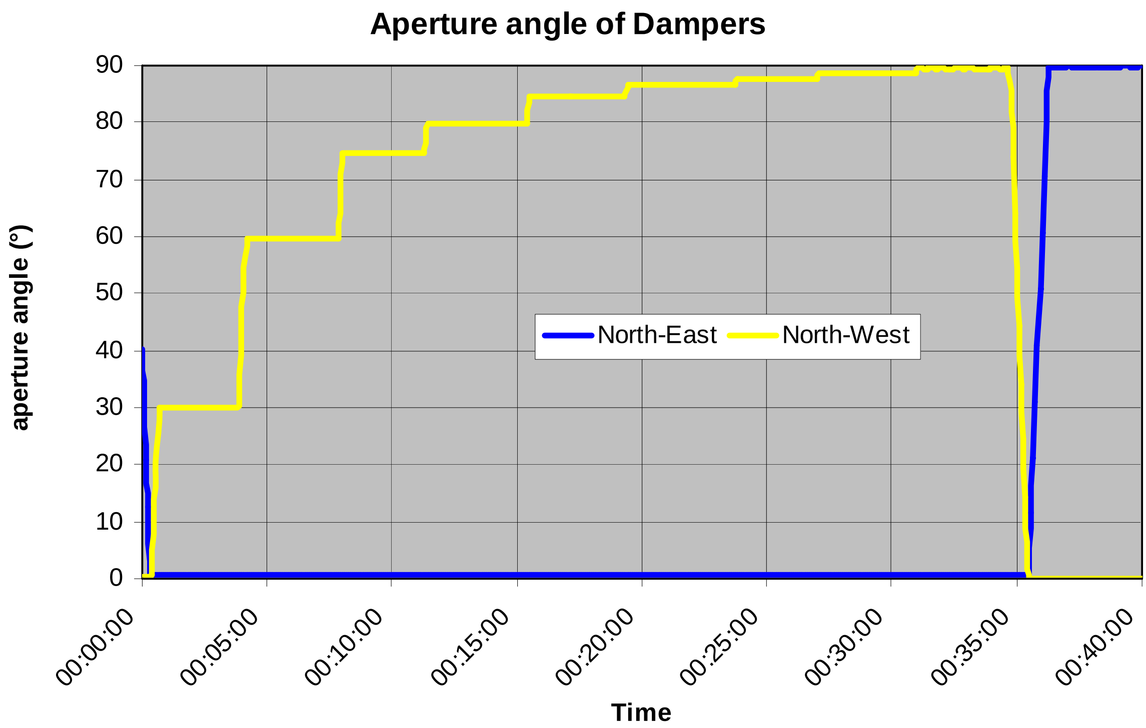

Figure 8: Aperture angle over time (0° --> open, 90° --> closed)

4. CONCLUSIONS

In the Lotschberg tunnel, a ventilation system for the installation phase was established. This system utilized one central fan to ventilate the roughly 70 km of main tunnel system. For the side branches, i.e. access galleries, additional smaller stations were installed. Both main tunnels were split into a north and a south section by large gates which are designed to open as a train approaches. This way, the main tunnel system is split into 4 main air paths.

Using controllable dampers with a worm gear drive and applying a 2 step control strategy, the flow distribution on the 4 main branches can be well controlled. The control strategy has to consider short, medium and long term changes in the boundary conditions.

With respect to energy consumption, this system is not ideal as the dampers are used to induce additional losses. However, this is only a subordinate aspect in a provisional ventilation concept which is in place for a comparably short period of time. If this system was to be used during normal operation in a permanent installation, the total costs of using one controllable fan for each flow path must be assessed.

However, this system is well in-line with the typical major requirements during the installation phase of a large railway tunnel. In particular, no major additional installations are necessary, the logistic is disturbed minimally and access to all parts of the tunnel can be achieved.

MEANS TO IMPROVE METRO STATION ENVIRONMENT WHEN VENTILATION SHAFTS ARE IN CLOSE PROXIMITY TO PLATFORMS

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ABSTRACT

Conventionally tunnel ventilation shafts are constructed at a certain justified distance from stations. They serve as pressure relief shafts during normal operation in order to divert as much air as possible from the tunnel, thereby minimizing the blast in the station. Insufficient draught relief may result in excessive train induced flows in the public areas of the station. This paper discusses the impact of very close proximity of tunnel ventilation shafts to station platforms on the environment, and the means that help to mitigate the problems. The effectiveness of the proposed technical devices is verified by CFD analysis.

Keywords: tunnel ventilation, draught relief shafts, station air velocity and rapid pressure change

1. INTRODUCTION

Train piston action induces air motion and air pressure changes. High air velocities and rapid pressure changes in metro systems can be a source of passenger discomfort and also be harmful to mechanical equipment and structure. This paper addresses the issues of how relocating the ventilation shaft closer to the ends of the platform will affect the station environment, and pressure changes in the tunnel, and on board the train.

Distance between the station portal and the draught relief shaft is an important value that affects station aerodynamics. When the required (computed) distance between the station portal and the draught relief shaft is greater than the actual distance, the maximum velocity in the station will occur before the train approaches the draught relief shaft (SES Handbook 1976). In other words, when the draught relief shaft is too close to the station, people standing on the platform waiting for the train may experience high pressures and high air velocities before the train reaches the draught relief shaft. The shaft, in this case, is not effective. A practical shaft location varies from 60 feet (20 m) to 300 feet (90 m). For example, 60 feet (20 m) could be found in the Toronto subway design and etc. This distance allows for piston pressure relief from the trains and a decrease of air velocities at the station. It will also decrease the station impact on tunnel airflow for smoke control in case of a tunnel fire emergency.

Relocation of the ventilation shafts closer to the station to within approximately 15 feet (4.5 m) of the end of the platform, may be considered as the unique nature of the design as it effects the station environment. Such relocation may be required for geotechnical and economical considerations due to the soil conditions and metro station overall length limitations.

2. IMPACTS OF VENTILATION SHAFTS LOCATION ON STATION ENVIRONMENT

2.1. Pressure Transient Impact

The purpose of the draught relief shaft (one of the functions of ventilation shafts) is to divert as much air and pressure as possible from the tunnel, thereby minimizing the blast in the station. Insufficient draught relief may result in excessive train induced flows in the public areas of the station. Taking into consideration relatively low metro train speeds, problems with pressure transients are not expected at stations and in the running tunnels (see fig. 1).

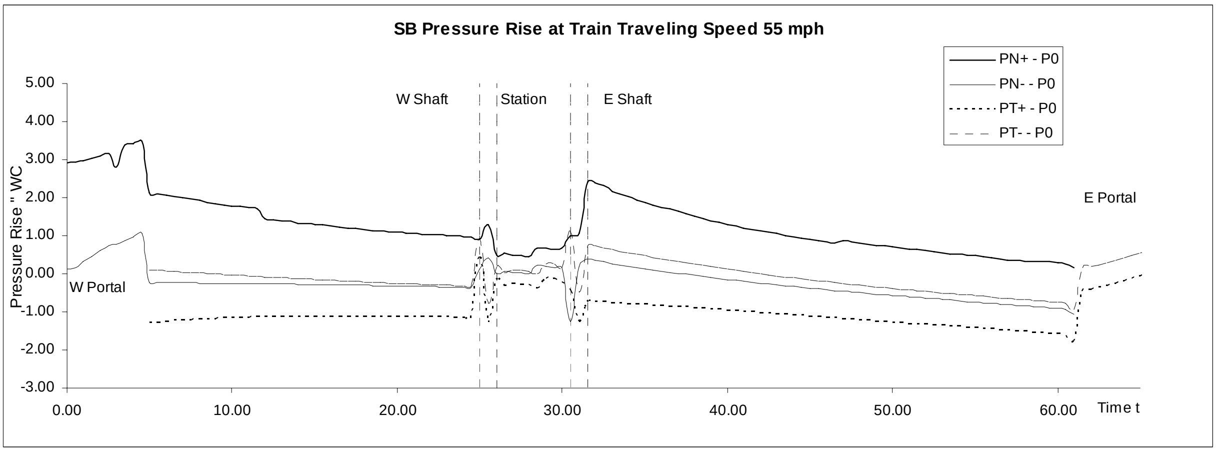

Fig. 1: Pressure rise inside the tunnel as a function of train travel time

The major impact of relocating the ventilation shafts closer to the ends of the platform is expected to be on air velocities at the platforms as discussed below.

2.2. Air Velocities at the Platform

The effect of air velocity increase at the platform of metro stations can result in the following:

- Discomfort to passengers;
- Hats, bags, etc. to be blown away / over;
- Raising dust and lose paper;
- In a worst-case scenario, people could stumble or fall over.

Factors that affect airflow at the station are:

- Train speed;
- Distance from the station where train starts deceleration and where the train starts acceleration when leaving the station;
- Single or multiple train scenario;
- Draught relief shaft cross section area;
- Location of the draught relief shaft relative to station;
- Cross passage area and features;
- Draught relief shaft length and resistance;
- Resistance (friction loss) in the tunnel section between the draught relief shaft and the station portal;
- Station impedance; and
- Expansion loss as tunnel air expands into the station platform area.

This paper focuses on the location of the draught relief shaft relative to the station. Air velocities at the platform should not exceed 5 m s^{-1} (1000 fpm). The maximum airflow depends on the ratio of air speed to train speed as well as the resistances to flow in the tunnels, up the vent shafts, and through the station. Air jet velocity entering the station will depend upon the velocity of the air in the tunnel just beyond the draught relief shaft, but before the station:

$V_{jet} = V_{tunnel}$(1-mass flow ratio for the draught relief shaft)

Areas along the first 50 ft (15 m) to 150 feet (45 m) of the platform adjacent to the approach tunnel may be exposed to peak jet velocities. As the air jet expands, its velocity is reduced.

Preliminary estimates, based on braking distances and up to 55 mph (88.5 km h^{-1}) train speeds for the vehicle approaching the station from either side, indicate predicted maximum station air velocities to be 20% higher than the maximum allowed of 5 m s^{-1} (1000 fpm) if no means for velocity reduction is implemented. Such air velocities will create moderate breeze, raising dust and loose paper. The resultant manually estimated air velocities require verification.

It should be noted that Mr. Pope (Pope and others 1976) stated “the largest mean flow velocities on the platforms and in the cross passages are little affected by increasing the distance between the shafts and the station head walls. There is a small increase in the peak flow velocities in the platform tunnels. The peak flow velocity in the cross passages increase quite significantly (by about 16%), however, as the separation of the draft relief shafts from the headwall of the station is increased from 0 to 20 m [60 ft]. Increasing the separation further only results in relatively small further increase in the peak flow velocity through the cross passage.”

3. MEANS TO IMPROVE STATION PLATFORM ENVIRONMENT

The goal is to improve the efficiency of the draft relieve shaft. A short length of tunnel between the blast shaft and the station portal can be used to increase overall impedance. The intent of the design is to create additional resistance and turbulence in the short tunnel, between the station portal and the ventilation shafts, and to direct as much air flow as possible to the ventilation shafts that serve as draft relief shafts under normal train operation. This short tunnel length should accommodate track tunnel dampers.

Several potential solutions were reviewed that address the means to reduce the station air velocities:

- An orifice plate was proposed by engineers from the AEA Technology Rail, UK for railway tunnel from Sweden to Denmark (T. Prevezer, J. Johnson, 2003). The orifice plate was constructed in concrete as part of the tunnel wall and designed to constrict the flow locally and provide a high pressure loss at its location. In theory, if the orifice plate is located between a draught relief shaft and station entrance, then the pressure loss would discourage the airflow from travelling down the tunnel towards the station. Instead, it would encourage airflow to travel up the airshaft, where there would be an easier path to the open air. Simulations showed that the orifice plate could provide a significant influence on the flow velocity in the station. The optimum design, they say, could reduce the air velocity by the same amount as reducing the speed of the train by 40 km/hr. Air velocities at the station would reduce by 15% to 20%. The effectiveness of the orifice plate is fairly insensitive to its location within the tunnel between the station and the air shaft.

- Baffle plates were proposed to reduce station air velocity by engineers from the Technical University of Vienna, Austria (P. Paseva, H. Sockel, 2000). Analyses were performed with 15% reduction of cross section as well as with 20% reduction of cross section. The idea and theory is very similar to the one presented above.
- Isolation of the station from the tunnel by air jets and air curtains are discussed in the SES Handbook (1976). The air jet concept has been proposed to isolate the station from the tunnel. This is an air jet located between the draught relief shaft and the station, which is used to deflect the incoming tunnel air up into the draught relief shaft. Potential problems with noise, control, cost, and train operations are evaluated. This solution seems expensive, difficult to implement, and is not considered.
- Space orifices at a distance of 8 feet (2.5 m) to 11 feet (3 m) apart, along the tunnel between the draught relief shaft and the station portal, are recommended by Russian engineers (V.I. Tcodikov 1975). This introduces a significant increase of pressure drop in the tunnel between the draught relief shaft and the station portal.
- Orifice (baffle) plates along with airshafts, as a means to reduce underground station air velocity, are considered for installation as part of the City-tunnel-project in the tunnel that connects Sweden and Denmark (T. Prevezer, T. Johnson, 2003). In theory, if the orifice plate is sited between a specifically located airshaft and the station entrance, the pressure loss would discourage the airflow from travelling down the tunnel, towards the station, and instead it would encourage it to travel up the airshaft, where there would be an easier path either to the open air or to the opposite track as noted above. The additional blockage did not adversely affect the tunnel pressures.

3.1. Proposed Design Improvements

The need to relocate ventilation shafts as close to the platforms as practical came due to the geotechnical reasons as the result of the soil conditions. Our proposed design changes (see fig. 2) include extension of the platform tunnel to the track damper area, relocation of the ventilation shafts closer to the station to within approximately 15 feet (4.5 m) of the end of the platform, and construction of a platform headwall (an orifice plate). This platform headwall leaves the minimum acceptable clearance for the vehicle and serves to divert pressure waves travelling in front of the vehicle into the draught relief chamber and shaft, and hence, decreases the airflow to the platform area itself. This isolated end section of the platform tunnel forms a draught relief chamber at the entrance to the ventilation (draught relief) shaft.

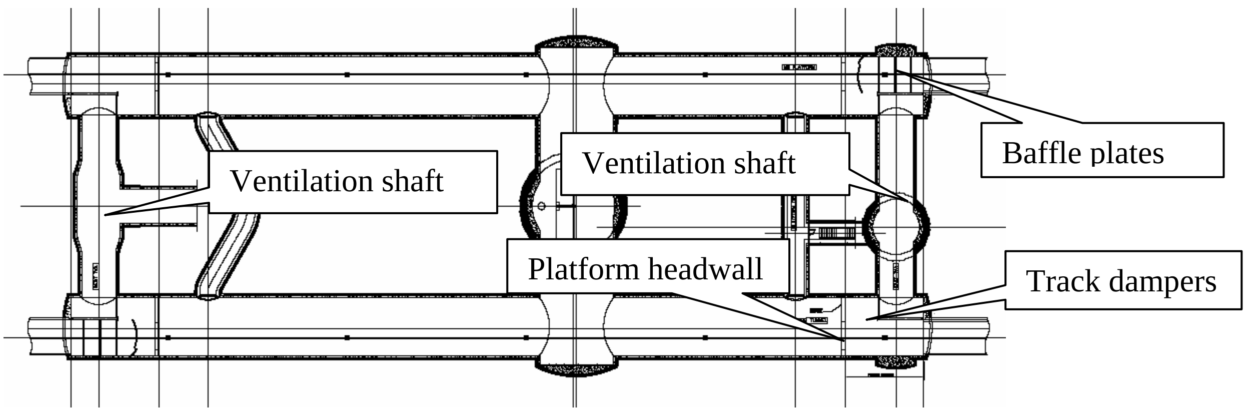

Fig. 2: Proposed changes due to ventilation shafts relocation.

We also propose to use baffle plates (orifice plates) spaced at a distance of 8 feet (2.5 m) along the draught relief chamber. Plates should be constructed out of concrete as part of the tunnel wall and designed to constrict the flow locally and provide high pressure loss at their location.

Baffle plates (orifices) are good for both – reduction of station air velocity and reduction of pressure waves. When a train enters a tunnel, a compression wave is induced which passes through the tunnel at the speed of sound relative to the velocity of air. During the propagation of a compression wave along the tunnel, the gradient of the wave increases due to non-linear effects (“steepening”). Baffle plates reduce steepening of the pressure waves. (P. Paseva, H. Sockel, 2000)

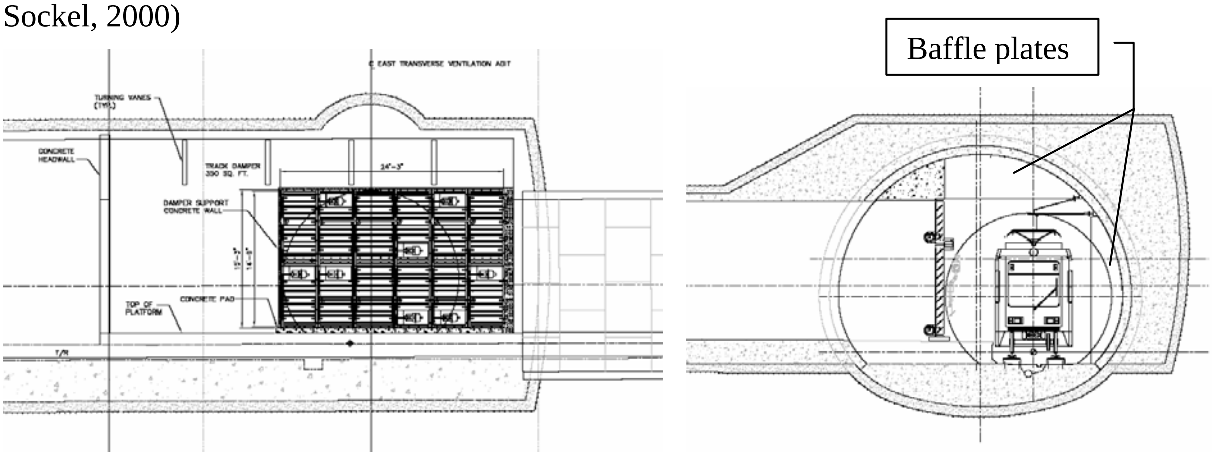

Fig. 3: Damper chamber sections with baffle plates, track dampers and platform headwall

Clearly, the ability to use an orifice plate is constrained by the size of an existing tunnel since the orifice plate will reduce the available tunnel cross-section area locally. The free area (defined as the tunnel cross section area minus the orifice plate area) must still allow enough space for the train vehicle dynamic envelope, catenaries equipment, fire standpipe and walkway. Thus our design includes an extension of the platform tunnel to accommodate track damper and orifice (baffle) plates. Airflow from the tunnel will have to go through a set of sudden expansions and contractions that would lead to increased pressure losses and would direct part of the airflow into the ventilation shaft. Increased tunnel area will locally decrease air velocity, while plates will increase turbulence, creating secondary airflows behind them, leading to increased pressure drops. The platform headwall will serve a dual purpose – firstly as the last barrier (resistance) before airflow gets into the platform tunnel and will protect the platform adjacent to the headwall from high air velocities. Secondary, it will serve as an architectural and security feature that will hide the track dampers, plates, and fire equipment from public at the station. We should note that this is true that the platform headwall will create local increase of air velocity, however the resistance it creates to the airflow will eventually decrease average airflow through the station and hence platform air velocities.

Using train speed restrictions to control air velocities is very effective, but may be very expensive and should be considered only as the last means. Platform screen doors are not considered.

4. AIR VELOCITY AND RAPID PRESSURE CHANGE ANALYSIS

Analyses were performed using the SES methodology (SES Handbook, 1976) for the scenarios when trains by-pass the station at 88.5 km h^{-1} (55 mph) and when trains operate according to the train operation schedule. (Fig. 4) Results were verified and analysed in details using sliding mesh features of the Computational Fluid Dynamics (CFD) Fluent program.

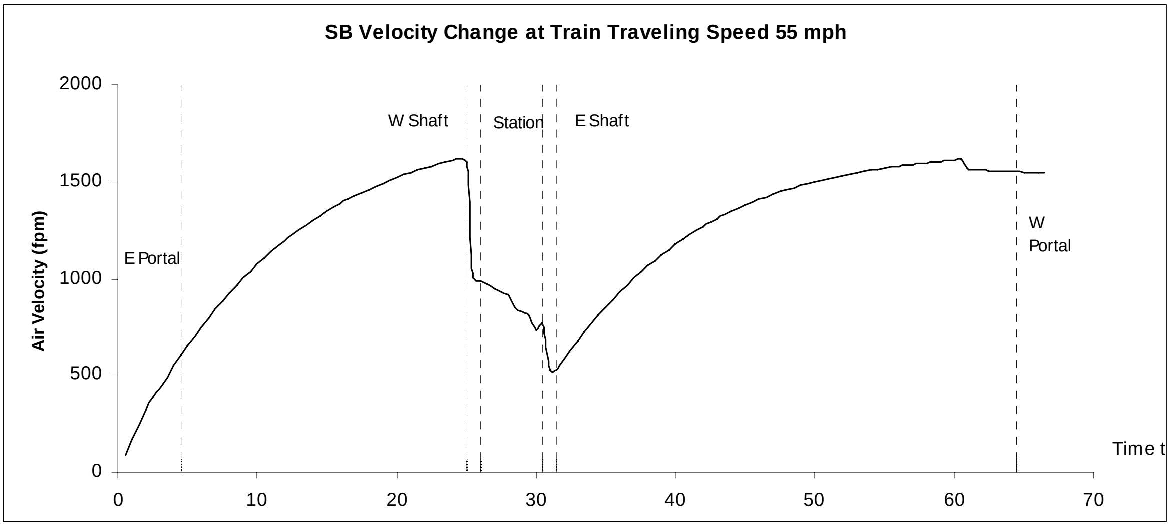

Fig. 4: Air velocity as a function of train travel time

Using Computational Fluid Dynamics the following cases were analysed:

- Two trains running from opposite directions at constant speed 64 km h^{-1} (40 mph) passing the station with ventilation shafts located at 60 feet (20 m) from platform ends (typical ventilation shaft location).
- Two trains running from opposite directions at constant speed 64 km h^{-1} (40 mph) passing the station with ventilation shafts located at 15 feet (4.5 m) from platform ends as required. No orifices in the damper area modelled.
- Two trains running from opposite directions at constant speed 64 km h^{-1} (40 mph) passing the station with ventilation shafts located at 15 feet (4.5 m) from platform ends. Orifices in the damper area modelled to compare results with the previous case.
- Two trains running from opposite directions at variable speed passing the station according to the train operation schedule with ventilation shafts located at 15 feet (4.5 m) from platform ends. Modelling was performed with and without orifices in the damper area.
- Detailed 3D Aerodynamic analysis of the damper area with and without orifices / baffle plates. The sensitivity analyses were used for setting time dependant pressure boundary conditions.

As a result of the analysis we confirmed the proposed design changes:

- Extend the platform tunnel length to the end of the vent shafts to accommodate track dampers, to accommodate orifices and baffle plates.
- Install a station platform headwall at each end of the public platform area to separate the public area from a damper chamber area and to create an effect of the orifice, increasing resistance to the airflow and creating an aerodynamic shade area at the platform for public use.
- Install a set of baffle plates / orifices on the inbound side at the track damper chamber, as shown in fig. 2, 3, to direct tunnel airflow to the ventilation shaft.

The baffles installed in the outbound damper chamber, however, create additional pressure to the airflow to further escape. Thus the effectiveness of the baffle plates in the outbound chamber was questionable and the final decision was to eliminate them.

5. HOW RELOCATING THE VENTILATION SHAFTS CLOSER TO THE END OF THE PLATFORM WILL EFFECT THE PERFORMANCE OF THE TUNNEL VENTILATION SYSTEM

The following design changes may effect the air distribution:

- Relocation of the ventilation shafts closer to the east and west ends of the station to within approximately 15 feet (4.5 m) of the end of the platform may result in greater airflow getting into the station and less flow getting into the tunnels;
- Baffles, orifices and platform end walls may provide an opposite effect increasing the resistance of the airflow to get to the station and improving airflow into the tunnel;
- Tunnel size increase in the track damper area allows for less resistance and thus greater station airflow.

If balancing between the tunnel and station airflow is required, the motorized deflecting vanes should be installed to control air distribution. However, motorized deflecting vanes will:

- increase the airshaft pressure drop that will effect the fan pressure and horsepower;
- make the control system more complicated;
- increase the capital and maintenance costs.

Thus the question that needs to be answered by this study is the necessity of the motorized deflecting vanes installation for fire / smoke management. The focus of this study is to find out if the vent shafts relocation would cause the misbalance so much, that motorized deflecting vanes or other means would be needed to balance the system properly.

A comparison CFD study performed to find out the system balancing in order to make a decision on motorized deflecting vanes:

- Supply and exhaust tunnel ventilation fans operation with ventilation shafts located at 60 feet (20 m) from platform ends (typical ventilation shaft location). Full tunnel and station length was modelled.
- Supply and exhaust tunnel ventilation fans operation with ventilation shafts located closer to the station at approximately 15 feet (4.5 m) from platform ends with and without orifices and baffles.
- A detailed 3D CFD analysis of the track damper area with orifices and baffles. Tunnel ventilation fans running in supply and exhaust modes. The results of detail analysis help to understand aerodynamics around baffles, orifices, platform end wall and in the damper chamber.

If the difference of airflow between the original geometry and the new geometry exceeds the allowable misbalance, the motorized deflecting vanes are needed. Otherwise no deflecting vanes are required.

When modelling the full tunnel length, it would take a huge amount of computer memory and time to do 3D CFD analysis. Thus 2D CFD analyses were performed for the entire tunnels that were used for boundary conditions of a detailed 3D CFD analysis of a damper chamber (see fig. 5). Nevertheless a 2D model can not represent all the features as a 3D model can, we believe that based on the Reynolds Re number modelling, we can get a close result that can be further verified.

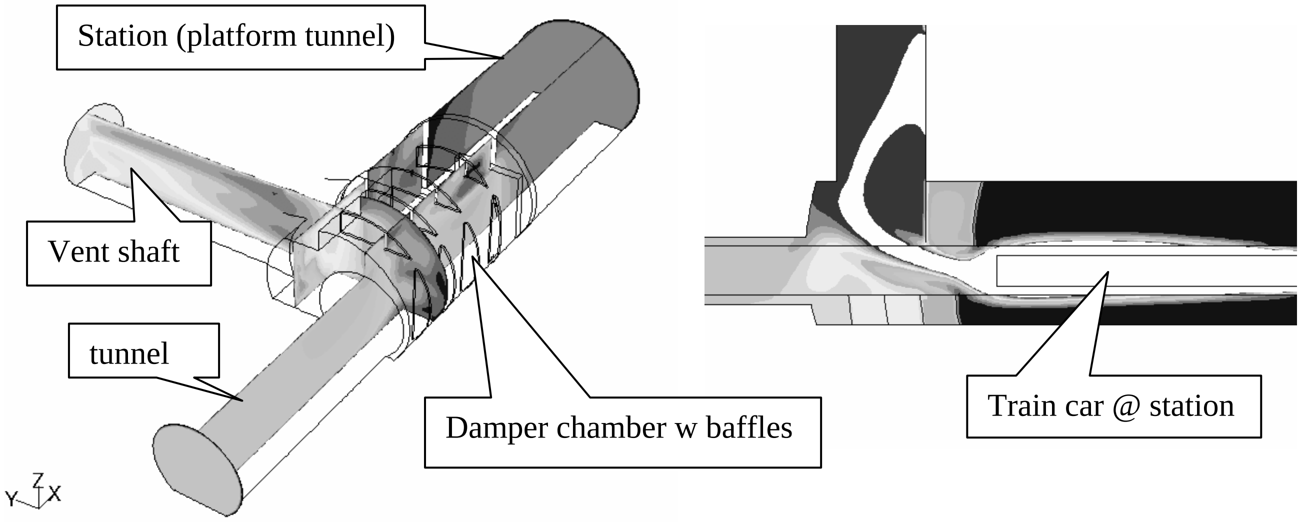

Fig. 5: CFD analysis of track damper chamber with baffles and end platform wall

The main conclusions that come from the results of the analyses are:

- Relocation of the ventilation shaft close to the platform impacts on airflow distribution from the tunnel ventilation system by increasing airflow from / to the station tunnels and decreasing airflow from/ to the running tunnels;
- When the ventilation shaft is closer to the station, we get more airflow to the platform tunnel and less airflow to the running tunnel, as proved by the CFD results with NO baffle plates. In this case, the motorized deflecting vanes may be effective to direct the airflow into the running tunnel.
- Baffle plates and orifices significantly effect the airflow distribution. This was proved by results of CFD analysis with baffle plates, and by a 3D CFD analysis that show complicated aerodynamics around baffle plates, and the resistance the baffle plates create to the airflow.
- Complicated aerodynamics and impact of baffle plates and other design features cannot be evaluated using a 1D computer program, or manual calculations, and requires CFD analyses.
- Orifices and baffle plates proposed for platform air velocity control create a significant resistance for the ventilation air, and create an opposite effect by increasing airflow from / to the running tunnels and decreasing airflow from / to the platform tunnels;
- When baffle plates are installed, the resistance they create to the airflow decreases the flow rate the station tunnel gets and increases the airflow through the running tunnel. No motorized deflecting vanes are needed to direct airflow into the running tunnel, but airflow to the platform tunnel is to be considered.
- No motorized deflecting vanes are recommended for air distribution tunnel ventilation system control;
- No baffle plates are needed in the outbound damper chamber, but baffle plates in the inbound damper chamber should remain for platform air velocity control and for ventilation system balancing;

The changes to the ventilation shafts relocation impact the pressure drops and eventually the pressures required by the fans. This happens due to changes to track dampers locations, the addition of baffles and orifices, and also due to changes in air distribution between the tunnel and station. However, overall impact on the fans horsepower was found insignificant.

6. CONCLUSIONS AND DESIGN RECOMMENDATIONS

Calculations and CFD analyses demonstrate that relocation of the ventilation shafts closer to the ends of the platform does not impact significantly on the pressure transient results and that the pressure transients at the train and in the station are acceptable.

Movement of the ventilation shafts close to the platform effects on platform air velocities. However, by implementing design recommendations, station platform air velocities will be within the comfort limits under normal operating conditions. When a train travels at 55 mph (88.5 km h^{-1}) (higher than the design speed) and bypasses the station at that speed, some precautions should be taken for people standing at the platform, or the train should slow down to a speed of 41 mph (66 km h^{-1}). The platform air velocities locally may slightly (within 10%) exceed the 1000 fpm (5 m s^{-1}) design criteria limit, which should not create any major problems.

Also, maintenance people should take some precautions when working in the ventilation shaft in wintertime, when two trains simultaneously pass the ventilation shaft at speed 55 mph (88.5 km h^{-1}), and fan dampers are closed.

Results of air flow CFD analysis confirmed that relocating the ventilation shafts closer to the platform ends with the proposed design changes allows to control platform air velocities within the design criteria limits, or close to them when trains bypass the station at 40 mph (64 km h^{-1}), or operate according to the design schedule. Results also confirmed the effectiveness of the orifices / baffle plates at the inbound side that can decrease the airflow to the platform for up to 16% by directing airflows to the ventilation shafts. When orifices / baffle plates are not installed, platform air velocities may slightly exceed 1000 fpm (5 m s^{-1}).

Based on the results of the analysis, the following design changes are recommended to be included in the relocation ventilation shaft:

1. Increase the platform tunnel length to the end of the vent shafts to accommodate track dampers, to accommodate orifices and baffle plates.
2. Install a station platform headwall at each end of the public platform area to separate the public area from a damper chamber area and to create an effect of the orifice, increasing resistance to the airflow and creating an aerodynamic shade area at the platform for public use.
3. Install a set of baffle plates / orifices to direct tunnel airflow to the ventilation shaft under normal operation and to balance air flow created by the tunnel ventilation system in fire emergency.
4. No motorized deflecting vanes are needed for air distribution tunnel ventilation system control;
5. No baffle plates are needed in the outbound damper chamber, but baffle plates in the inbound damper chamber should remain for platform air velocity control and for ventilation system balancing;
6. Impacts on the fans horsepower requirements are insignificant.

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USE OF DUST FILTERS DURING THE CONSTRUCTION OF TUNNEL SYSTEMS

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Gamsjäger H., Wienerwaldtunnel (Vienna Woods Tunnel) consortium

BASIC PRINCIPLES

During tunnel construction a large quantity of dust develops through the different work process, such as boring, blasting, milling, etc. Aeration systems (ventilation) must be installed to supply the oxygen for workers and the combustion engines, and they are also necessary to ensure compliance with the limit values for dust and/or other components in the work area.
Thus the use of filtering dust collectors on tunnel boring machines (TBM) or direct collection with mobile filter units in the work area (e.g. tunnelling with roadheaders) is to be regarded as state of the art. Modern filtering units thereby exhibit a collection efficiency of > 99.9%.
The air requirements derived from the above requirements is vast. In conventional tunnel construction work is usually conducted using pressurised ventilation without the use of filtering systems. Therefore dedusting of the portal with a filter is rarely conducted for numerous reasons, such as space requirement, high energy consumption or costs.
A new concept of portal dedusting was realised for the first time when tunnelling the east section of the Wienerwaldtunnel (Vienna Woods Tunnel). The filter used for this purpose was developed during operation for the purification of exhaust air from road tunnels and it can be used in two different versions; as electrostatic filters ECCO, or without high voltage technology as EccoDust.

1. PROJECT DESCRIPTION

1.1. General

The Vienna Woods Tunnel consortium is constructing a 13.35 km railway tunnel to the west of Vienna. Two tunnel boring machines (10.6 m diameter) with dedusting filters are used in the west, while the tunnelling of the east section is conducted using a mining process with tunnel excavator (with milling cutter) and rock blasting. The length of the east section is 2,350m and its ventilation hole is situated in the residential area of the 14th District of Vienna, whose closest neighbours are located at intervals of approx. 30m.

A commissioned immission assessment (Felbermayer, 2004) suggests the adherence to the contractually guaranteed limit values within the area of the neighbouring units. Nevertheless the Vienna Woods Tunnel consortium decided to construct a filter system with a completely new concept for the purpose of the neighbouring units and the building contract.

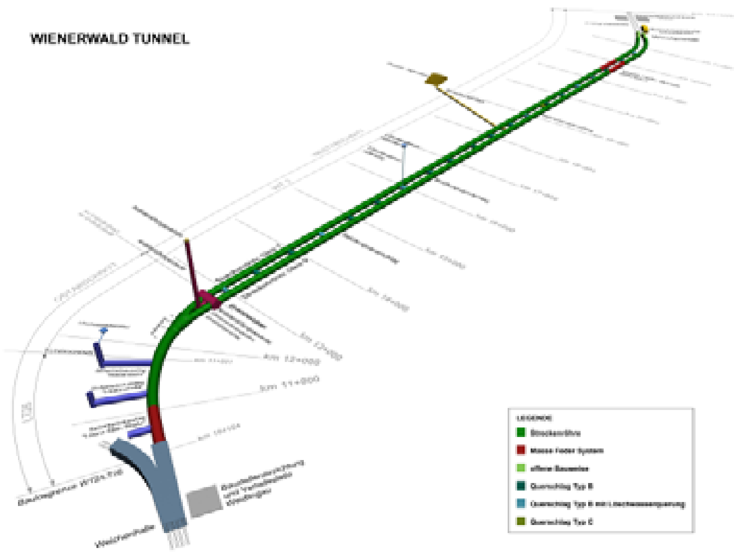


Figure 1

1.2. Sources of dust in the tunnel

The most diverse activities cause particle emissions in conventional tunnel construction.
In this particular case these include:

Loosening work	Loosening of the rock mass using tunnel excavators (accessory equipment such as excavator buckets, hydraulic hammers or mounted milling cutter) Part face heading machine (fig. 2) Blasting
Safety work	Wet and dry mix shotcrete Boring Dry boring in the moisture-sensitive rock
Mucking	Dispersion of dust by debris collection vehicles Loading of the debris collection vehicles
Emissions of diesel vehicles	DME-diesel engine emissions are collected directly by diesel particle filters
Cement dust	Filling of the cement silos underground Dry filling of the cement mixer truck (Mixed in Car System Underground)

Figure 2: Milling process

1.3. Ventilation concept

1.3.1. Ventilation and purification of exhaust air

A blowing ventilation unit (SIA 196 1998) was selected as the ventilation system. The air is supplied via a suction duct and a metal air conduit with an axial ventilation fan (fig. 3). The supply air is fed into the work area with a flexible plastic air conduit d=2.4 m (fig. 4), which is constantly extended to match the building progress. This ensures that the tunnelling area has a permanent supply of fresh air.

The exhaust air fan is located directly next to the ventilation fan. The air is blown out via the dedusting filter, which is installed in a cover opening.

Volume of supply and exhaust air: 60 m^3/s

Exhaust air via filter

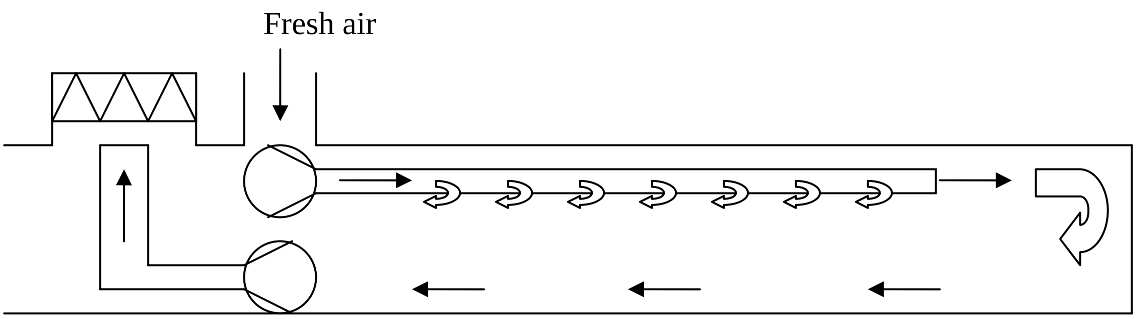


Figure 3: Diagram for blowing ventilation in the Vienna Woods Tunnel with additional exhaust air fan and filter in the air outlet section.

Figure 4: Ventilation and exhaust air fans and air conduits

1.3.2. Direct collection of cement dust (Mixed in Car)

The process of dry filling the cement mixer truck (fig. 5) also creates an enormous amount of dust. The process of dampening the dust with a sprinkling of water was tested initially, however it did not have a sufficient effect. Therefore it was decided to conduct a direct collection procedure via a suction hood, which was attached above the filling hole.

Volume of air: 4500 m³/h

Figure 5: Filling the mixer truck with cement

1.4. Concentrations of dust for filter layout

Standard values for the filter layout could be derived from comparative measurements in the Plabutsch tunnel, Graz (ÖSBS, Schuster A. 2002) see table 1.

Table 1: Dust emissions during tunnel excavation

Total dust TSP	Fine dust PM_{10}	Fine dust $PM_{2.5}$	Comments
mg/m³	mg/m³	mg/m³	
20	20	10	
2	2	2	Distance 200 m
5-20	5-10	1-2	
3-5	3-4	1	Before blasting
5-25	5-20	2-5	After blasting

The measurements were conducted in the tunnel section, therefore they represent the concentrations in the ambient air. The concentration of dust measured varies depending on the activity conducted and it reaches e.g. the highest values after the blasting procedure. At a distance of approximately 200 m the proportion of fine dust is the same as the total dust, which means that the coarse dust settles and falls to the ground.

As the total dust TSP (total suspended particulate) is approximate to the PM_{10} value (particulate matter), it can be concluded that practically all particles are smaller than 20 µm.

2. FILTER CONCEPT

2.1. EccoDust

In principle the problem would naturally be solved with a classic dedusting filter. However, the space requirement for the relatively large volume of air is significant. Besides this, the pressure loss of 1,500 Pa is not insignificant and it causes a corresponding power requirement of the fan.

EccoDust is an alternative solution with regard to the requirements for residual dust and it has a low resistance of approx. 500 Pa.

The concept is based on the ECCO$^{\oplus}$ filter system that has been developed for road tunnels. The separation of ultra-fine particles is also possible with the high voltage technology. However, during tunnel construction the particle spectrum in the dust separation process primarily ranges between 1-10 µm. Therefore EccoDust also makes it possible to dispense with the entire high voltage technology and to use a filter that operates in a purely mechanical manner.

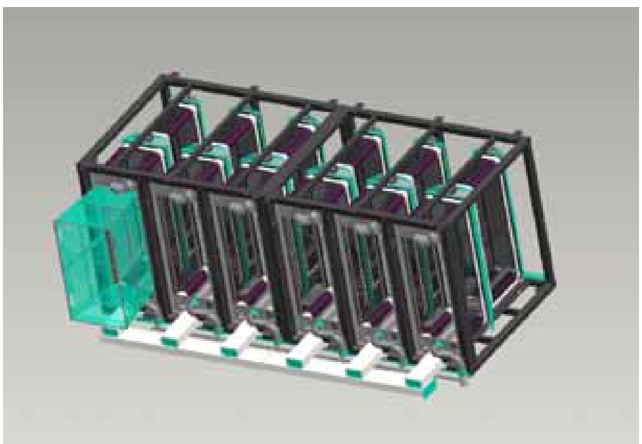


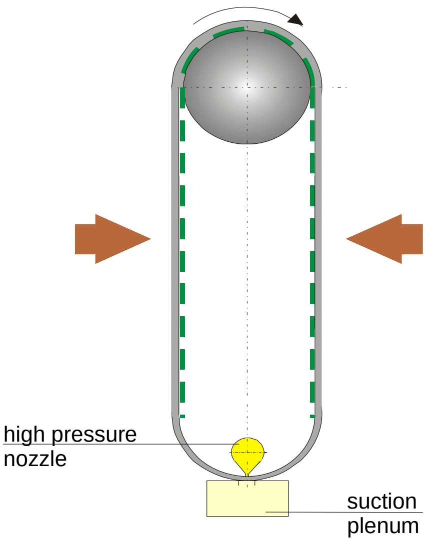
Figure 6: EccoDust

Technical data:

Average filtration efficiency:	97%	Average synthetic dust weight arrestance according to ASHRAE 52.2 – 1999 and EN779
Classification:	F5	
Dust storage capacity:		360 g/m²
Pressure loss:	500	Pa (whole filter)

2.2. Dedusting system

If the filter is saturated it is cleaned with purge air. Due to the fact that several individual modules are used, this cleaning process can also occur whilst the system is being operated. In doing so the modules are dedusted one after the other. The filter medium is thereby placed in rotation (fig. 7) and the dust is blown out via a high-pressure nozzle. At the same time the dust is sucked in on the opposite side and collected in a conventional dust filter.



The dedusting process is triggered by 2 parameters:
- Pressure loss above the filter
- Setting of a fixed time interval

Figure 7: Purge air cleaning of EccoDust

The dust filter that is required for the dedusting process can also be used for other tasks. The same applies for this as for the direct collection of cement dust during the filling of the cement mixer truck, as described under point 1.3.2. Very high concentrations of dust develop here, which can be controlled efficiently with this filter.

3. MEASURING DATA

The system has been in operation since spring 2005. Two measurements were conducted by the ÖSBS (Austrian Dust and Silicosis Prevention Unit). Different filter media were also tested during the measurements.
The crude gas side in the exhaust air pipeline and the clean gas side on the air outlet section were measured after the filter respectively.
Two Grimm laser aerosol spectrometers were selected as the measuring method for the simultaneous measurement before and after the filter. Measurements were conducted with a plan filter head probe STE 40 to determine the gravimetric factors.

3.1. Measurement from 24–25/8/2005

3.1.1. Total dust TSP

The measurements were conducted using a G4 filter medium, which has a lower pressure loss in comparison with the technical data specified in point 2.1, however it also has a lower filtration efficiency of 94%.

Figure 8 displays the half-hour mean values that were recorded over 2 days during normal tunnelling conditions. The peaks indicate a particularly dust-intensive operation; in this case it was during cutting with the hydraulic milling cutter.

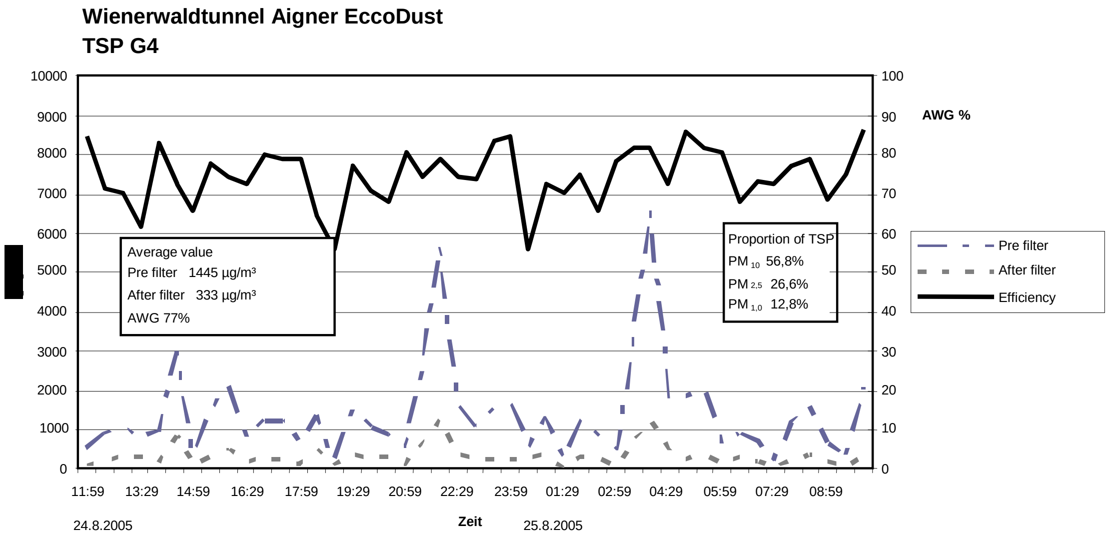


Figure 8: Total dust TSP during tunnel excavation

3.1.2. Fine dust PM_{10}

Even though PM values are immission values, a filter will also probably be evaluated in the future according to e.g. PM_{10} as a result of the fine dust discussion. The proportion of fine dust PM_{10} is displayed in figure 9. With 56.8 % PM_{10} is the largest proportion of the total dust collective.

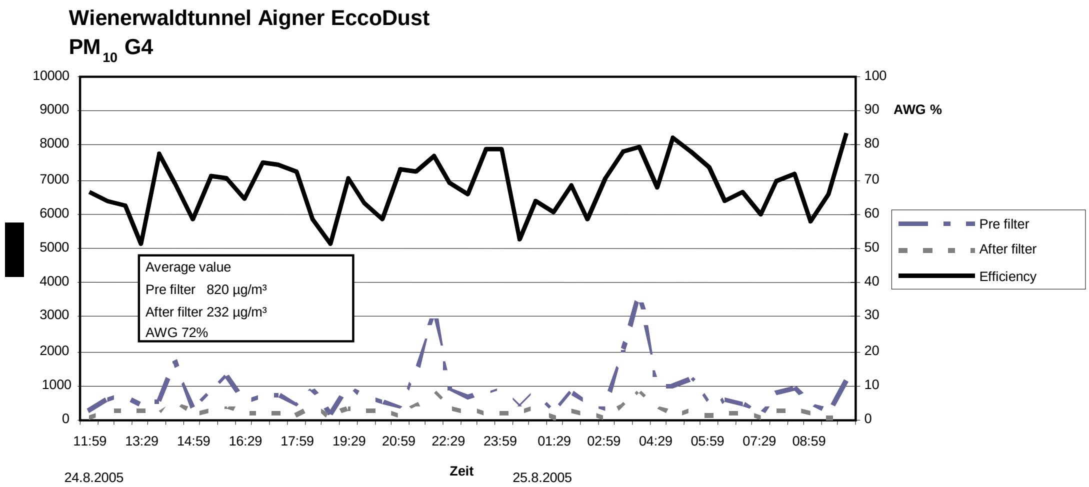


Figure 9: PM_{10} fraction, thoracic fine dust proportion

3.2. Measurement from 19-20/12/2005

The filtration efficiency could be improved with the fine dust filter medium as specified in the technical data. The distribution of the residual concentration of dust is clearly more constant in fig. 10 and the filtration efficiency curve also becomes smoother.

The individual particle fractions were determined at the same time during this measurement; an overview of the distribution can be viewed in table 2.

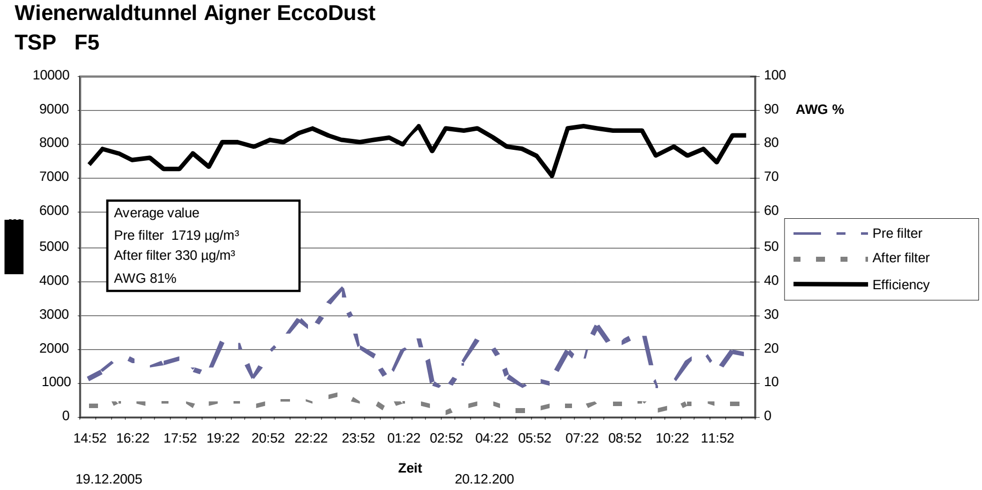


Figure 10: Total dust TSP with fine dust filter F5

Table 2: Particle distribution of coarse dust

Particle size µm	0.3-0.4	0.4-0.5	0.5-0.65	0.65-0.8	0.8-0.9	0.9-1.0	1.0-2.0	2.0-3.0
Proportion in %	5	3	3	2	2	5	5	17
Particle size µm	3.0-4.0	4.0-5.0	5.0-7.5	7.5-10	10-15	15-20	>20	
Proportion in %	16	14	18	6	4	1	1	

The largest fraction proportions are highlighted in grey, which clarifies that the determining proportion, with some 65%, is between 1 and 10 µm.

Comments: The data included in the tables and diagrams exclusively comprises the accumulation of dust from tunnel excavation and not the collection of cement dust mentioned.

120 kg of dust per week!

Figure 11: Dust filter of the cleaning system from EccoDust

The proportion of cement dust is naturally the largest with regard to weight. The total weekly accumulation of dust, which also includes the collection of cement dust, amounts to 120 kg (see fig. 11) and it is collected in big bags.

4. SUMMARY

The accumulation of dust during the construction of tunnel systems can cause a strain on the neighbouring units in sensitive areas

The removal of portal dust with EccoDust filtering systems causes a clear reduction in the emission of fine dust. In comparison with conventional filtering dust extractors, the advantages here are: the smaller space requirements, reduced filter resistance and competitively priced filter material. This results in substantially reduced costs for the operation of the filter system.

5. ACKNOWLEDGMENT

The authors would especially like to thank Toni Schuster, ÖSBS Leoben and the employees of the Vienna Woods Tunnel consortium for support with the measurements.

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VEHICLE TUNNEL RISK REDUCTION BY ACTIVE FIRE SUPPRESSION AND SMOKE CONTROL

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With acknowledgement for their assistance to:
Gary J. Hudson and Robert Bartlett

ABSTRACT

The paper advocates use of professional risk engineers and establishment of risk criteria to be met in vehicle tunnels. It outlines a methodology for establishing risk criteria and assessment of system effectiveness in risk reduction. It does not venture into the realm of quantification of risk, or of definition of a level of risk that the community will tolerate.

The Australian experience in using fire suppression systems in conjunction with smoke management systems is reviewed, and outcomes of a professional risk engineering study outlined. The additional 2-3% overall new tunnel cost for a suppression system is concluded to be worthwhile.

1. INTRODUCTION

There is a growing perception in the community that risk can be eliminated; that if risk remains, it is the fault or responsibility of someone other than the individual involved. Professionals and government bodies are being held accountable for issues that previously have had an implied acceptance by the community, as a tolerable risk.

Decisions to travel are taken with every expectation of safe arrival; even with the knowledge of road injury and fatality statistics. Whilst there is a tacit acceptance by the community of risk in road travel, largely based on the traveller's past experience, there is little understanding of the potential increase in risk involved in tunnel travel, especially in "long" tunnels. Engineers thus far have been making the decisions on behalf of the community in the provision of facilities they deem to be at a level of tolerable risk and at a reasonable cost for the benefit provided, based on judgement and experience. This position is now challenged.

Additional safety facilities and reduction of risk are now being demanded by the community, but with no means of defining what is tolerable, acceptable or affordable.

The paper seeks to make a contribution to the on-going debate by suggesting a methodology for the assessment of risk and explores the relative merits and effectiveness in risk reduction, of tunnel configuration, fire suppression and smoke management systems, and operator and emergency services response to an incident.

2. WHAT ARE THE THREATS? - RISK ISSUES

Risk is present in all vehicle tunnels and Table 1 schedules the main risks. This paper considers issues of risk associated with a fire incident only.

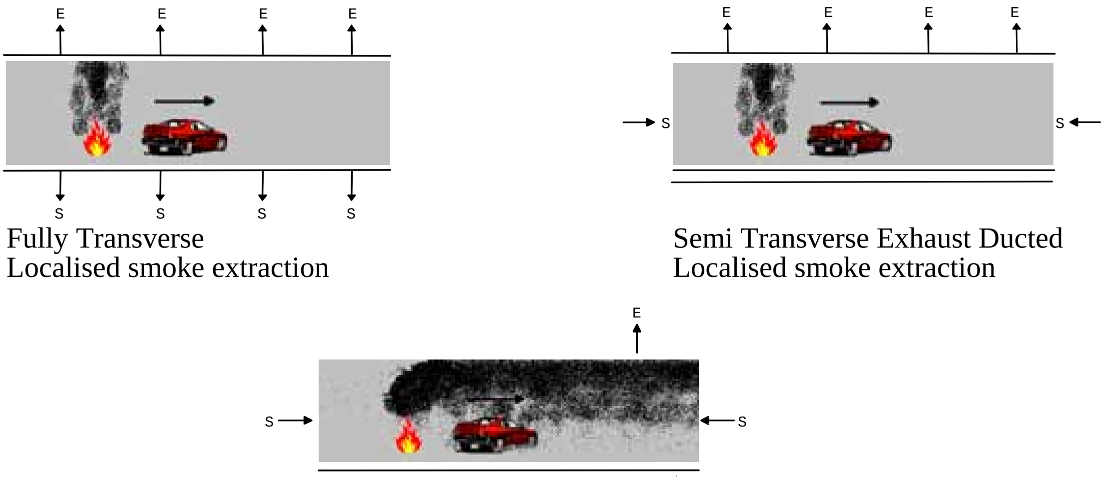
Table 1: Vehicle Tunnel Risk Issues

Risk Issue	Threat
Health and safety of the public, operators and emergency services	Air quality, vehicle accident, vehicle fire incident
Assets - tunnel facilities and user vehicles and goods	Vehicle accident, vehicle fire incident

Fire occurrence has been shown by PIARC1 data and tunnel operator records to be of low probability, and fires, when they occur, to be of low intensity and usually extinguished quickly by the motorist without assistance of trained fire fighters. Nevertheless the potential for a major disaster, involving loss of multiple human lives remains, as has been realised in several disasters in European tunnels in the past decade.
Prevention of fire is always a better option than measures to control or extinguish it. Control of a fire, once started, is a better option than dealing with the effects of a fully developed fire.
Measures being adopted in major European tunnel new construction, and upgrade of existing facilities, are aimed at prevention as far as is possible, and/or dealing with the effects of a fully developed fire. Europeans are not yet embracing fire control, beyond that of Brigades intervention.
Smoke is known to be more of a threat to human life than the fire itself; both however can be lethal. There is now no argument among tunnel designers as to the need for a means of effective smoke management in the event of a tunnel fire; argument centres on how to achieve this.
Internationally, there are considerable differences of opinion and judgement in respect to provision of fire suppression systems, particularly sprinkler or deluge suppression systems. Designers either passionately believes such systems provide a substantial benefit in tunnel risk reduction or equally passionately, believe they present a substantial additional risk!
In Australia, there is no argument about this - we have universal agreement from authorities, emergency services, operators and designers that deluge systems provide a very worthwhile contribution to life safety, not otherwise available.

3. CURRENT PRACTICE - CONSENSUS AND DISAGREEMENT

There is an emerging consensus that in ‘long tunnels’ (whatever these may eventually be defined to be), where fully or semi transverse ventilation is a necessity for tunnel air quality control, the added benefit of containment of the smoke and hot gases by fresh air introduction either side of the fire site and exhaust at a rate of 200-250m3/s at (or in the region of) the fire site, is an effective solution.
In “short tunnels” there is no real consensus. Longitudinal ventilation is the preferred and lowest cost solution for tunnel air quality control and by developing a tunnel air velocity sufficient to prevent smoke “back-layering”, it is generally agreed that the ventilation can effectively protect vehicles upstream of the fire site.
Longitudinally ventilated “short” tunnels with free flowing traffic are less of a threat to tunnel occupants in a fire incident than are those with congested traffic. In free flowing traffic, vehicles downstream of the fire incident have every chance of exiting the tunnel before the fire develops and smoke envelopes the downstream tunnel section. In an urban environment where regional traffic congestion may well prevent vehicles downstream of a fire incident from exiting, longitudinal ventilation smoke management will propel smoke over vehicles trapped downstream, with a probability of injuries or fatalities.



Fully Transverse
Localised smoke extraction

Semi Transverse Exhaust Ducted
Localised smoke extraction

Longitudinal
Smoke passes over entrapped vehicle downstream

Figure 1: Vehicle Tunnel Smoke Management Comparison

Australian regulators have required a comprehensive range of smoke management and fire suppression measures since 1990, including use of multiple zone deluge systems in all tunnels. There has not yet been any attempt to define the type of smoke management system that should be used in urban tunnels where traffic congestion may be present concurrent with a fire incident. Nor has there been any attempt at quantification of probability and consequence of such an occurrence.

Australian tunnel deluge systems are required by authorities to:

1. Have a minimum discharge density of 10mm/m^2/min, within nominated variance criteria
2. Achieve minimum discharge over the full width of the tunnel - including breakdown lane/bay and ramps
3. Have a zone length adequate to cover the longest vehicle permitted (usually 25 – 30m zone length)
4. Operate two zones and three hydrant streams at full design rate concurrently
5. Operate a third zone with a degraded discharge rate permissible over all operating zones
6. Have fully redundant water supply service capable of supplying the fire services for a defined period (up to 4 hours, depending on time for Fire Brigade to attend)

Currently European and USA designers have avoided use of suppression systems, as such installations are considered to present a higher level of risk in the tunnel than non-installation, and to not be cost effective. A number of reasons are cited to support this conclusion:

1. Possibility of spread of liquid fuel fire
2. Possibility of developing a dangerous situation from mixing water and chemicals spilt
3. Generation of scalding steam
4. Cooling of smoke causing smoke to drop to the human breathing level and general smoke logging of the tunnel
5. Inability to extinguish a fire located in a closed container, cabin or vehicle
6. Probability of non-operation of the fire water system from ice formation at sub-zero temperatures

In our view, each of these issues may be dealt with effectively by appropriate design response, such as by:

1 & 2 Appropriate grading of road surface, drainage and flame traps

3 & 4 Smoke management system capacity and development of containment air velocity at the 'fire face'

5 Control of fire size to limit human exposure until the Brigades arrive for extinguishment action
6 Use of 'dry-pipe' distribution downstream of control valves and insulated, 'trace heated' pipe and storage

4. LEGAL AND TECHNICAL REQUIREMENTS

Arnold Dix[2], lawyer and Professor of Engineering, has presented an excellent summary of the legal and technical requirements in respect to fire and life safety considerations for designers (Appendix).
Robinson, Francis & Anderson[3] who practice in risk engineering and consulting, have similar observations in respect to risk (Appendix). In their view:
"The use of vulnerability assessments supported by cause-consequence models to assess risk in tunnels seems a peculiarly efficient form of 'due diligence' demonstrating that it is vital to give priorities to measures that will address matters before loss of control can occur. Regulators and corporate lawyers seem to find them attractive".
There is strong agreement between these experts on the approach needed to address the legal and technical issues. There is a common emphasis on examination of every possible event and need for a considered response to each. Control - early control - is strongly advocated by the risk engineers; indeed they are unequivocal in their opinion that reliance on one measure (eg. ventilation) for smoke management, whilst allowing a fire to develop uncontrolled, would be a non-supportable position from a legal perspective.
The risk engineers also note "*Risk control is primarily focussed at rare, high consequence events"*. What does this mean in a vehicle tunnel? What is "high consequence"? In life safety terms, how many injuries or fatalities constitutes a community definition of "high consequence". These issues need definition and determination so both risk engineers and tunnel designers can address them.
Relative risk can be established fairly readily, but this would not be sufficiently definitive for legal scrutiny. Table 2 schedules some examples.

Table 2: Vehicle Tunnel Relative Risk

Relative risk	Reason
Bi-directional traffic flow presents higher risk than uni-directional traffic flow	Vehicle collision potential higher with bi-directional flow
Long tunnel presents higher risk than short tunnel	Vehicle and occupant numbers likely to be trapped in long tunnel are greater
Urban tunnel presents higher risk than rural tunnel	Vehicle and occupant numbers likely to be trapped in urban tunnel are greater
Tunnel subject to traffic congestion presents higher risk than free flowing	Vehicle and occupant numbers likely to be trapped in congested tunnel are greater
Longitudinally ventilated tunnel presents higher risk than fully transverse or exhaust ducted semi-transverse tunnel	Vehicles and occupants may not be able to drive away from the smoke exhaust path (the tunnel vehicle envelope)

To move forward, quantified and agreed definitions of risk levels that match community expectations at a cost they are prepared to pay, are required.
Risk is influenced by decisions on the use or non-use of fire suppression or smoke management system, the design criteria to be adopted, the system type, and the interaction between systems. These then are not decisions designers alone should be called upon to make.
Determination of risk level is properly in the realm of authorities and governments, who are the ultimate arbiters of community values, including definition of tolerable risk. A stronger lead is warranted in this area, than has yet been evident.

The role of the designer therefore, should be to define the options available and bring forward the relative advantages, disadvantages and comparative costs, and the role of the stakeholders and authorities should be to determine the tolerable risk criteria for design, and measures to be incorporated.

5. RISK EVALUATION

Robinson, Francis & Anderson[3] have provided a sensible methodology for evaluation of vulnerability assessments, supported by cause-consequence models, to assess risk in tunnels.
Risk engineering specialists can provide the expertise for evaluation, comparison and even quantification of risk which may then be related to known statistics with which the public are familiar and tolerant, if not accepting. Tunnel risk may well be expressed in terms of incidents, injuries or deaths/vehicle number/annum or incidents, injuries or deaths/vehicle km/annum, or similar statistics.
Statistics exist for our major transport systems - roads and highways, railways, airlines - against which projections for vehicle tunnels may be compared.
The tools exist for professional assessment of risk, but a benchmark of performance, needs to be established by authorities and governments on behalf of the public, and the role of professional risk engineers and methodology they adopt, agreed.

6. RISK CONTROL

Robinson, Francis & Anderson[3] have noted a relationship between fire size and number of deaths: "… There appears to be an empirical connection between the size of a fire and the number of deaths. That is, small fires are less likely to kill people. The larger the fire the less room for error there will be in any emergency response".
Kumar[4] comments on the danger of fire size: "It is the pre-flashover stage which is the most relevant to life safety, for, if escape is not completed then, there is no chance after flashover".
The obvious conclusions to be drawn from these sensible and readily accepted observations are:

- Limit fire growth and size, so that flashover cannot occur.
- Limit fire size to the smallest practically possible.
- Limit the number of fire incidents.

Robinson, Francis & Anderson[3] cite three primary risk control regions:

- Threat reduction
- Precautions
- Vulnerability reduction

In practical terms for the designers, this translates to:
Threat Reduction: Incident prevention measures.
Reduction of incident potential:

- Exclusion of large fire load vehicles or goods transported. In practical terms, this is not fully achievable. Rogue vehicles may enter a tunnel. Alternatively, large fire load vehicles may be scheduled to have 'sole use' of the tunnel at defined times.
- Improved tunnel geometry, alignment and information systems. PIARC[1] data is available which indicates there is a correlation between vehicle incidents, tunnel geometry and advisory signs.
- Limiting vehicle numbers in the tunnel. Traffic management is inevitable, in congested conditions. (In the bi-directional Mont Blanc tunnel, vehicles must now maintain a minimum separation distance for increased driving safety).

Precautions: Incident management measures.
Limitation of incident magnitude:

- Identification by CCTV, traffic monitoring, fire detection, for early response.

- Initiation of suppression system. To provide a margin of safety, the suppression system capacity may be in excess of likely developed fire size.
- Effective smoke management system. To provide a margin of safety, the capacity of the smoke management system may be in excess of the likely suppression system controlled fire size.
- Early advice to emergency services for rapid response.
- Ready access to the incident by emergency services - vehicle cross-overs between tubes, breakdown lane in each tube.

Vulnerability Reduction: Evacuation measures.

Limitation of occupant exposure:

- Limiting vehicle numbers in the tunnel. Traffic management is inevitable, in congested conditions, to minimise the number of vehicles subjected to a potential threat and to maintain vehicle separation for driving safety.
- Smoke management systems to provide smoke-free escape paths.
- Simple, clearly understood communication with occupants.
- Public education in tunnel use.
- Design features facilitating prompt evacuation of all tunnel occupants.
- Prompt emergency team response.

The combined input of the whole of the design team, working in conjunction with professional risk engineers and operators is required for a full evaluation and quantification of risk issues.

7. TIME - THE CRITICAL ELEMENT

A lot has been written about the importance of actions to be taken within “the initial minutes” of a fire incident initiation. The importance of rapid detection, evaluation and response cannot be overemphasised. This involves everyone associated with the tunnel - operators, users, maintenance staff and emergency services personnel.

The response time capability is a function of the systems installed, operator training, tunnel length and traffic congestion in, and on the approaches to, the tunnel. A full response is unlikely to be in place in less than 20 minutes.

In the time the response is developing, the fire is growing in intensity, with the threat to tunnel occupants growing in scale, trending to exponential, with elapse of time. The possibility of a delayed response due to human error or system malfunction must be considered, together with a back-up response. Control and minimisation of the threat (the fire) at the earliest opportunity should be a prime consideration. Control of the (minimised) hot gases and smoke then becomes a less critical issue, and potential delays in emergency services access to the incident site become less critical.

If for no other reasons, these alone should be sufficient to justify incorporation of suppression systems, as is the practice in Australia where deluge systems are used.

Robinson, Francis & Anderson[3] have, in their paper, focussed on the need for ‘control’ of the fire incident and have suggested a definition of the point at which ‘loss of control’ may occur: *“As cause-consequence models invariably demonstrate, control before the loss of control point is the only way to reliably prevent large scale multiple life loss scenarios when large energies and many people are involved”* and *“The loss of control point appears to be that fire which overwhelms the usual air handling system”*.

The control point interpretation by Robinson, Francis & Anderson may not be acceptable to all. A very large capacity smoke management system may be provided to cater for the largest conceivable fire incident, including the ‘fanning’ effect of the ventilation system, which would meet the Robinson, Francis & Anderson ‘control point’ requirement. However, this involves a considerable installed cost, time for the system to develop a full response, and an acceptance of substantial collateral damage and consequent tunnel closure for repair as a consequence of an uncontrolled fire size.

8. SUPPRESSION SYSTEM BENEFITS

The needs, both technical and legal, to maintain the fire incident within the bounds of ‘control’ are obvious. Limiting the fire growth and intensity through early intervention is critical to the process of maintaining control, an issue Robinson, Francis & Anderson emphasise.

Suppression systems may not extinguish a fire, but they certainly do limit the developed intensity and in doing so provide an added margin of safety and outcome certainty by:

- Providing more certainty of maximum fire size, even with the wide variation in possible combustible materials, to which the smoke management system may be designed
- Limitation of gas temperature
- Limitation of radiation effects
- Reduced potential for structure and fit-out damage
- Reduced potential for smoke extraction system to be overwhelmed; rather it would be operating well within capacity
- Reduced threat to motorists and emergency personnel
- Closer proximity access to fire site by Brigades
- Enhanced prospect of maintenance of fire control in the event of one system’s failure
- Enhanced prospect of maintenance of control in the event of a delayed response initiation

It is a given that there will be a time delay between fire inception, detection of it, initiation of a response to it, and development of full effectiveness of the response. The earlier systems are operated after fire inception, particularly the suppression system, the more certain will be the ability to maintain control and to overcome the fire. Typically, activation of the suppression system within 5 minutes of fire initiation will limit the fire intensity to <16MW, based on a worst-case ultrafast t^2 fire growth.

Whilst the benefits of automatic initiation of a deluge system are advocated by Robinson, Francis & Anderson, the consequences of an accidental discharge or discharge at the incident site before vehicles are stopped, are not considered. A number of options are available for deluge system initiation which would minimise the possibility of human error or detection malfunction, including hybrid manual/automatic intervention.

In our opinion, detailed risk and technical evaluation of the full range of options for this important fire control system is warranted, for optimisation of approach.

Australian tunnel operators have acknowledged the benefit of use of their suppression systems on the several occasions when a fire incident has occurred. In each occurrence the fire size was quickly contained and size limited, and the tunnel operations (generating revenue) restored within about 2 hours, with little to no damage to tunnel facilities.

Based on the Australian experience, the cost of a suppression system will almost certainly be substantially less than a large capacity smoke management system; in most fire incidents it will prevent collateral damage and facilitate return to operation within 2 hours.

9. SMOKE MANAGEMENT ISSUES

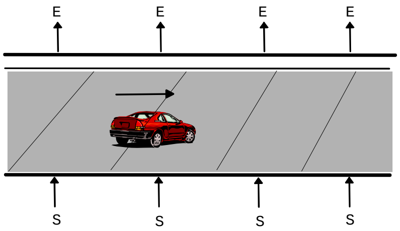
Smoke in a fire incident is acknowledged to be a bigger threat to human life than the fire itself.

There is no universal acceptance on when or when not to select a particular type of ventilation system to address smoke management.

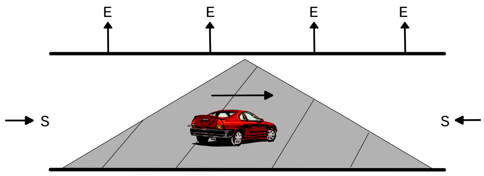
The following table summarises in simple form the complex and sometimes opposed considerations to be taken to account in selection of an appropriate ventilation system:

Table 3: Comparison of Vehicle Tunnel Ventilation System Characteristics

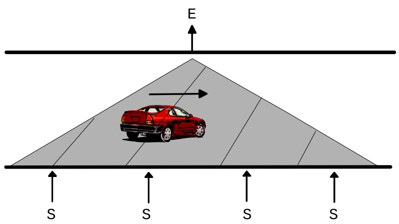
Issue	**Ventilation System Type**		
	Fully Transverse	Semi Transverse	Longitudinal
Environmental performance	Constant quality throughout tunnel length	Ducted supply: Constant quality throughout tunnel length Ducted exhaust: Increase in contaminants from supply to exhaust point	Increase in contaminants from supply to exhaust point
CO Exposure[5]	Higher within same time frame than with longitudinal	Ducted supply: Same effect as fully transverse Ducted exhaust: Same effect as longitudinal	Lower within same time frame than fully transverse or ducted supply semi transverse
Smoke Management Performance	Can exhaust directly from fire site in any length tunnel Effective in uni-directional and bi-directional traffic flows.	Ducted supply: Same effect as longitudinal Ducted exhaust: Same effect as fully transverse, but is limited in length by make-up air intake capacity through the tunnel cross section	Effective in unidirectional traffic flows that are always free-flowing. Not suitable for bi-directional traffic flows or uni-directional traffic flows where congested traffic is possible.
Relative Cost - ventilation and structures	Highest cost system	Mid range cost system	Lowest cost system



Fully Transverse
Air quality uniform throughout



Semi Transverse Exhaust Ducted
Variation in pollutant concentration from portal/s to exhaust point



Longitudinal
Variation in pollutant concentration from portal/s to exhaust point

Figure 2: Vehicle Tunnel CO Exposure

10. A PRACTICAL USE OF RISK PROFESSIONALS

Risk professionals were used to assess the relative merits of several alternative smoke management systems, with and without use of a deluge system, on a recent design proposal for an ~4km long twin tube, unidirectional, dual carriageway, urban tunnel.

The design tolerable level of risk for the exercise was defined as not greater than that derived from incident statistics for comparable urban roads and highways. Risk analysis was

undertaken using the principles and processes espoused by Robinson, Francis and Anderson, which are referred to elsewhere in this paper.
Longitudinal ventilation met the design criteria for air quality and was the lowest-cost in terms both of ventilation and excavation cost. However, the risk to motorists potentially trapped downstream of a fire incident in congested traffic was assessed to be much higher than the tolerable risk criteria.
Provision of a separate smoke exhaust system (or a semi transverse ducted exhaust system), with exhaust capability focussed over a fire site at any point in the tunnel (multiple motorised dampers) was found to meet the tolerable risk criteria, but the additional excavation cost to house the exhaust system was considered prohibitive.
A deluge system meeting authority requirements (costing <30% of a smoke exhaust system), acting alone with no smoke management system, failed to meet the tolerable risk criteria.
The combination of limitation of the fire size by a deluge suppression system and a smoke management system of longitudinal ventilation, used in conjunction with enhanced emergency services access to an incident site, strict emergency handling procedures, and operator training, were then examined. The low probability of suppression system failure coincidentally with a congested tunnel occurrence, and the use of a smoke management system that was simply a 'fire rated' upgrade of the air quality ventilation system were shown to result in an acceptable outcome in terms of risk.
The results of this study suggest that, from a meeting of tolerable risk criteria perspective, the limitation of use of longitudinal ventilation for smoke management to be in the range of 3-4 km, and require a robust suppression system.
The professional risk analysis and the outcomes proved to be very helpful, both in the design process and in the development of optimised operational procedures.

11. RISK DESIGN CRITERIA

The ultimate criterion defining tolerable risk and the methodology for evaluation of risk needs to be established on behalf of the public by their representatives - the authorities and governments. Once established, recognised risk evaluation and quantification techniques may be adopted, as Robinson, Francis & Anderson[3] have noted.
Identification of potential threats will require input from the whole design team and stakeholders. Probabilities may be assigned to each threat, in conjunction with the risk engineers. Incident event and response times will require input by designers, operators and emergency services, with comment and review by the risk engineers.
Definition of the point at which the fire incident is 'out of control' needs to be established and agreed and a factor of safety determined, to ensure loss of control does not occur. Limits to the many response time variables must be set and system design and operational response safety factors established to ensure the time limits are met.
Review and revision will almost certainly be necessary to achieve acceptable outcomes for risk profile, system performance and cost benefit evaluation.
Current Australian practice is empirically and prescriptively based, requiring design of fire suppression and smoke management systems for a single incident in one tube of the tunnel complex, usually of 50MW maximum fire intensity. This involves large capacity fire suppression and smoke management systems that, if activated at an early enough stage of the fire growth, may be shown by a professional risk evaluation to meet the tolerable risk criteria. Design for a 50MW fire may then not be justified, as such would then not develop. An overcapacity smoke management system in particular may involve considerable unwarranted excavation.

Alternatively, a professional risk evaluation may substantiate the added cost of the conservative approach, by quantifying the better risk outcome and potentially lower community cost from reduced injury or death incidents.
Risk studies inclusive of ‘worst case’ time scenarios for the various response activities to an incident may well substantiate adoption of lesser capacity fire suppression and smoke management systems than is current practice. Similarly, risk studies may well indicate longitudinally ventilated smoke management systems are not acceptable to the tunnel risk profile, particularly in ‘long tunnels’.

12. INCREMENTAL COST

Drencher fire suppression systems to address a 50MW intensity fire represent around 2-3% of the total construction cost of most tunnels, ‘short’ tunnels being at the high end of the scale.
Smoke management systems of the longitudinal ventilation type utilise the system capacity required to address the environmental issues, as for all but ‘short’ tunnels, the air flow rate is determined by environmental, not fire criteria. Thus the cost for smoke management in such tunnels is related to upgrading the ventilation system performance criteria for operation at hot gas temperatures - a cost of less than 1% of the total construction cost of most tunnels.
If localised smoke exhaust is required, and a longitudinal ventilation system is adopted for normal operation, then a supplementary exhaust system is required. This involves an additional air passage/duct area of around 20-25%, consequent additional excavation beyond that required for the vehicle envelope, plus fire rated air passage/duct construction.
The added construction cost for a localised smoke management facility will be a function of the tunnel construction method, itself a function of the geotechnical characteristics of the excavated site. In sandstone/hard rock tunnels, the added cost will be proportional to the extra area over that required for the vehicle envelope - about 20-25%. In soft ground, using circular section tunnels, the added cost will be less than proportional to the air passage/duct extra area, as there will be ‘spare’ space available above, below, and to the sides of the vehicle envelope section. The added cost may be in the order of 10-15% overall construction cost.
Smoke management systems that do not propel smoke longitudinally, but have a capability of extraction from the fire incident area, may be incorporated in transverse or semi-transverse (ducted exhaust) systems. Additional excavation and cost would be of the same order of magnitude as for a localised smoke exhaust.

13. CONCLUSION

Community attitudes toward risk acceptance and expectations for safety have changed substantially since vehicle tunnels were first introduced. Internationally, many current vehicle tunnels fail to meet even empirically rated safety expectations of the community. The European Union has recognised this and has instituted a number of research programs to provide data for use in fire and life safety analysis and services design.
Professional procedures are available to assess and quantify fire and life safety risk in vehicle tunnels, to guide and recommend to authorities and governments and to work within the design teams to facilitate an understanding of potential outcomes in fire and life safety using the range of options being considered.
The community needs to accept that there will be added costs - both initial and ongoing - to achieve a higher level of safety in vehicle tunnels.
Use of vulnerability assessments supported by cause-consequence models to assess risk in tunnels provides a valuable means of evaluating threats, quantifying of risk and development of worthwhile cost-benefit comparisons from the range of design options available.
Use of professional risk engineers to assess smoke management and fire suppression system options has demonstrated the risk outcome benefits and cost minimisation benefits of combined smoke management and fire suppression systems.

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APPENDIX

Arnold Dix, lawyer and scientist, has presented an excellent summary of the legal and technical requirements in respect to fire and life safety considerations for designers:

Design Objectives

Technical: *The design objectives may be a broad statement of what the final design is required to achieve*

Legal: *…the objectives must be achievable and demonstrated to have been achieved.*

Acceptance Criteria

Technical: *The acceptance criteria are the benchmarks against which the design will be tested.*

Legal: *The acceptance criteria, which are set, provide pivotal and identifiable criteria, which can be examined retrospectively to determine whether or not a particular design met the objectives.*

Hazard Identification

Technical: *Undertaking hazard identification for fire safety design of projects is a process that needs to involve all relevant stakeholders. The fire safety design provisions and procedures are required to integrate with operations.*

Legal: *In the future a hazard, which was not considered credible, may occur - and the fact that it occurred may be used as evidence that the hazard identification process was flawed. Alternatively despite identifying a potential hazard, its consequences might not have been fully appreciated. As a result the hazard may meet acceptance criteria and still fall outside the acceptance limitations.*

In both instances the allegation against the professional fire life safety engineer is that the failure to predict the event demonstrates the failure of the engineer to meet their professional standards.

The test for professional liability, in almost all countries of the world, is not retrospective. That is, the test is related to what can reasonably be expected of the fire life safety engineer at the time they considered the issues - not after an event.

A. Dix "Building and infrastructure safety. Balancing legal and technical requirements" Technical Paper, March 2002

Robinson, Francis & Anderson, who practice in risk engineering and consulting, have the following observations in respect to risk:

- Senior decision makers and the courts require a demonstration that all practicable reasonable precautions are in place.
- If something untoward occurs the courts immediately look to establish (with the advantage of 20:20 hindsight) what precaution/s that should have been implemented, weren't.
- Risk is not strictly relevant since, after the event, likelihood is not relevant.
- Risk control is primarily focussed at rare, high consequence events.
- The lawyers/courts always focus on the prevention side first. Trying to restore control after the event is always difficult.
- As cause-consequence models invariably demonstrate, control before the loss of control point is the only way to reliably prevent large scale multiple life loss scenarios when large energies and many people are involved.
- The loss of control point appears to be that fire which overwhelms the usual air handling system.
- Emergency ventilation to prevent a situation becoming a confined space is an attempt to restore control and acts after the event.
- It is the change of the tunnel environment by the fire that creates the loss of control.
- There is a certain size fire that will disrupt the air flow, place remote persons at risk and thus bring about the need to impose emergency measures including an emergency ventilation system and the like. This appears to be the loss of control point

Robinson, Francis & Anderson cites three primary risk control regions.

Threat reduction *- …reduce the source of fire, for example, combustible trucks with large combustible loads.*
Precautions *- …such as deluge systems that can control fire before the normal air handling system is overloaded (small fires are safe fires)*
Vulnerability Reduction *- …. by ensuring no one is present during a fire (minimal stalled cars) and the provision of emergency response, ventilation and evacuation systems.*

They further comment:
… There appears to be an empirical connection between the size of a fire and the number of deaths. That is, small fires are less likely to kill people. The larger the fire the less room for error there will be in any emergency response. With automatic operation, early in the development of a fire, small fires should be the norm. That is, flashover (well after the loss of control point) should not occur.

Robinson, Francis & Anderson "Lessons from cause-consequence modelling for tunnel emergency planning" - Fifth International Conference Safety in Road and Rail Tunnels, 2003, Marseilles, France. Tunnel Management International

Kumar comments:
It is the pre-flashover stage which is the most relevant to life safety, for, if escape is not completed then, there is no chance after flashover.

Kumar S (1992) Fire Development and Smoke Spread in Tunnels – Some Modelling Considerations. Safety in Road and Rail Tunnels Conference, Basle, Switzerland, Nov 1992*.*

Robinson, Francis & Anderson summarise:
This (Kumar) argument is particularly powerful if there is stalled traffic in long tunnels with longitudinal ventilation. If the fire has achieved flashover the smoke has to be blown one way or the other potentially exposing up to half the tunnel occupants.

SOLIT – PROJECT: WATER MIST FIRE SUPPRESSION SYSTEMS AS PART OF THE TUNNEL SAFETY SYSTEM

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Keywords: Fire Protection, Fire suppression, water mist

1. INTRODUCTION

Fire safety measures were increased during the last years. But recent serious fires in tunnels again showed that there are still similar problems with evacuation of people and access for fire fighters as well as serious damages on tunnel structures. Mainly this is affected by extremely high temperatures and smoke spread due to rapid fire development.
Automatic fire suppression systems were considered for years to improve the situation in tunnels, especially shortly after fire detection. First tunnels with innovative suppression systems based on water mist technology are under installation. For these tunnels, applicability was proven in special fire tests. To create sufficient basics for a performance based layout of such systems more research work is carried out now.

2. CURRENT KNOWLEDGE ABOUT FIRE SUPPRESSION SYSTEMS IN TUNNELS

Based on a report of PIARC active fire protection measures by means of sprinkler or water mist systems, most tunnel safety designers declined to propose such systems. However, due to lack of knowledge by real scale fire test, the arguments given in this report must be taken seriously into account in past.
Anyway, in Australia and Japan, automatic fire suppression systems are to be installed in longer tunnels or tunnels with a high traffic density as a general rule. But the aim and therefore the performance of these systems are mostly different to the aforementioned systems, as they are installed for protection of the tunnel structure against collapse. If a fire occurs, these systems will be activated after completion of the evacuation process, often after 30 – 60 Minutes. Recently it is under consideration if this strategy should also be changed to an activation of the system as early as possible.

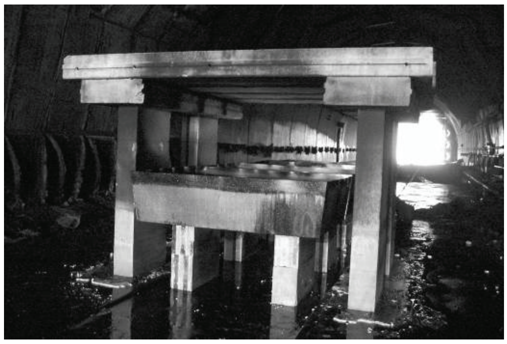

Figure 1: UPTUN Fire Test Scenarios

Beside some other experiments with suppression systems in tunnels or similar applications, the European research project UPTUN includes also scientific development of innovative and effective fire mitigation systems for use in tunnels. The main focus was given to a full scale fire test program to assess effectiveness of such systems independently.
Fire scenarios for this test program were developed by Sintef (Norway) based amongst others on the results of the Runehamar fire tests.

Two different scenarios were used:
- Partly covered pool fire with a maximum HRR of 20 – 25 MW
- Partly covered wooden crib fire with a potential HRR of approx. 50 MW

These scenarios were designed not to simulate any specific fire load, e.g. trucks, cars, but repeatable fires with specific HRR. Obviously, 20 MW or even 50 MW, are not HRR of a full developed fire in a tunnel, but as the aim of such system is fire suppression on early stage, this figure is sufficient and should be taken into account in design process, e.g. for interface with the detection system.
According to the internal UPTUN test report, test result of this test program can be summarized as follows:

Figure 2: UPTUN Fire Test

- Generally, water mist systems are able to suppress fires in tunnels up to a certain limit efficiently even with ventilation. HRR can be stabilized or even reduced. Temperatures nearby the fire as well as in a distance of 20 m are reduced significantly.
- Evacuation conditions as well as conditions for fire fighters are improved during activation of the system.
- Due to reduction of the smoke production during activation of the system, visibility was improved particularly on the upstream side of the fire
- The layout of the system (nozzle position, flow rates, droplet size distribution) has a high effect on efficiency of the system. Scaling is only limited.

The UPTUN fire tests have shown that especially designed and tested water mist systems can be a very effective fire safety tool for tunnels. Furthermore it turned out, that scaling, even with advanced simulation tools, is very limited. Real scale fire tests are necessary.

Maximum effectiveness of such systems can be achieved by adequate interaction with other parts of the tunnel safety system, e.g. detection or ventilation.

Although a lot of new knowledge was gathered during the UPTUN project, there are still some important questions to be answered; some even came during the test program and its assessment. Some general questions are as follows:

- Up to now, any suppression system was only tested with longitudinal ventilation. Are there any differences with other types such as semi – transversal or transversal?
- It already turned out that interaction with other safety systems is of special importance. What influences do these safety systems have against each other?
- How to assess results of fire tests. Are strict acceptance criteria more useful or should results assessed case by case?

3. ASSESSMENT OF EFFECTIVENESS OF ACTIVE FIRE SUPPRESSION SYSTEMS

3.1. SOLIT Project

The research project SOLIT (Safety of Life in Tunnels) – further info at www.solit.info - addressed itself to the task to pick up current knowledge about suppression systems for tunnels to enhance these systems and test methods so they can be installed in tunnels efficiently and safe.
SOLIT, funded by the German government, has two focal points:
The technical aspects are mainly dealing with reliability and life – cycle issues of such systems and are not described in this paper.
The other main task is focusing on development of methods how such suppression systems for tunnels can be tested and assessed regarding their effectiveness for a wider range of

applications than today. Furthermore, above mentioned questions should be analyzed more in detail. Experience has shown that full scale fire tests are still necessary.
The SOLIT project is guided by a scientific advisory board containing organizations and institutions that are well experienced in the field of tunnel fire safety e.g. STUVA, Sintef, TNO, BaST or German ministry of transport and infrastructure and TÜV.

3.2. SOLIT Full Scale Fire Test Program

Scenarios for real scale fire testing are always a compromise between reality and feasibility. Indeed, real trucks or cars as fire load would be more realistic but due to extreme differences in size and material composition any comparable and repeatable results would be achieved. Therefore, similar to other fire test procedures, scenarios for tunnel fire testing should also consist of common agreed standard fire loads, e.g. EUR wood pallets, so repeatable results can be ensured.

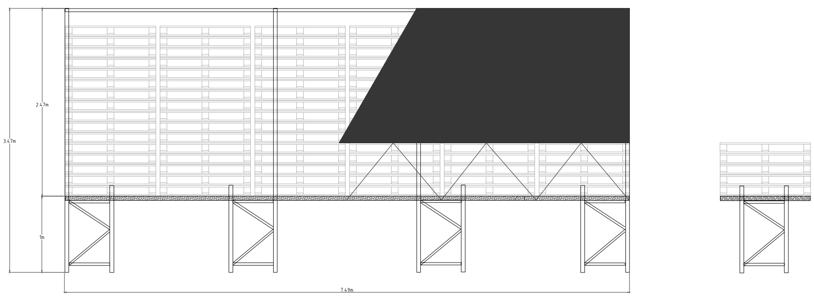

Figure 3: SOLIT Class A Fire Scenario

Based on a study of real tunnel fires and scenarios used in full scale fire tests, following scenarios will be used for to assess effectiveness of the tested system. The scenarios as well as the measurement concept were gathered together with the scientific advisory board of the SOLIT project, which consists of national and international well accepted experts in tunnel fire safety.

Class A Scenario: Wood and plastics
The mock up should simulate a common used loaded truck similar to the Runehamar tests presented by Ingason (2003). The load consists of wooden EUR pallets and plastic pallets with the ratio of 80:20. The whole load is covered with a tarpaulin.

Total weight:	approx. 8 to.
Total energy content:	200 – 240 GJ
Wood/plastic ratio:	80:20

To assess the control of fire spread between vehicles, target objects also consisting of wooden pallets will be used sideward and on downstream side of the mock up.

Class B Scenario: Partly covered diesel pools
According to the UPTUN fire tests for suppression systems, the scenario is slightly modified. By means of this scenario, specific HRR can be produced as well as fires of burnable liquids.

Max estimated HRR:	approx. 30 MW
Total energy content:	20 – 30 MJ

The cover ensures that the pool surface can not be hidden directly by any suppression system as this would be the situation with real vehicles in a tunnel. By using a similar scenario than within the UPTUN test program, available data can be compared.

The measurement concept is not based on any fixed acceptance criteria. Moreover data should be collected in a way that assessment of efficiency can be done during design of performance based safety measures.

Following data will be measured in general:

- Temperatures in different positions
- Radiant heat
- Gas concentrations (CO, CO_2, O_2)
  Of course, toxicity of smoke is an important issue. Standard fire loads are not able to simulate different material compositions of real material. Therefore extended smoke measurement, e.g. HCl, HCN, NO_x, is not indicated.
- Humidity
- Longitudinal air velocity
- Visibility
  In past, no satisfactory results were achieved for visibility measurements during tunnel fires with suppression systems as measurements did not reflect subjective impressions. Therefore new methods of visibility measurements will be studied during these tests.

The test program will be carried out between March and June 2006. More information about the test program and results will be available at www.solit.info

3.3. Assessment of Test Results

Regarding performance of suppression systems for tunnels until know it was only spoken about "effective" in general. Assessment of effectiveness of such systems can be conducted in two different ways: performance based analysis or prescriptive based.
Particularly in the field of fire protection, prescriptive based layouts of safety systems are often used. If a system fulfils specific requirements, e.g. water flow rate or spacing in case of sprinklers, the system is assumed to be effective. In case the layout of systems is based on real fire tests, e.g. for passive fire protection material but also for water mist systems, there are specific acceptance criteria which must be passed during the testing procedure.
Acceptance criteria in a prescriptive way are fixed values based on measurements for defined aims of the system.
For simple standard applications prescriptive guidelines are usually well accepted and can be seen as very safe. But especially for complex systems, such as tunnel safety systems, it is extremely complicated to adapt these guidelines and values on specific projects.

Performance based layout of safety systems is usually based on an extended risk analysis. Thereupon individual safety measures and systems can be arranged for this specific application. Normally this method is used, when prescriptive guidelines are not available or applicable. Although even for performance based layout accepted guidelines and values should be used as far as possible.
Performance based layout of safety systems gives much more flexibility to consultants to adopt systems especially for each project. But of course a much better knowledge and understanding of the whole safety system is necessary.

In case of fire suppression systems for tunnels it can be assumed, that even after full scale fire testing no general acceptability for the system can be given. Moreover, for every tunnel project it should be verified individually, how such systems can be applied in combination with other safety measures. For such analysis profound knowledge and performance data, generated during real scale fire testing, is strictly necessary.

The methodology to assess effectiveness of suppression systems for tunnels developed within the SOLIT project should not specify approval criteria which must be passed during fire testing but should give suitable fire scenarios and measurement concepts to determine sufficient data for a performance based layout.

4. CONCLUSIONS

Based on new knowledge of scientific full scale fire testing open questions, e.g. given by PIARC can be answered basically. Water mist fire suppression systems as a part of the tunnel safety system are able to improve the atmosphere in tunnels during a fire significantly. As knowledge regarding scaling and analysis of test results as well as interaction with other parts of the tunnel safety system was limited in past the research project SOLIT is focusing on these questions. An extended full scale fire test program is carried out to develop a general accepted methodology to assess effectiveness of fire suppression systems in tunnels.

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APPLICABILITY OF WATER SCREEN FIRE DISASTER PREVENTION SYSTEM TO ROAD TUNNELS IN JAPAN

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ABSTRACT

With the enforcement of the Special Measures Act for Public Use of Deep Underground as well as with ongoing urban renewal, there is a need for fire disaster prevention technology to secure the occupants' safety in case of fire breaking-out in any underground space.

In this respect, a fire disaster prevention system using a water screen was developed for potential fires in underground spaces. This system is aimed at securing the occupants' integrity from the fire by partitioning the fire zone using a water screen and also at the safety of a structure by reducing damage due to the fire. It would correspond to the performance-based-design for providing refuge for the occupants.

In the paper to be prepared, results obtained from experiments on the characteristics of the water screen when used as partitioning technology will be described first. Next, the applicability of this water screen fire disaster prevention system to road tunnels will be examined.

Keywords: water screen, fire disaster prevention system, tunnel

1. INTRODUCTION

Although Japan has entered days of population decline, the demand for space in urban areas has greatly increased under the recognition of the importance of improved urban infrastructures. In order to cope with the decrease in population while maintaining the urban functions within limited areas, it is necessary to further improve the infrastructures of big cities. For that purpose, the Special Measures Act for Public Use of Deep Underground was enforced with the view of making full use of underground spaces and urban reproduction projects for effectively utilizing underground spaces with a depth of 40m or more have been carried forward.

However, it is difficult to take appropriate and prompt measures to meet with a fire breaking out in underground spaces where routes through which heat, smoke and particles can pass to the outside are limited.

Large-scale fires which broke out in tunnels such as the Euro Tunnel and the Mont Blanc Tunnel and at a subway station in Taegu city in Korea inflicted severe damage. Due to the fact that these spaces were enclosed and the supply of air from outside was limited, the occupants took refuge in a direction to which high temperature smoke spread and eventually big disasters occurred.

In cases where fires break out in tunnels or in underground spaces, it is very important to secure the “safety of structures” by restraining the spread and extension of flames while also cooling structures to ensure the “safety for evacuation” in order to isolate occupants from heat, smoke and any poisonous gases generated by a fire and to guide them to safe places.

In cases where fires break out in tunnels or in underground spaces, it is very important to secure the “safety of structures” by restraining the spread and extension of flames while also cooling structures to ensure the “safety for evacuation” in order to isolate occupants from heat, smoke and any poisonous gases generated by a fire and to guide them to safe places. Namely, for the purpose of protecting lives, it is necessary to keep the temperature and air quality in a range where survival is possible as well as to secure passageways of refuge for leading occupants from underground spaces through to the outside spaces. Furthermore, rescue teams must move in close to fire zones in safety. In the case of a fire breaking out in a tunnel, two different methods are taken into account; one for protecting lives throughout the tunnel and the other for protecting them in partially compartmented spaces. In Japan, a method for compartmenting a fire zone using water spraying equipment installed in road tunnels has been standardized. With regard to deep underground tunnels in big cities, highly developed monitoring and safety measures for protecting lives from earthquakes, flood damage and terrorist attacks must always be maintained. In this respect, a method for creating compartments while always maintaining the function for monitoring and safety is required.

A water screen fire disaster prevention system for improving the safety of occupants escaping from a fire in order to protect their lives by compartmenting a fire zone using water screens (hereafter referred to as WS), was developed.

The characteristics of this water screen fire disaster prevention system as well as emergency facilities of road tunnels in Japan are described below for the purpose of indicating the applicability of this new fire disaster prevention system to the existing systems in the future.

2. EMERGENCY FACILITIES OF ROAD TUNNELS IN JAPAN

2.1. Procession

On the night of July 11,1979, the worst fire accident in Japanese history happened in the Nihonzaka Tunnel. 170 cars were caught in a fire that broke out in a tunnel with a length of 2045m on the Tomei [Tokyo-Nagoya] Expressway. 7 people were killed in this accident. Furthermore, the interruption of the Tomei Expressway, which is indispensable for the Japanese economy, inflicted a great economic loss.

Accordingly, the existing conception of the installation of emergency facilities for road tunnels in Japan was put in order to create the road tunnel emergency facilities installation standards in 1981 based on the lessons obtained from this accident. Later on, the standards were partially revised as a result of investigations carried out through fire tests in actual tunnels. Details of the road tunnel emergency facilities installation standard and explanations issued by the Japan Road Association in 2001 are described below.

2.2. Road tunnel emergency facilities

Road tunnels in Japan are classified into 5 ranks extending from class AA to class D depending upon the length of tunnels and traffic volume (Figure.1). Standards for the installation of emergency facilities are determined according to each classification rank. Namely, a scale for the extent of emergency facilities is decided upon due to the fire occurrence ratio for each tunnel. As for very long tunnels on national high ways classed AA complete facilities must be installed.

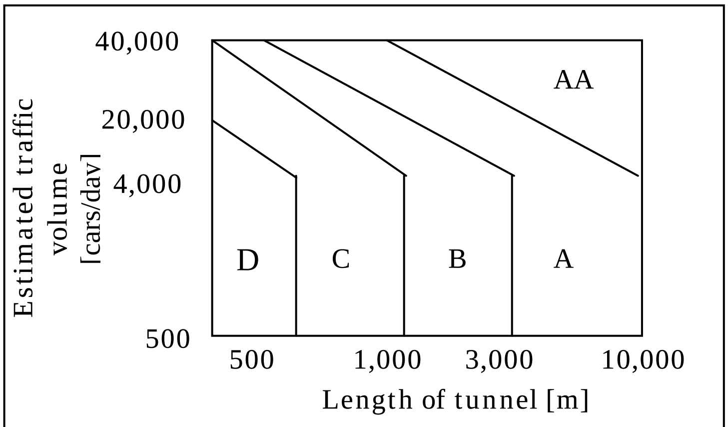


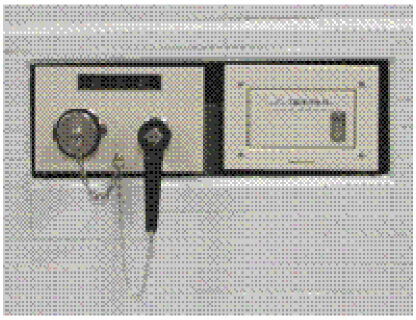
Figure 1: Road Tunnel Standard

Equipment for notification and alarm, extinguishment equipment, refuge instruction equipment and other pieces of equipment are installed as emergency facilities.

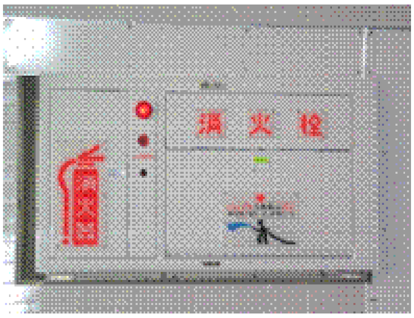
① Equipment for notification and alarm.

This equipment is used for notifying road management personnel, fire stations or police stations of the occurrence of a fire and other accidents in tunnels as well as for informing road users inside and outside the tunnels. Emergency telephones, push-bottom notification devices and fire detectors are all part of the notification equipment. Alarm equipment has emergency alarm devices (photo 1).

Fire alarm



Faucet

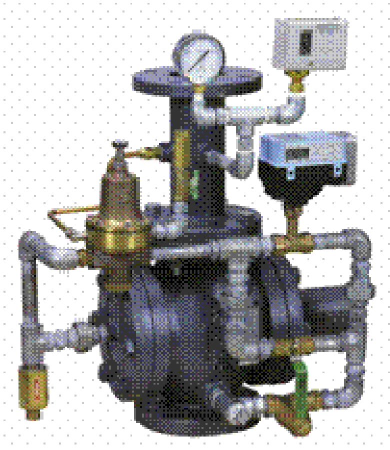


Fire hydrant

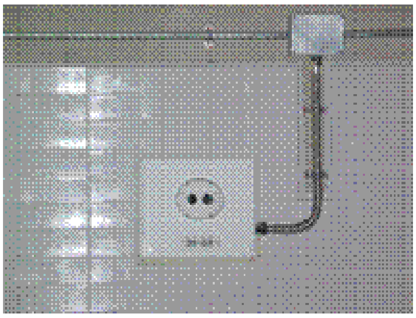
Pump unit

External faucet

Emergency exit



Deluge valve



Emergency telephone

Water Spray Head

Photo 1: Emergency Facilities

② Extinguishment equipment

Fire fighting implies initial fire fighting carried out by occupants in tunnels and full-scale fire fighting by fire-brigades. Extinguishment equipment including fire extinguishers and fire hydrants is installed assuming initial fire fighting.

③ Refuge instruction equipment

This equipment is used for guiding occupants who have met with a fire or accidents in tunnels for evacuation to the outside in safety.

There are guide sign plates, smoke exhaustion equipment and exit passageways included in the refuge instruction equipment. The guide sign plate indicates information with regard to distances to exits, the distances or directions to exit passageways and their locations.

The smoke exhaustion equipment restrains the spread of smoke in order to improve the environment for evacuation in the case of a fire breaking out in tunnels. It also compulsorily exhausts smoke permeating the whole tunnel to the outside in order to facilitate fire fighting and rescue・first aid activities easily. In general, ordinary ventilators are used for smoke exhaustion.

In the case of a longitudinal ventilation system being applied, a wind speed in a one-way traffic tunnel is set at 2m/s in order to restrain the spreading of smoke toward the windward side when a fire

breaks out. Moreover, in a two-way traffic tunnel at the initial evacuation stage just after a fire has broken out, operation of ventilators is stopped in order to control the spreading of smoke. When fire fighting or rescue and first aid activities are carried out, ventilators are activated in order to exhaust smoke.

Exit passageways are used for guiding occupants in a tunnel to other safe spaces for evacuation.

④ Other pieces of equipment

Other pieces of equipment supplement equipment for notification and alarm, extinguishment equipment and refuge instruction equipment in order to carry out effective fire fighting.
There are water taps, radio communication auxiliary equipment, radio rebroadcast equipment, loudspeaker, broadcast equipment, water spraying equipment and monitors as other pieces of equipment.

Water spraying equipment restrains the force of flames by cooling a fire source and its vicinity and supports fire fighting as well. Specifications of water spraying equipment were determined in 1968 based on the results of fire tests conducted in actual tunnels in 1960s. Since then, the specifications of water spraying equipment have been investigated through carrying out several model tests and fire tests in actual tunnels.

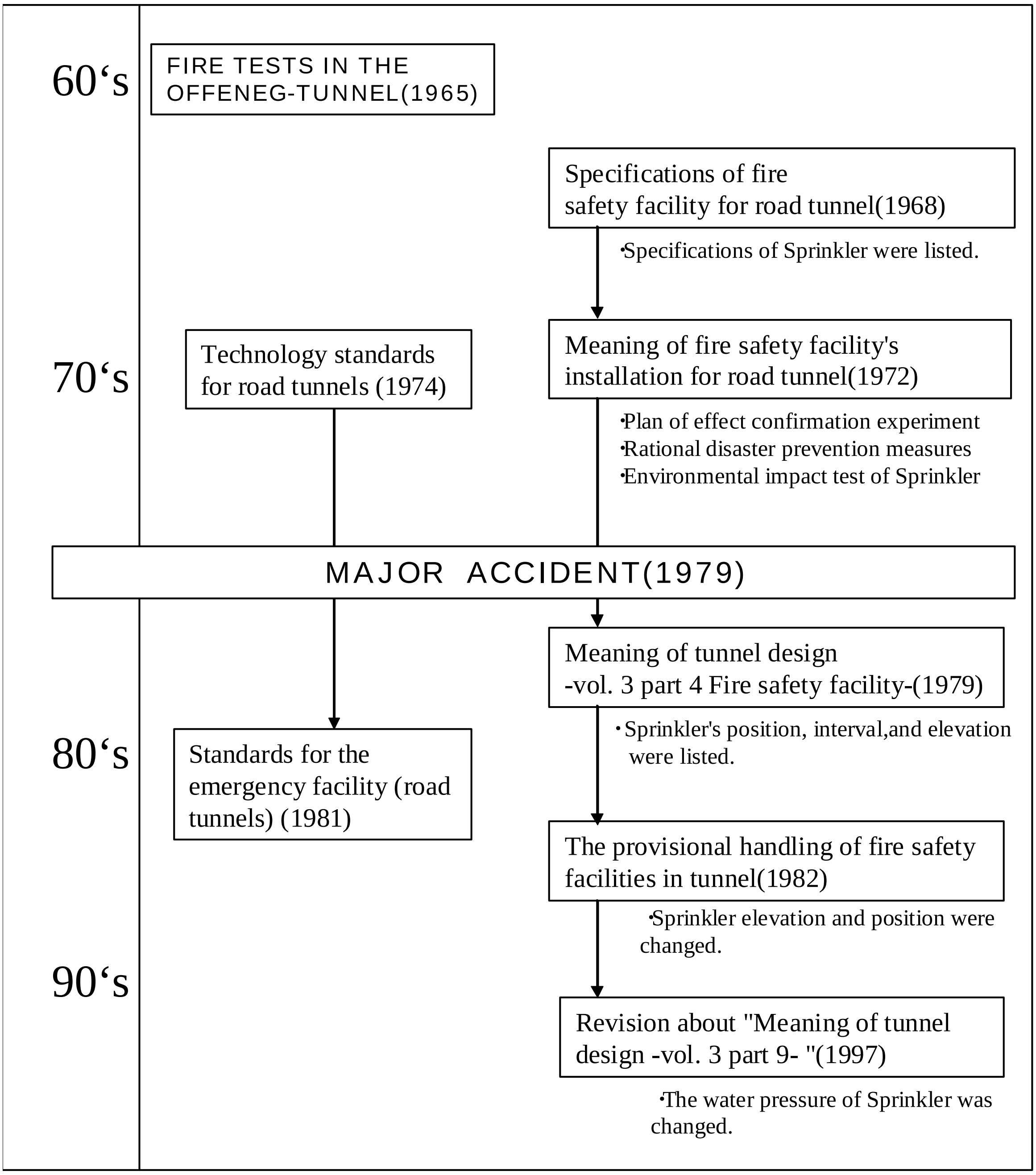


Figure 2: Progress

Emergency facilities for road tunnels in Japan have been installed on the basis of the aforementioned concept since the fire accidents happened in the Nihonzaka Tunnel. However, with regard to water spraying equipment, it has been pointed out that it may well be that the environment for evacuation will be deteriorated due to the spreading of smoke in the case of the water spraying equipment being activated at an early stage of a fire. It can be thought that when deep underground spaces are utilized in big cities in the future, technology to secure the safety of occupants there is necessary without fail.

3. WATER SCREEN FIRE DISASTER PREVENTION SYSTEM

The water screen fire disaster prevention system was developed as technology for improving the safety of occupants taking refuge in the case of fires breaking out in tunnels or underground spaces. This system aims at securing the safety of occupants by compartmenting a fire zone using WS, restraining the spread of heat and smoke and seizing and washing out poisonous floating particles. It also can minimize the degree of damage to structures. This system is a technology for creating water screens by spraying water under high pressure in a hanging bell shape from spiral type water screen heads (photo 2) arranged in lines in patterns which form compartments.

Photo 2:Spiral Head

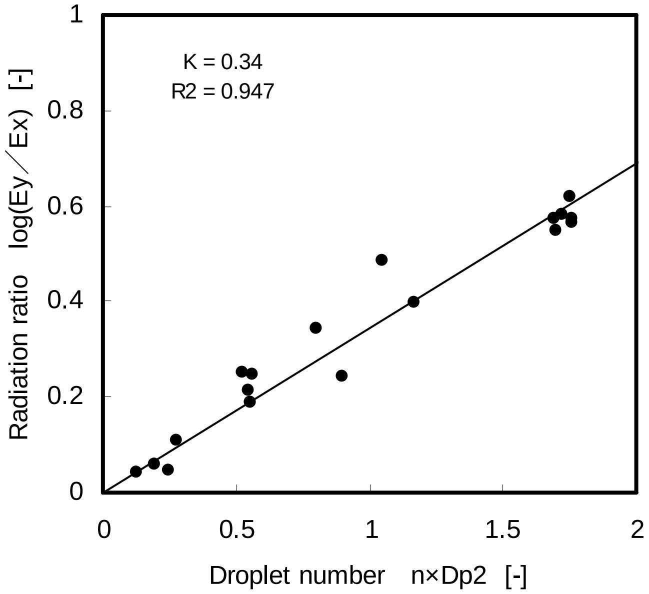


Figure 3: Relationship between mean particle diameter and heat radiation

3.1. Compartmenting using WS

Past studies have resulted in confirming the fact that the smaller a mean particle diameter and the slower a dropping speed for sprayed water under the condition of the same amount of water, the higher the heat radiation isolation effect (Figure 3). Furthermore, investigations were carried out under the condition of the mean particle diameter being 100 μ m or more in order that the water particles may not be swept away by fire plumes or be vaporized.

As a result, WS with a mean water particle diameter of about 200 μ m was developed as a new method for compartmenting a fire zone which has functions other than just the fire extinguishing performance of water sprinkling equipment, namely functions for fire prevention compartments and escape equipment. The water particle diameter of the WS is about 1/5 of about 1000 μ m for the diameter of a rain particle and the diameter of a water particle from a sprinkler. In this case, the volume of a water particle sprayed from the WS is about 1/125 of rain or sprinkled water particles and the number of water particles corresponding to the same volume of water is about 125 times. The surface area of a water particle from the WS becomes about 1/2, so the total surface area for the same volume of water reaches 5 times. This new compartmenting method with WS was developed utilizing the fact that the dropping speed for water particles from the WS decreases and the heat radiation isolation effect is heightened. Moreover, the water screen can be created by using the effect of water particles with a diameter of about 200 μ m (Figure 4).

This water screen can be formed by the water sprayed at 10L/min from each of the special spiral type heads in a hanging bell shape with a radius of about 800mm. Moreover, since the water is sprayed from each head in an almost horizontal direction under drainage pressure of about 1.0MP, there is no vacant space between the ceiling surface and the sprayed water surface.

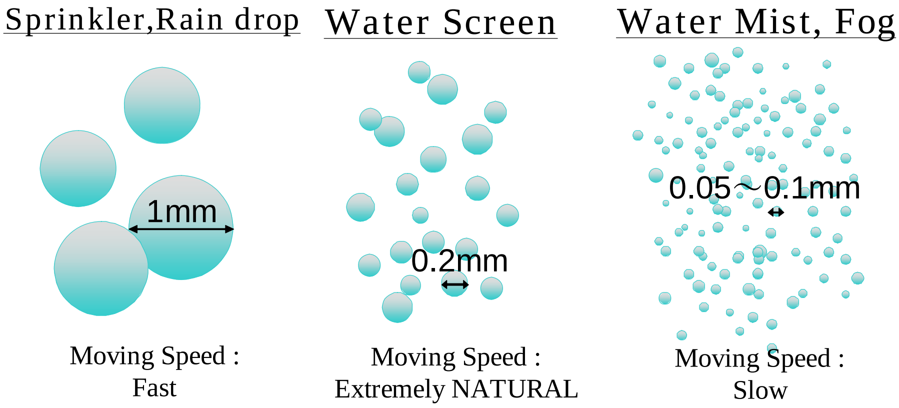


Figure 4: Comparison

In cases where a fire breaks out in a tunnel under natural ventilation conditions, with regard to the flow in an axial direction, the flow of high temperature smoke floating toward an exit at the upper part of the tunnel becomes a function of a heat release rate from the fire source and it agrees with the flow of air moving in the reverse direction at the lower part of the tunnel in the mass flow flux. When actuating the WS installed at right angles to the longitudinal direction of a tunnel at fixed intervals, the density difference at the upper end of the flow becomes small due to a cooling effect of the WS upon the high temperature smoke layer. Accordingly, the flow stops and the effects of the compartment such as the decrease in heat radiation are exerted. Compartmenting is based upon the conception that heat and smoke generated by a fire should be confined within a limited area to prevent them from spreading in the whole space. Furthermore, it can be estimated that the water screen fire disaster prevention system has an effect to restrain the heat release rate due to the decrease in the air flowing in from the outside of the tunnel.

3.2. Characteristics of WS

In order to confirm the compartmenting effect of the WS in a road tunnel, a fire test was carried out (Photo 3) using a ventilation control wind speed (0~3.2m/s) and a gasoline fire source (corresponding to 8.5MW, 28.5MW) as main variables assuming tunnels of class AA for the Road Standards Type 1.

Radiant heat absorption characteristics as well as heat generation characteristics in the case of a compartmenting length being set at 50m were obtained. This fire test was carried out using a 1/2 scale model of a tunnel (Photo 4). Each variable used in the test was reduced based on the Froude law (Table 1). As a result of the test, the following compartment characteristics of the WS were obtained.

Table 1 Coefficient of Reduced Scale

	Full-Scale	Model-Scale
Typical Length	50m	25m
Wind velocity	2.0m/sec	1.4m/sec
Heat Release Rate	8.5MW 28.3MW	1.5MW 5.0MW
Time	14min	10min
Interval of Head	25cm	50cm

Photo 3: Emergency Facilities

Photo 4: 1/2 Scale Model

Photo 5: Interior conditions
(Before WS are activated)

Photo 6: Interior conditions
(After WS are activated)

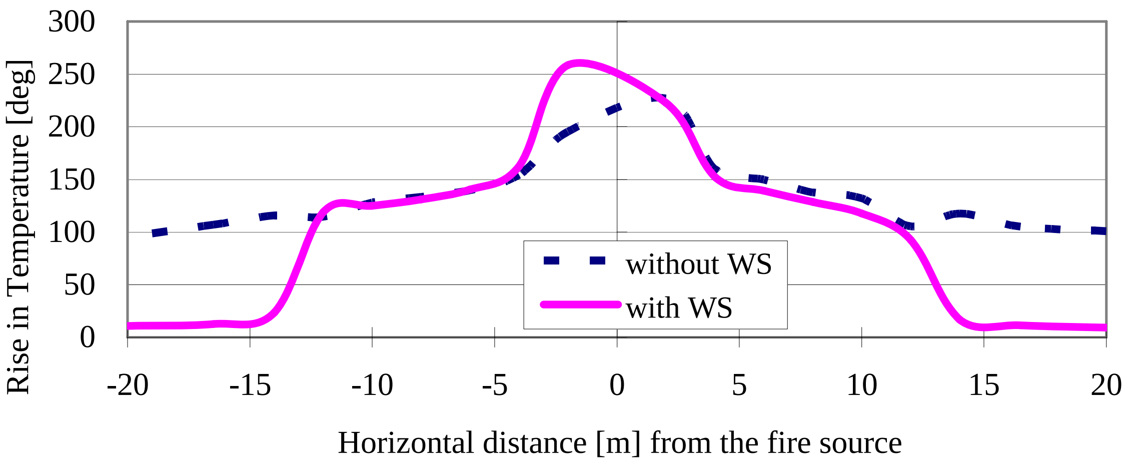


Figure 5: Ceiling Temperature

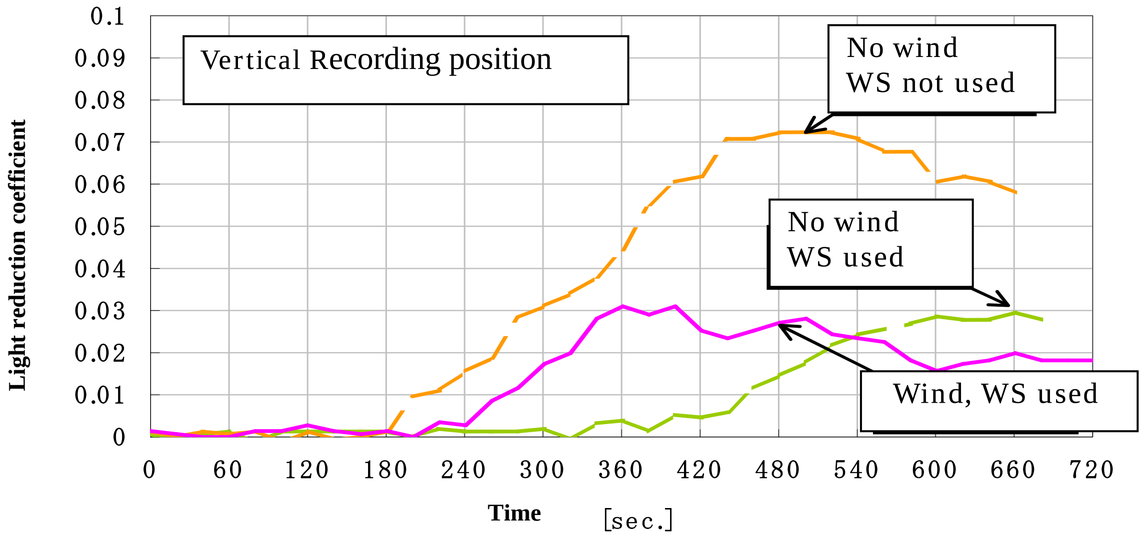


Figure 6: Smoke Density in the Test Site

① 70~80% for the reduction of heat, 60~80% for smoke and about 15% for poisonous gas (CO) were confirmed respectively.

② The water screen was formed at an inclination of 33° in the case of an actual scale conversion wind speed being 20m/s (test wind speed: 1.4m/s) and the same compartmenting effect as that mentioned above was confirmed.

③ A fire zone compartmented by WS can protect the lives of any occupants.

④ Evacuees can easily pass through water screens.

As mentioned above, it was verified that the WS is very effective as a technology for compartmenting a fire zone when a fire breaks out in tunnels.

3.3. Main Equipment of WS

The main equipment is relatively simple and consists of water supply units such as tanks, high pressure pumps and piping, and water screen spray nozzle heads connected to this as well as dedicated fire detectors and a control panel. It can easily in existing structures.

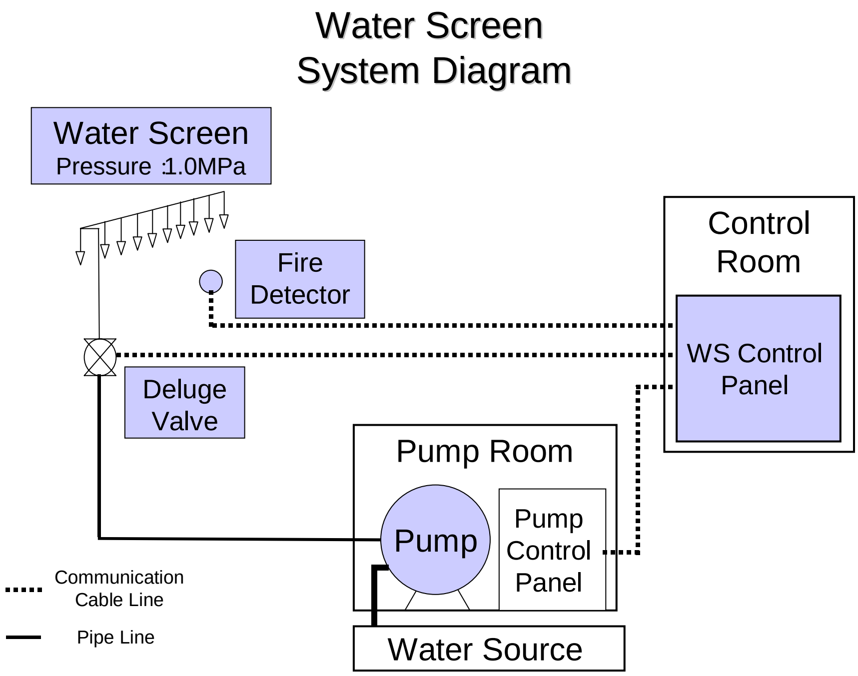


Figure 7: Main Equipment

4. APPLICABILITY OF THE WS TO ROAD TUNNELS

Up to now, road tunnels have yet to be compartmented in order to avoid traffic congestion. However, the applicability of the WS to road tunnels as a compartment technology has been investigated in order that occupants may take refuge in safety and that fire-fighting・rescue operations may easily be carried out. This is so because the WS does not obstruct traffic and it also reduces heat and smoke in road tunnels.

A deep underground tunnel in urban districts is subjected to the investigation this time. A shield tunnel such as Tokyo wan aqua-line which is a representative underground tunnel structure in Japan was assumed.

Places of safety are located under floor decks. Air pressure is applied to these places for the purpose of preventing the inflow of heat and smoke from driveways. The basic safety of occupants can be secured if they take refuge in these places. Therefore, it is important to guide them to places of refuge in safety from the viewpoint of security of safety for evacuation.

A longitudinal ventilation system was applied to vertical shafts for air ventilation. A tunnel section area was set at 100m2 or more. Water spraying equipment and WS were arranged at intervals of 5m and 50m respectively. Owing to the fact that in a tunnel the air flows toward a fixed direction due to effects of ventilation and the movement of vehicles, heat and smoke easily spread on the leeward. In particular, it is an important subject in tunnels in urban districts which are apt to be crowded with a great number of vehicles to check the spread of a fire for vehicles as well as to prevent the extension of damage caused by heat and smoke flowing on the leeward side.

The steps of procedure for the water screen fire disaster prevention system subjected to the investigations this time are as follows:

Figure 8: View of the system when applied to a road tunnel

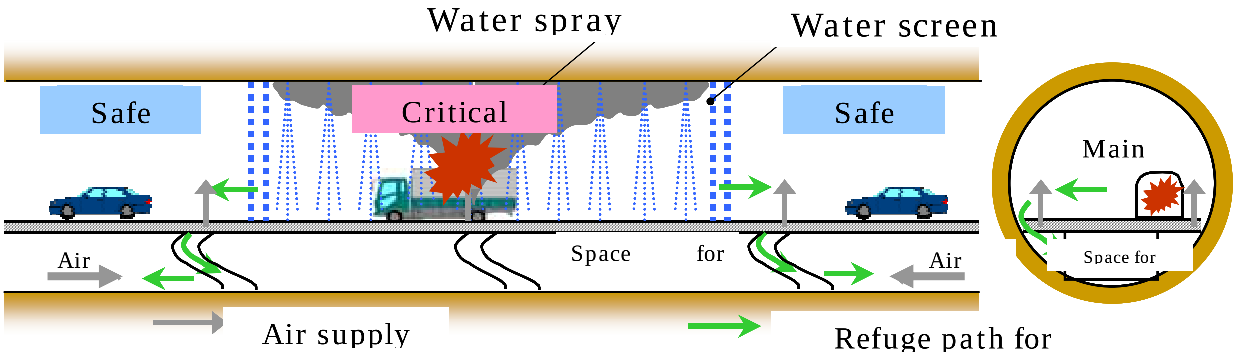


Figure 9: Water screen fire prevention system for road tunnels

[Steps of procedure for the water screen fire disaster prevention system]

① A fire zone is to be specified after detecting the occurrence of a fire.

② A fire compartment is to be formed by actuating WS so that it can surround the location of the fire in order to reduce heat and smoke spreading to other zones.

In the case of a one-way traffic tunnel, the wind speed is controlled at 2m/s. In the case of a two-way traffic tunnel, the operation of the ventilators is stopped.

③ Occupants move to safe zones (safety zones) on the road surfaces where the effects of heat and smoke are small after passing through WS from a fire zone. Then, they move to places of safety located under the road surface going down slopes from fire exits and they take refuge on the outside of the tunnel.

④ After the occupants have moved to the outside of the fire zone through WS, water spraying equipment in the fire zone is to be activated for initial fire-fighting in order to cool tunnel structures.

⑤ Fire brigades enter onto road surfaces outside the fire zone going up slopes from places of safety under the floor decks and move in close to the fire zone. Fire–fighting and rescue operations are carried out after confirming actual conditions in the fire zone from various sources located on the outside of it. It can be taken into account whether to activate ventilators for smoke exhaustion without using WS depending upon conditions in the fire zone.

The safety of occupants moving to refuge can be improved in accordance with these steps of procedure.

5. CONCLUSION

In this paper, application examples of the water screen fire disaster prevention system as a technology for the compartmenting of road tunnels are described. However, the applicability of this system to railways tunnels, places for doors leading to places of refuge in the case of mountain tunnels and junctions of two tunnels.

Furthermore, in view of the fact that the time, in which occupants can take refuge in safety, can be quantified as the time for actuating WS, a rational design of a fire disaster prevention system including specifications of ventilation equipment and fire prevention equipment for the arrangement of places of safety can be made by combining the simulation of occupants' actions for refuge and both a 3rd mode heat behavior analysis and a smoke flow analysis.

In the future, development for further improving this system will be carried out.

ACKNOWLEDGEMENTS:

The authors would like to express their thanks for the valuable cooperation given by Toshihide TSUJI of Hochiki Corporation, Hiroshi ISHIDA, Tatsuya HAYASHI and others concerned with the experiments and analyses.

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FIRE PROTECTION IN THE FELBERTAUERN TUNNEL: INSTALLATION OF A WATER MIST SYSTEM AND INTERACTION WITH THE TUNNEL SAFETY SYSTEM

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ABSTRACT

Tunnels get more and more attractive for leading transit routes through cities and mountains. Hoverer, the major tunnel accidents in the past showed the risks of such tunnels quite plainly: In case of a fire in a tunnel, this fire will rapidly develop 1.000°C and more inside the tunnel and thus, jeopardize the escape of the passengers, prevent the fire brigade from entering the tunnel and finally cause the tunnel structure to collapse.

In the recent years many tunnel operators increased the safety of their tunnels by implementing various safety devices like fire detection systems, ventilation systems, upgrade of traffic management systems, etc. However, all those measures are designed to allay the effects of a fire in a tunnel but they do not deal with the definite cause - all these measures do not suppress the fire itself.

Therefore Aquasys developed, designed, tested and validated an efficient water mist fire suppression system for tunnels, which can be activated upon fire detection at the initial stage of the fire already. The benefit and the main objectives of this Aquasys water mist system for tunnels are:

- enabling the fire brigade and emergency services to easily access the scene of the fire
- preventing the fire from spread and thus reducing the smoke quantity
- protecting the tunnel structure to minimise the impact of a fire accident for the operator

For reasons of verifying the efficiency of the water mist system and to validate the system under tunnel conditions, Aquasys carried out extensive full scale fire tests. These fire tests were carefully supervised by two notified institutes: IBS, Austria and VdS, Germany.

Both of these institutes confirmed that the Aquasys water mist system meets the above mentioned objectives and issued approval certificates accordingly.

The first installations of water mist systems stationary into road tunnels opened a new era of tunnel safety! From now on well proven technologies are available to mitigate not only the symptoms of a fire but to actively fight a fire in a tunnel.

Keywords: water mist, fire suppression, tunnel safety

1. INTRODUCTION

Due to increase of traffic and the simultaneous restriction of aboveground space for carrying this traffic, tunnels emerge to be the most attractive infrastructure for highly frequented transit routes. In the past many improvements and optimisations in terms of operating road tunnels have been achieved, however, fire safety became a public issue after Europe's main tunnel fires (Mont Blanc in France/Italy, Tauern in Austria and St. Gotthard in Switzerland) occurred.

These huge tunnel fires showed quite plainly the fatal consequences of a fire in a confined area of a tunnel, like spread of toxic smoke and considerable temperature increase of hundreds of degrees over a wide area of the tunnel. From all the three major accidents it could be derived that it was the spread of dense smoke which was responsible for most fatalities and it was the spread of the heat which enabled the fire to spread from the initial scene of the fire - an accident involving two trucks in this case - to a large section of the tunnel. And both, smoke and high temperatures obviated the emergency services in all the three cases to access the scenes of the accidents to extinguish the fires and to rescue the victims of the incidents.

In the mean time many efforts ware undertaken by national authorities within Europe to improve the safety of road tunnels and subsequently many tunnels ware up-dated with a number of features like new technologies to provide better orientation of the users in case of an emergency, like new fire detection systems aiming to get aware of a fire as soon as ever possible and the ventilation systems of tunnels ware upgraded to cope with the toxic smoke of a tunnel fire. All those measures are designed to allay the effects of a fire in a tunnel but they do not deal with the definite cause - all these measures do not suppress the fire itself.

It is self-evident that fires in tunnels can not be prevented at all - any appreciated improvements to tunnels could not eliminate the risk of fire. Thus, an effective and efficient system is required to actively suppress a fire and therewith enabling the other safety systems to commonly minimise the effects of a tunnel fire.

2. THE WATER MIST SYSTEM

The Austrian company Aquasys developed, designed, tested and validated an efficient water mist fire suppression system for tunnels. The main objective of this system is to use the favourable characteristics and advantages of water mist, as already proven in the fields of various industries, and apply them to the very specific requirements of suppressing tunnel fires.

The Aquasys water mist system for tunnels is stationary installed in the tunnel. The heart of this water mist system is the tailor-designed nozzle, which produces the very efficient water mist in case of a fire. Each tunnel installation requires a number of nozzles, which are integrated into fire suppression sections. Each of these fire suppression sections is connected to a water main line and can be individually activated to evenly distribute the water mist into the affected area of the tunnel. Additionally a pump station, preferably located outside the tunnel nearby the portals, provides the required water supply via the main line leading through the entire length of the tunnel.

This water mist system utilises the most decisive properties of fine dispersed water for fire suppression: Upon activation of the water mist system the specially designed nozzles evenly distribute tiny water droplets at the scene of the fire. As a result the major proportion of the water in the proximity of the fire is evaporated and producing a vast cooling effect coming from the energy demand of water when evaporated.

Together with cooling high temperatures arising from a tunnel fire, the lots of water droplets are also working like plenty of small reflectors, shielding the radiant heat of the fire. Last but not least water considerably expands when evaporated and there- fore provides oxygen depletion in the immediate place of the flames, which also contributes to the fire suppression efficiency of water mist.

On top of the beneficiary features of this fire fighting agent, water mist is harmless to human and can be applied even at a time when evacuation of the tunnel is not finished.

A prerequisite for using an advanced water mist system for tunnels is the installation of a state-of-the-art tunnel fire detection system for localisation of a fire in its initial stage and many tunnels are already equipped with such detection technologies. Upon fire detection the particular fire suppression section of the water mist system, where the scene of the fire is located, can be activated as well as adjacent sections. This system can be triggered immediately upon receipt of the detection signal or can be delayed until confirmation of the fire by the tunnel operator, whatever is preferred.

The objectives of the Aquasys water mist system for tunnels are:

- enabling the fire brigade and emergency services to easily access the scene of the fire
- preventing the fire from spread and thus reducing the smoke quantity
- protecting the tunnel structure to minimise the impact of a fire accident for the operator

3. STATE OF THE ART / CERTIFICATION

Prior to installation of a water mist system to any particular field of application, Aquasys subjected its systems to fire tests for optimisation reasons and for design validation.

Thus, the Aquasys water mist system for tunnels was subjected to a series of full scale fire tests in a test-tunnel, which were carried out together with two notified bodies: VdS, Germany and IBS, Austria.

For the purpose of these certification fire tests a 200m long test tunnel in the size of a two lane motorway tunnel was erected and equipped with a smoke exhaust system capable to extract $100m^3/s$ to provide similar conditions as in a real tunnel in operation. Additionally the test tunnel also had a certified linear fire detection system installed and a ventilation system to provide a longitudinal wind speed during the fire tests.

In this test tunnel a series of full scale fire tests involving a completely loaded semi-trailer were carried out under supervision of the two notified institutes. With respect to a dense array of temperature probes in the tunnel and even in the concrete above the ignited semi-trailer, the institutes investigated whether the water mist system was capable to provide access for the fire brigade to the scene of the fire and whether it prevented spread of the fire and protected the tunnel structure.

After extensive full scale fire tests under various conditions, both independent institutes confirmed that the Aquasys water mist system meets the above mentioned objectives and issued approval certificates accordingly.

Hence water mist systems are forming part of state-of-the-art tunnel fire protection and the first tunnel owner in Europe is already using this advanced technology of Aquasys.

4. INTERACTION WITH TUNNEL SAFETY SYSTEM

In the recent years a number of different safety devices for tunnels were developed and installed. Each of these devices and systems, such as lightning, traffic management systems, smoke exhaust systems, water mist systems, etc. are focused on meeting one particular hazard of a tunnel in full operation. However, a professional tunnel safety concept has to combine and interlink these available systems according to the circumstances and requirements of each individual tunnel.

One prerequisite for an effective fire safety concept of a tunnel is the installation of a suitable fire detection system, capable to locate a fire in the tunnel already at the initial stage. Upon receipt this fire alarm the operator has to immediately close the tunnel by means of the traffic management system to prevent any more vehicles to enter the tunnel.

At the same time and on the basis of the detection signal, the water mist system has already automatically pre-selected the water mist sections to be activated. Then two alternatives could be realised: Either the water mist system with the already pre-selected sections could be activated manually by the operator, for example after verification of the fire by use of the tunnel video system, or as a second alternative the water mist system could be activated automatically after a pre-determined intervention time, allowing the operator to verify the fire and in case of a false fire alarm to prevent activation of the water mist system manually.

With either of the above alternatives the operator is able to provide such conditions in the tunnel to enable people to escape from the scene and to allow the fire brigade to enter the tunnel and access the scene of the fire after arrival at the tunnel.

With well inter-linked safety systems in combination with an active fire safety system, a tunnel operator can even in case of a major fire accident restrict the interruption of the tunnel to a minimum time and can finally safe the tunnel structure.

5. PROTECTED TUNNELS IN AUSTRIA

In January 2006 the Felbertauernstrasse AG decided to protect their Felbertauern Tunnel, a major transit route through the Alps in north-south direction, with a well proven water mist system as designed, manufactured and installed by Aquasys.

The Felbertauern Tunnel is a bi-directionally operated road tunnel in the length of some 5,5 km. This tunnel is equipped with a recently upgraded ventilation and smoke extraction system. The water mist system to be installed into this tunnel is in the manufacture phase at the time and completion of installation and thus start of operation of the water mist fire suppression system will take place in 2007.

However, the first road tunnel equipped with a water mist system for fire suppression is an Austrian road tunnel close to the industrial area of the city of Linz. The tunnel is bi-directionally operated and, typical for urban tunnels, frequently jammed especially during rush hours. Additional hazards for traffic accidents are a traffic light at one of the portals, the double bend layout and the high share of heavy goods vehicles.

This installation of a water mist system into the tunnel was carried out during night hours as the local authorities as well as the tunnel operator considered a closing of this tunnel impossible during day time due to high peak traffic and it was finished in summer of 2004.

This first installation of a water mist system stationary into a road tunnels opens a new era of tunnel safety! From now on well proven technologies are available to mitigate not only the symptoms of a fire but to actively fight a fire in a tunnel.

POSITION OF PIARC – LATEST DISCUSSIONS AND VIEWS ON FIXED FIRE SUPPRESSION SYSTEMS

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ABSTRACT

First discussions on fixed fire suppression systems started within PIARC at the World Road Congress 1983 in Sydney. Later for the World Road Congress 1999 in Kuala Lumpur, Malaysia PIARC expressed some concerns regarding the installation of fixed fire suppression systems because fires often start in the motor room or in the loading compartment of a heavy goods vehicle (HGV). On the other hand PIARC stated 1999 that sprinklers can be used to cool down vehicles to stop any fire spreading from the burning vehicle to others in its vicinity. With regard to the escape process PIARC expressed then that sprinklers or deluge systems – if they are installed – must not be activated until all occupants have evacuated. In the past PIARC's view about the use of fixed fire suppression systems tended to be negative. This created an extended discussion world-wide. During the last years a lot of research work on fixed fire suppression systems has been conducted. With regard to the application of fixed fire suppression systems PIARC's view is changing considering the latest findings gained with the remarkable research work conducted during the last couple of years. But there are still good reasons to be cautious and to weigh the advantages of the installation of a fixed fire suppression system project wise. It is highly recommended to conduct a risk analysis in the sense of the European Direction Road which was published by the EU in April 2004 as well as a cost-benefit analysis project by project.

Keywords: fixed fire suppression system, road tunnel, research on safety

1. INTRODUCTION

Fires in traffic tunnels can result in real catastrophes as we had to learn at least by the recent incidents in road tunnels as in the Mt. Blanc Tunnel (France/Italy, 24.3.1999), the Tauern Tunnel (Austria, 29.5.1999), the Gotthard Tunnel (Switzerland, 24.10.2001), or in the funicular tunnel of the Kitzsteinhorn (Austria, 11.11.2000), and most recently in the Metro of Daegu (South Korea, 18.2.2003). All these incidents cost too many life's and they taught us some new aspects which were neither known nor expected before, if we do not consider the fire in the Nihonzaka road tunnel in Japan 1979, where about 189 vehicles were involved. One of the new lessons has been the extremely fast development of the fire combined with a tremendously fast increase of temperature up to about 1000 °C (Fig. 1) and even more as well as the enormous emission of masses of smoke from the very beginning of the fire. The second was the fire jump from one car to another even over sections of more than 200 m as in the Mont Blanc Tunnel where no vehicle was stopped. The third and most shocking aspect was the wrong behaviour of many road tunnel users. Too many of them did not realise the danger to which they were exposed. They felt safer in their cars which might be right for the very first minutes and they did not want to leave back their property unobserved. If ever and finally they realised that they are extremely endangered it was too late for a successful escape. They did not save their cars, but lost their not retainable life's. This is by far the most tragic experience.

Against this background every proposal for any improvement in the direction of avoiding a vehicle fire especially in a tunnel, easing the escape conditions, rescuing tunnel users, and automatic fixed fire suppression is welcome. There never is any stupid idea in this field. But immediately after a new or modified idea is born we have to evaluate systematically and seriously, if it is feasible, effective and reliable. In case the first theoretical judgement is positive we have to investigate carefully the details for realisation and finally we should do tests under conditions as realistic as possible. Those tests are a key issue to avoid investments in systems which at the end do not keep what they according to the theoretical thoughts promised. In this connection it is highly recommended – not to say essential – to come to an international agreement and co-operation for planning and conducting the various steps of those practical tests. The increasing shortage of public money asks for a concentration of financial sources. National going it alone must be avoided last but not least against the necessity of harmonised safety concepts in multinational units such like the European Union (EU) or the North America Free Trade Agreement (NAFTA). Purely national efforts will lead to a situation where the first and simplest specific technical aspects are investigated several times again and again instead of combining various important questions in one multinational project supplemented by collecting the different national experience.

Figure 1: Burning lorry in the Gotthard Tunnel (Switzerland) on 24.10.2001

2. PREVIOUS WORK OF PIARC

First discussions on fixed fire suppression systems started within PIARC at the World Road Congress 1983 in Sydney. Later for the World Road Congress 1999 in Kuala Lumpur, Malaysia PIARC expressed some concerns regarding the installation of fixed fire suppression systems because fires often start in the motor room or in the loading compartment of a heavy goods vehicle (HGV). In its publication PIARC also mentioned that under specific conditions extinguishing water could cause an explosion, flammable gases could be produced and may cause explosion and vaporised steam could hurt people. Furthermore, it was stressed that an early activation of the fixed fire suppression system could lead to an immediate destratification of the smoke and thus effects the escape procedure in a negative way. The released water masses as well as the vaporised steam and fog like conditions could significantly reduce the visibility and again affect the escape procedure in a negative way. Finally, PIARC saw the problem of high maintenance costs.

On the other hand PIARC stated 1999 that sprinklers can be used to cool down vehicles to stop any fire spreading from the burning vehicle to others in its vicinity. With regard to the escape process PIARC expressed then that sprinklers or deluge systems – if they are installed – must not be activated until all occupants have evacuated.

In the past PIARC's view about the use of fixed fire suppression systems tended to be negative. This created an extended discussion world-wide. During the last years a lot of research work on fixed fire suppression systems has been conducted. The aspects previously mentioned by PIARC have been studied to more details. In the result the findings gained by these intensive investigations provide a better insight in the pros and cons of fixed fire suppression systems. This forms a better basis for a more up-to-date judgement by PIARC.

3. PRESENT STATUS

Taking into consideration the latest research activities and their results one has clearly to be aware that fixed fire suppression systems in most cases are not able to extinguish major and severe vehicle fires as often still assumed. Neither are they technically able to create such a far reaching effect nor are they laid out for it especially considering financial aspects. In this direction quite often an overestimation not to say a misunderstanding can be met among clients. The aim of using fire suppression systems is instead to slow down the fire development, to reduce or completely avoid a fire spread from one vehicle to another and so to improve the conditions for escape.

Tunnel fixed fire suppression systems (Fig. 2) did not find a far ranging application so far. Their affectivity and general benefit is worldwide under an intense discussion (Directive 2004, Haack 2004, Haack 2005). For example one important question is related to the optimum timing of activating the system not to harm the escape and rescue process by destroying the smoke stratification or creating hot steam too early. Another open question deals with the generally cost-benefit evaluation of those systems in comparison with the safety measures commonly taken nowadays.

Figure 2: Test of a water mist system (Fogtec), conducted within the UPTUN Research Project

To gain better knowledge in this direction it is necessary to conduct an internationally agreed test program with large scale tests. First steps in this direction have been the most recent tests in the Runehamar Tunnel in Norway (Oct. 2004) and in the Virgolo Tunnel in Italy (Feb. 2005). Both large scale tests were conducted in the frame of a huge European research project with more than 40 partners involved: Cost-effective, Sustainable and Innovative **Up**grading Methods for Fire Safety in Existing **Tu**nnels – better known under the acronym UPTUN. For the same purpose the European Commission launched a feasibility study for a **L**arge-**S**cale **U**nderground **R**esearch **F**acility on safety and security under the acronym **L-Surf** most recently. This facility will surely contribute to avoid failures in large investments in tunnel safety systems which may at the end not fulfil the expectations.

In general, there are some basic requirements with regard to fixed fire suppression systems (PIARC 1999). According to the present and still ongoing discussion in the according working group of PIARC those systems have to be function able at any time. They must be and stay reliable even under the rough conditions of the tunnel atmosphere which is normally characterised by high moisture and in the winter time salt content of the air and dust because of steady wear of the road pavement and the tyres as well and additionally particle loaded air because of diesel exhaust fumes. The investment costs must be acceptable and the maintenance costs kept low. The installation as well as the operation of the system should not be too complicated.

There are some very important questions left in connection with the installation of fixed fire suppression systems. Those are for example:

- Is there any economic compensation given with the investment for a fixed fire suppression system for example in form of savings for the layout of the ventilation?
- What is the mutual impact of the various components of safety systems in a modern tunnel additionally equipped with a fixed fire suppression system?

Since Kuala Lumpur (1999) and Durban (South Africa, 2003; report not yet published) the latest discussions in PIARC working group no. 6 “Ventilation and Fire Control” of the Technical Committee C3.3 “Tunnel Operations” tend to lead to the following view of PIARC:

It is still not possible against the present status of knowledge to set up general rules whether to install fixed fire suppression systems in tunnels or not. For a given tunnel a specific **risk analysis** concerning the appropriateness of a fixed fire suppression system has to be conducted. Such a risk assessment of a tunnel encountering a fixed fire suppression system should take into account the following aspects:

- Safety of users
- Capacity/possibilities of the fire brigades and rescue services in the area of the tunnel
- Resistance of structure against fire
- Balance between costs and benefits of a fixed fire suppression system
- Interaction between the various safety related components of the tunnel

4. CONCLUSION

With regard to the application of fixed fire suppression systems PIARC's view is changing considering the latest findings gained with the remarkable research work conducted during the last couple of years. But there are still good reasons to be cautious and to weigh the advantages of the installation of a fixed fire suppression system project wise. According to PIARC's present view 3 absolutely important requirements have to be met when discussing whether to install a fixed fire suppression system in a specific tunnel or not:

- The installation of a fixed fire suppression system is to combine with an appropriate fire detection and fire localising system.
- Great care must be taken into account regarding maintenance and operating costs of such a system.
- During the whole life cycle of a tunnel it must be guaranteed to meet an acceptable cost frame as well as the full capacity and function of the fixed fire suppression system.

It is highly recommended to conduct a risk analysis in the sense of the European Direction Road (STUVA 2002) which was published by the EU in April 2004 as well as a cost-benefit analysis project by project.

In the end it can be stated that without any question we need tunnels in our daily life to ensure a high level of mobility for persons and goods which is a highly ranked political requirement. Tunnels for road, rail, and mass transit must be safe and for this all necessary efforts have to be taken while considering an optimum balance between technical solutions, their affectivity and reliability, and a reasonable relation of costs and benefit.

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SAFETY IN ROAD TUNNELS : SHOULD WE EDUCATE THE USER TO THE TUNNEL ? OR ADAPT THE TUNNEL TO THE USER IN PANIC ?

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ABSTRACT

The presentation shows the main points of the actions undertaken, and their consequences, in various countries, focuses then on the aspects of human behaviour, based on the work of the corresponding Working Group of PIARC : training of the user of course, but also training of the operator, of the rescue services, the taking into account of the specificities of tunnels in the driving schools (as well for the "common" users as for the "road professionals"), in the technical control centres for vehicles, etc.

INTRODUCTION

Tunnels are more and more used for allowing roads and railways to cross natural barriers such as mountain chains, rivers and canals, or even straits. The environmental problems and the restricted urban space result also in carrying out underground facilities such as mass transit systems, railway and road tunnels. In general, tunnels became vital parts of the land transport networks. Many of them ensure vital economic links and allow to carry out high-ranked political aims for mobility of people and goods.

A recent study by the Academy of Sciences of Vienna indicates that private motoring in Europe will rise by around 20 % by the year 2010 compared with 1997, and by as much as about 40 % by 2030. Other forecasts indicate that goods traffic in Europe will rise by about 60 % during the next 30 years.

Against this background it is imperative that new logistics concepts, new ways to secure mobility and also new supplementary measures to improve the infrastructure are found. One of the solutions is certainly to use the chances afforded by the underground. Latest statistical data give rise to the expectation of substantial tunnelling activities on a world-wide scale over the next 10 to 15 years : the European tunnelling market can expect a total construction volume of around 2 100 km of transport tunnels. Statistics relating to the Asian market indicate a volume of around2 350 km. Roughly 650 km is scheduled for construction in South America and at least the same magnitude on the North American continent. Australia and northern and southern Africa are also planning tunnelling projects, although to a less degree.

The presentation will first show the main points of the actions undertaken, and their consequences, in various countries.

It will further focus on the aspects of human behaviour, based on the work of the corresponding Working Group of PIARC : training of the user of course, but also training of the operator, of the rescue services, the taking into account of the specificities of tunnels in the driving schools (as well for the "common" users as for the "road professionals", in the technical control centres for vehicles, etc.

The debate will finally be opened on the design of tunnels starting from the knowledge acquired on the behaviour of users in case of incident in a tunnel : as the panic reactions are better known and understood, should one not take them into account in the design of new achievements or in the improvement of existing ones ?

SAFETY IN ROAD TUNNELS BEFORE THE ACCIDENTS OF 1999-2001

Road safety in general, and specially safety in road tunnels, has for long been the competence of national, or even local authorities. If there has been since a few decennia some harmony in Europe and even in the world in the field of signalisation (meaning the way of indicating a regulation or giving information, compulsory or not), inter alia thanks to the efforts of the ECE/UNO1, the basic rules remain most of all national. Three typical examples in Europe are the colour of signalling to and on the motorways, the speed limits on roads and motorways, and even left or right driving.

Normalisation activities were not inexistent, but the regulations could not be made compulsory out of national borders.

This was also the case for the equipment of road tunnels, where mainly the Road Tunnel Committee of PIARC2 had produced since long recommendations about the types of equipments to use. But it were only recommendations, and each country or even each operator remained free to implement them or not. These activities thus got the attention only from the professionals, but not from the general public.

THE ACCIDENTS OF 1999-2001 IN EUROPE AND IN THE WORLD, IN ROAD- AND OTHER TUNNELS

The dramatic fires that happened during the five last years took mostly place in road tunnels : the Mont Blanc Tunnel (France/Italy, 1999; 39 fatalities), the Tauern Tunnel (Austria, 1999; 12 fatalities), the Gotthard Tunnel (Switzerland, 2001; 11 fatalities).

Let us however not forget the much more dramatic fires in the funicular tunnel of the Kitzsteinhorn (Austria, 2000; 156 fatalities), and in the metro of Daegu (South Korea, 2003; 196 fatalities).

THE NATIONAL AND INTERNATIONAL ACTIONS UNDERTAKEN SINCE 2000

These catastrophes have had a large echo in the public opinion, specially in Europe. The political authorities have so started to be involved in tunnel safety, what led to a strong request for its improvement. Numerous other initiatives have then been launched at various national, European and international levels : for road tunnels it mostly concerns (in chronological order of their actions) the ECE/ONU, the EU3 and the numerous European research programmes and thematic networks, as DARTS4, FIT5, UPTUN6

Their objectives are to set up recommendations and reinforced, if possible internationally harmonized regulations, as well as the starting of new research to improve the understanding of fires in tunnels and to limit their consequences.

1. Economical Commission for Europe of the United Nations (ECE/ONU)

The ECE/UNO includes representatives from all European countries from the Atlantic to the Ural. It also administers international legally binding instruments, including the European Agreement on Main International Traffic Arteries (AGR), the Vienna Conventions on Road Traffic and on Road Signs and Signals, the 1958 and 1998 Agreements on Vehicle

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[1] *ECE/UNO : Economical Commission for Europe of the United Nations (Geneva)*
[2] *PIARC : World Road Association (Paris)*
[3] *eu / European Union (Brussels)*
[4] *DARTS : Durable and reliable Tunnel Structures*
[5] *FIT : Fire in Tunnels*
[6] *UPTUN : Cost-effective, sustainable and innovative upgrading Methods for Fire Safety in existing Tunnels*

Regulations and the European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR).

In February 2000, the ECE/UNO Inland Transport Committee, the highest ECE/UNO transport body, approved the creation of the Ad hoc Multidisciplinary Group of Experts on Safety in Tunnels. The creation of the Group was supported by the European Commission. The Group was given the mandate to elaborate, on the basis of best national practices and international knowledge, recommendations to reduce the risk of accidents in road tunnels of various types and lengths, while maximizing the economic efficiency of their construction and operation.

The first task of this Group of Experts was to launch a questionnaire in order to have an up-to-date picture of European road tunnels and of existing tunnel safety legislation. The Group decided to confine its work to tunnels over one kilometre in length. The survey showed that in Europe there are about 700 road tunnels longer than 1 km, of which 8 tunnels are longer than 10 km. A large number of these tunnels are on the E road network which is defined in the AGR Agreement.

The report of the ECE/UNO Group of Experts contains 43 Recommendations to which 2 more, prompted by the Gotthard Tunnel fire in October 2001, were added in January 2002, bringing the total number to 45. The Recommendations are structured in 4 categories reflecting the main factors influencing tunnel safety.

Give that human error is the main cause of accidents, the Group recommended that measures addressed at road users be implemented on a priority basis. They include information campaigns and other measures that target the behaviour of drivers and their training. In the Mont-Blanc fire drivers died in their cars or close by them because they did not know how to react to the fire in front of them. In these measures particular attention is paid to the drivers of heavy vehicles.

The second group of measures concerns tunnel operation and management. Among the measures proposed is the creation of a national coordinating body, the appointment of a safety officer for tunnels longer than 1 km and the regular undertaking of rescue exercises and trials.

The third group of measures concerns the infrastructure. These include criteria for the number of tubes and lanes, emergency exits, ventilation, connections between tubes in twin-tube tunnels, etc. and for equipment and signs.

The fourth group of measures is for vehicles and particularly for heavy vehicles. They include recommendations regarding the quantity of fuel carried, the fire resistance of fuel tanks and the use of highly inflammable materials in the construction of vehicles.

In February 2002, the Inland Transport Committee approved the Recommendations, invited Governments, the EC and organizations to implement them and requested its subsidiary bodies to consider their introduction into the legally binding instruments administered by them.

One can say, without going into details, that amendments are under preparation

- to the Vienna Conventions on Road Traffic and on Road Signs and Signals to introduce rules to be respected by drivers when they have to make an emergency stop in a tunnel and to incorporate new signs including for emergency stopping places and emergency exits ;
- to the AGR introducing a new chapter on management, safety equipment and general arrangements for tunnels, which includes stricter requirements regarding access to the profession of road transport operator ;

- to the ADR to include tunnel safety in the training of drivers of dangerous goods. Work is continuing on the possible incorporation into the ADR of the OECD-PIARC proposal for groupings of dangerous goods whose transport is allowed in tunnels.

The Recommendations of the Group of Experts can be consulted on the website of the UNECE Transport at the following address:
http://www.unece.org/trans/doc/2002/ac7/TRANS-AC7-09e.doc.

2. European Union (EU)

a. Procedure

In its White Paper on transport policy, the European Commission emphasises the need to consider a European Directive on minimum safety requirements to guarantee a high level of safety for the users of tunnels, particularly those in the trans-European road network (TERN). The fires in the Mont Blanc and Tauern tunnels in 1999 and in the Gotthardtunnel in 2001 demonstrated an insufficient safety level of certain road tunnels and have put the risks in road tunnels in the spotlight again and have called also for decisions at political level.

In order to prevent accidents/incidents and to limit the consequences of them, if they occur, a new Directive 2004/54/EC (in the following the Directive) fixes for existing and future tunnels over 500 m length on the TERN minimum safety requirements. It details the duties and the responsibilities for the owner of a tunnel, whether that is a public or private operator, and also fixes a number of traffic requirements. To provoke suitable and rapid reactions, an accent is also put on information and communication. In order to inform the users on best behaviour harmonized information campaigns are envisaged in the future and proposals for a harmonized signalisation in all incident cases in road tunnels are given.

In nearly all European Union Member States there are tunnels which fall within the scope of the Directive. A total of 515 TERN tunnels more than 500 m in length were identified in 2002, around 50% of which are located in Italy. A number of them have been built to specifications that with time have become outdated; either their equipment no longer corresponds to the state of the art or traffic conditions have substantially changed since their initial opening.

co-ordination has been identified as a contributory factor to accidents in trans-border tunnels. The Directive stipulates therefore that all the emergency organisations will have to be associated with the preparation of intervention and rescue plans, which will have to be established under the responsibility of a safety officer for each tunnel.

Moreover, recent serious accidents show that non-native users are at greater risk of becoming a victim in an accident, due to the lack of harmonisation of safety information, communication and equipment.

The proposal for a Directive was prepared by the Commission, and forwarded to the Council and the European Parliament at the end of 2002. Between February and September 2003 a Council working group came at the end to a global common proposal, which was approved in Council on the 9th of October 2003. The European Parliament accepted a report with 75 amendments. This amended final proposal was adopted in April 2004. The Directive was published in the Official Journal of the European Union on the 30th of April 2004 and entered into force at that very date, implying that it has to be transposed in national legislations in the 25 countries before the end of April 2006.

b. Content

The primary objective of the Directive is the prevention of critical events that endanger human life, the environment, tunnel structure and installations.

The secondary objective is the reduction of possible consequences of events such as accidents/incidents by providing the ideal pre-requisites for :
- enabling people involved in an accident/incident to rescue themselves ;
- allowing immediate intervention of road users ;
- ensuring efficient action by emergency services ;
- protecting the environment ;
- limiting material damage.

c. Organisational requirements

Considering that the diversity of organisations involved in managing, operating, maintaining, repairing and upgrading tunnels increases the risk of accidents, the Directive harmonises the organisation of safety and clarifies the different roles and responsibilities. In particular, the Directive asks that each Member State appoints an administrative authority which is the competent authority responsible for all safety related aspects of a tunnel, assisted by an inspection entity for commissioning visits and periodical technical inspections. In most cases, Member States will have the possibility of appointing existing administrative services as administrative authorities for the purposes of the present Directive. Responsibility for safety in each tunnel will lie with the Tunnel Manager and the responsibility for control with an appointed Safety Officer.

d. Technical requirements

The proposed technical requirements are based on works done in international bodies e.g. PIARC and the ECE/UNO).

The safety level in tunnels is influenced by a number of factors that can be classified in the following four categories : infrastructure, operation, vehicles and road users. The Directive takes into account the infrastructure, the operation, and the road users.

The minimal requirements included in the Annexes of the Directive are firstly based on the traffic volumes and the length of the tunnel, and include all structural components, ventilation and the other electromechanical equipments. The Member States can impose more strict requirements, on the condition that they do not contradict the requirements of the Directive. Limited deviations of these minimal requirements can be accepted for a specific Member Country, on condition that a procedure has been followed, which includes the participation of the Commission and all the other Member States.

The following tables give informative summaries of the minimal requirements for the structural safety measures (table 1) and the measures concerning the safety equipments (table 2).

Table 1: Informative summary of structural safety measures

• Mandatory for all tunnels 0 Not Mandatory * Mandatory with exceptions			Traffic < 2000 veh/lane		Traffic > 2000 veh/lane			Additional conditions for mandatory implementation, or comments
			500-1000 m	> 1000 m	500-1000 m	1000-3000 m	> 3000 m	
Structural measures	2 tubes or more	§2.1						Mandatory if a 15 years forecast shows a traffic >10000 veh./lane
	Gradients < 5 %	§2.2	*	*	*	*	*	Mandatory unless not geographically possible
	Emergency walkways	§2.3.1 §2.3.2	*	*	*	*	*	Mandatory when there is no emergency lane ; in existing tunnels where there is neither an emergency lane nor an emergency walkway, additional/reinforced measures shall be taken
	Emergency exits at least every 500 m	§2.3.3-§2.3.9	0	0	*	*	*	Implementation of emergency exits in existing tunnels to be evaluated case-by-case
	Cross-connections for emergency services at least every 1500 m	§2.4.1	0	0/•	0	0/•	•	Mandatory for twin tunnels > 1500 m
	Crossing of the central reserve outside each portal	§2.4.2	•	•	•	•	•	Mandatory for twin tunnels bi-tube where geographically possible
	Lay-bys at least every 1000 m	§2.5	0	0	0	0/•	0/•	Mandatory in new bi-directional tunnels > 1500 m without emergency lanes ; in existing bi-directional tunnels depending on analysis
	Drainage for inflammable and toxic liquids	§2.6	*	*	*	*	*	Mandatory if transport of dangerous goods is allowed
	Fire resistance of the structures	§2.7	•	•	•	•	•	Mandatory if a local collapse can have catastrophic consequences•

Table 2: Informative summary of safety equipment

• Mandatory for all tunnels 0 Non Mandatory * Mandatory with exceptions Θ Recommended			Traffic < 2000 veh/lane		Traffic > 2000 veh/lane			Additional conditions for implementation to be mandatory, or comments
			500-1000 m	> 1000 m	500-1000 m	1000-3000 m	> 3000 m	
Lighting	Normal lighting	§2.8.1	•	•	•	•	•	
	Safety lighting	§2.8.2	•	•	•	•	•	
	Evacuation lighting	§2.8.3	•	•	•	•	•	
Ventilation	Mechanical ventilation	§2.9	0	0	0	•	•	
	Special provisions for (semi-) transversal ventilation	§2.9.5	0	0	0	0	•	Mandatory in bi-directional tunnels with control centre
Emergency stations	At least every 250 m	§2.10	•	•	•	•	•	Equipped with telephone and 2 extinguishers
Water supply	At least every 250 m	§2.11	•	•	•	•	•	If not available, mandatory to provide sufficient water otherwise
Road signs		§2.12	•	•	•	•	•	For all safety facilities provided for tunnel users (cf. annexe III)
Control centre		§2.13	0	0	0	0	•	Surveillance of several tunnels can be centralised in a single control centre
Monitoring systems	Video	§2.14	*	*	*	*	•	Mandatory when there is a control centre
	Automatic incidents and/or fire detection	§2.14	•	•	•	•	•	At least one of the two systems is mandatory in tunnels having a control centre
Equipment to close the tunnel	Traffic signals before the entrances	§2.15.1	0	•	0	•	•	
	Traffic signals inside the tunnel at least every 1000 m	§2.15.2	0	0	0	0	Θ	Recommended if there is a control centre and if the length exceeds 3000 m
Communication systems	Radio re-broadcasting for emergency services	§2.16.1	0	0	0	•	•	
	Emergency radio-messages for the users	§2.16.2	•	•	•	•	•	Mandatory if radio is rebroadcast for tunnel users and if there is a control centre
	Loudspeakers in shelters and exits	§2.16.3	•	•	•	•	•	Mandatory when evacuating users must wait before they can reach the outside
Emergency power supply		§2.17	•	•	•	•	•	To insure the functioning of the indispensable safety equipments at least during the evacuation phase
Fire resistance of equipments		§2.18	•	•	•	•	•	Shall aim to maintain the necessary safety functions

e. Operational requirements

In the event of a serious accident or incident, all appropriate tunnel tubes shall be closed immediately to traffic. This shall be done by simultaneous activation not only of the above-mentioned equipment before the portals, but also of variable message signs, traffic lights and mechanical barriers inside the tunnel, if available, so that all the traffic can be stopped as soon as possible outside and inside the tunnel.

The access time for emergency services in the event of an incident in a tunnel shall be as short as possible and shall be measured during periodic exercises. In the event of an incident, the Tunnel Manager has to work closely together with the emergency services. Emergency services must at least be consulted when defining operation of the tunnel in emergency cases and emergency response plans.

f. Information of the road users

In-depth analyses of incidents on roads show that an accident is the consequence of one or more faults in a complex system involving drivers, vehicles, the road and its surroundings. Thus, efforts to increase the level of road safety have to aim primarily at preventing human error. The second step will have to ensure that errors made by drivers do not have serious consequences. There are various ways of having a direct or indirect influence on the way people act.

The Directive calls for better information for road users on tunnel safety, e.g. through information campaigns at national level and improved communication between the Tunnel Manager and road users inside a tunnel. On the basis of the work of PIARC the Commission produced 2 information leaflets on how to react in accident/incident cases in tunnels.

As recent accidents show that self-rescuing offers the highest potential for saving lives in the case of an accident in a tunnel, the introduction of clear and self-explanatory signs in sufficient numbers indicating the safety equipment in each tunnel is an important measure that can be implemented at relatively low cost. Therefore in addition, the Annexes contain also a description of, and requirements for, the positioning of obligatory road signs, panels and pictograms relating to safety.

g. Follow-up

The Commission will set up a committee which may then decide to create a working group of national experts from the Member States, third countries and competent organisations with the following objectives:

- to gather the data needed to prepare a harmonised procedure for risk analysis if necessary ;
- to prepare further improvements to the minimum safety provisions for construction, operation, maintenance, repair, upgrading, rehabilitation and refurbishment of tunnels of various types and lengths, and to improve traffic conditions in these tunnels, e.g. signs, restrictions on vehicles and dangerous goods, driver training ;
- to collect information on safety provisions in tunnels, in particular on new traffic management techniques.

3. Research Programmes and Thematic Networks

An important number of research projects were also initiated by the European Commission. They are multinational projects awarded and funded within the fifth Research Framework Programme of the European Union.

Durable And Reliable Tunnel Structures (DARTS) started in March 2001 and ended in early 2004. The initiative included eight European partners and was structured into six technical work packages. It was primarily dedicated to the problem of exceeded cost during the construction of underground transport facilities. Furthermore, the quality and lifetime of tunnels as the most cost-intensive component of the entire traffic infrastructure was to be improved. For more information see www.dartsproject.net and the more detailed adjoining article.

Fire in Tunnels (FIT) was established in March 2001 for four years. This is a “thematic network” which includes 33 partners from twelve European countries. It gathers information from all over Europe and around the world about existing research results and general experiences with fire safety in transport tunnels and makes recommendations. For more details see: www.etnfit.net and the adjoining article.

Cost-effective, sustainable and innovative Upgrading Methods for Fire Safety in existing Tunnels (UPTUN) is designed as a research and development project for four years and was started in September 2002. 41 partners from 16 European countries are part of this co-operative effort. The principal goals of this large-scale project with a budget of approximately 12 million euros are described in the adjoining article. For further details see www.uptun.net.

Innovative Systems and Frameworks for Enhancing of Traffic Safety in Road Tunnels (Safe Tunnel), began in September 2001 for a project term of three years involving nine partners. This research project will primarily contribute to reducing the extent and number of accidents in road tunnels with the help of preventive safety measures. For further details see www.crfproject-eu.org.

Virtual Fires (Virtual Real Time Emergency Simulator) also started in 2001 for a duration of three years with eight partners from five European countries. The objective is to develop a suitable and practical simulator to train fire fighters in confining and fighting fires in tunnels. A computer model will be used to create virtual simulations of fires in tunnel situations. For more information visit: www.virtualfires.org.

Safety in Tunnels (Safe-T) is another thematic network with a three-year term started in the end of 2003. The primary objective is to harmonize the European requirements regarding tunnel safety. Experiences gathered at national level are to be compiled and assessed. For further details see www.safetunnel.net.

Safety Improvement in Road & Rail Tunnels using Advanced Information Technologies and Knowledge Intensive Decision Support Models (SIRTAKI) was initiated in September 2001 for a term of three years. The initiative is shared by twelve European partners. The main focus of the project is to reform operative concepts with regard to safety and emergency management. For further details see www.sirtakiproject.com.

THE ACTIONS REGARDING HUMAN BEHAVIOUR AND THE BEHAVIOUR OF USERS IN CASE OF INCIDENT, ACCIDENT AND FIRE

Previous chapters, and specially those concerning ECE/UNO and EU, have shown sufficiently the capital role played by human behaviour in traffic in general, and in tunnel safety in particular.

The most detailed study of human behaviour has been done by an ad hoc Working Group of the Committee of Operation of Road Tunnels of PIARC.

The most important points are quoted hereafter.

1. Behaviour of drivers and passengers

The observations and investigations of the Gotthard tunnel fire in October 2001 showed once again that human behaviour is crucial for the limitation of consequences of a fire. The users, which did not survive the incident, either stayed in their vehicle or tried to save their vehicle rather than their live or left too late their vehicle to reach existing exits to the emergency gallery. This wrong human behaviour lead to the conclusion that it is urgently necessary to launch an information campaign using international harmonised information of experts including those of traffic psychologists and public relation experts.

In the aftermath of the Mont Blanc and Tauern tunnel incidents a considerable number of different national information leaflets were distributed for information of tunnel users. Among them were also those asking the users in case of smoke in the tunnel *"to close their windows, shut down the air intake and restrain from smoking"*. This contra-productive information may lead users to believe they can survive in their vehicles. In some leaflets human behaviour was asked for rules, to which, according to psychologists, nobody will respond, if it can not be controlled and enforced. Therefore a harmonised approach using also these experiences and also the expertise of information and communication specialists is urgently necessary.

The EU information campaign throughout the Member states will include the above mentioned EU-leaflet "Safe driving in Road Tunnels" and two videos prepared on behalf of the Commission: one on human behaviour based on the leaflet and the other one on minimum requirements of tunnel safety for the Trans-European Road Network (TERN)**.** The leaflet includes on the front page a short introduction into the minimum safety equipments of road tunnels and most important on the back page recommendations for best behaviour of road tunnel users. This campaign will use the information channels used by the Commission as well as those of associated and interested parties in the Member states.

2. Leaflets

A common proposal for an information leaflet for non-professional tunnel users was developed after a common work of PIARC and ECE/UNO, and published in 2002 by the European Commission in the 11 languages of the member countries.

In spite of the many discussions on the use of mobile phones in tunnels, this topic is actually not yet resolved. Some countries have forbidden the use of this devices in tunnels in order to push users to use existing emergency phones in tunnels in order to allow there immediate localisation and so shorten the alarm times. It will be hard to ask the public to act against the technological main stream of using this devices to restrain from using it also in tunnels. *"It is harder to change human behaviour than to invent new technologies"*.

It is however clear that all emergency calls from inside a tunnel should automatically go directly to the tunnel operation centre.

3. Driving schools

There are in no countries neither driving examinations including questions about behaviour of users in case of incident/accident in a road tunnel, nor written recommendations on the way drivers should behave when they detect smoke or a fire in their own vehicle or when they drive trough a tunnel. In only few countries there are information and recommendations about the best behaviour in tunnel, as well as specific data about incorrect behaviour of drivers. In most of the countries regulations exist for control and implementation of driving rules, even in road tunnels.

4. Professional drivers

As the initial stages of a fire are the most critical, there is also a need to investigate what the users, and here especially professional drivers, can do to fight the fire and reduce its consequences. Therefore it was felt necessary that professional drivers should know more about behaviour in tunnel environments than the normal driver, and should be considered as examples to follow in case of incident.

5. Tunnel operators

As it appears that in some tunnel fires the human reaction of the operators and the fire fighting services was crucial, it seemed needed to take into account all other categories of people whose behaviour is important. The qualifications of controllers have to be re-evaluated. Therefore it was decided to develop a guide for the best practice of tunnel operators in accident/incident cases. This manual includes the following points :

- detection
- information
- action
- intervention

In general, the majority of European road tunnels operated from manned control centres have already automatised help systems that optimise the work of the operator. In all cases the operators must follow strict procedures in case of incidents. These vary in complexity, but operators must in general follow the same constraints in all control centres.

6. Intervention forces

It is not the aim to tell the intervention forces what to do in case of incident, but try to rectify some of the basic misconceptions commonly held be these services with respect to road tunnels and their equipment. The aim is not to provide a guide, but an information of tunnel equipment and operations with special emphasis of the views of these services.

EMERGENCY EXERCISES IN AUSTRIAN RAILWAY TUNNELS

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ABSTRACT

Emergency exercises are an important part of safety concepts for railway tunnels. This report presents time sequences and experiences acquired when performing emergency exercises in three railway tunnels.
Additional conclusions could be drawn when conducting unannounced emergency exercises with passenger trains transporting pupils.
In the course of these exercises, a new rescue concept involving a ballastless track system inside the tunnel, which is accessible to road vehicles was tested, which revealed advantages as well as disadvantages.
All these exercises confirmed the necessity and the importance of emergency exercises, with the lessons learned being beneficial to railway companies and design offices alike, as they offer valuable information for the improvement of tunnel safety.

Key words: tunnel safety, emergency exercises, railway safety

1. INTRODUCTION

In line with national and international guidelines established for Austrian railway tunnels, a wide range of safety measures has been developed for both the construction of new tunnels and the retrofitting of existing tunnels.
Thanks to very high safety standards in general, very few railway accidents occur and as a result, staff members are hardly ever challenged to cope with scenarios of this type. In the endeavour to verify the efficiency of safety measures, conclusions are often drawn by analogy resorting to other traffic and transport areas (e.g. road tunnels).
It is in the light of these facts that the ÖBB Betrieb AG is stepping up its emergency exercise efforts, simulating scenarios which are as close to reality as possible to be able to gain insights and learn lessons for the further development of tunnel safety concepts.

2. REQUIREMENTS STIPULATED IN RAILWAY OPERATION REGULATIONS

Emergency management manuals not only define requirements regarding systematic measures (search for causes, advanced professional training, technical measures) which come into play following an incident, but also stipulate requirements regarding the frequency and scale of emergency exercises. These requirements shall not just be applicable to the tunnel area, but shall be applicable to the entire line section.
In this context, a differentiation is made between the following types of emergency exercises:

Exercise	Emergency and alarm exercises of fire brigades and rescue organisations, which are planned and executed in conjunction with the railway operator.
Emergency training	In every monitoring sector of a train operations centre, an emergency training is performed once a year involving the entire equipment available as well as all necessary actions. This training shall be designed not to affect normal railway operation.
Practice alarm	Practice alarms are exercises without previous notification or information of the parties intended to participate. For the duration of the practice alarm, the emergency response is coordinated with the commanders of the individual rescue organisations. For every tunnel exceeding 1 km in length, a practice alarm shall be carried out at least once every three years.

The responsibilities regarding preparation, implementation, performance evaluation and feedback are clearly defined.

For the entire monitoring area of the operation control centres there is a standardized emergency folder, which stipulates the organisational and operational standards for the existing infrastructure.

For every railway tunnel exceeding 1500 m in length, a tunnel safety plan exists, which describes all safety-relevant building structures and equipment components and which contains all necessary orientation plans and schematic drawings.

3. LINES OF COMMUNICATION AND ALLOCATION OF RESPONSIBILITIES IN CASE OF AN EMERGENCY

Figure 1 shows the key communication lines in case of an emergency in a railway tunnel.

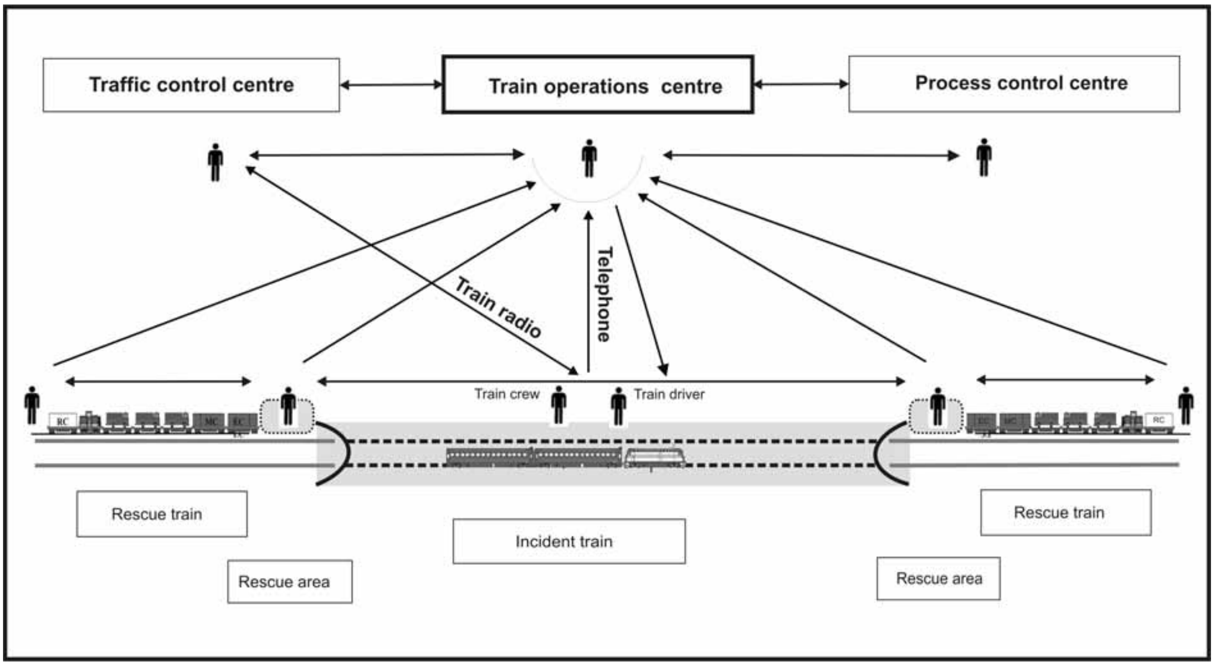

Figure 1: Communication scheme for railway tunnel (rescue concept involving rescue train)

In case of an emergency, different tasks are assigned to the individual parties involved. Table 1 lists the main tasks to be performed.

Table 1: Parties involved and allocation of responsibilities in case of an emergency

Train driver Train crew	Search for causes, internal communication, emergency call to traffic control centre (train radio) or train operations centre (telephone), switching on of tunnel lights, information of passengers, elimination of potential hazards (e.g. fire fighting), decision for self-rescue, instructions for and support of self-rescue
Traffic control centre	Forwarding of emergency calls to train operations centre, support of train operations centre, diversion of train traffic
Train operations centre	Switching on of tunnel lights, alerting of rescue organisations and internal rescue teams, driving trains out of tunnel, stopping of all train traffic, preparation for earthing of overhead lines, communication via emergency telephone, emergency coordinator of railway company (up to arrival of standby emergency coordinator)
Process control centre	Earthing of overhead lines, indication of overhead line status, activation of special light switching cycles, monitoring of electrical equipment (e.g. ventilation) and of switching operations in case of a power supply failure
Emergency coordination at rescue area (portal)	Communication between fire brigade, rescue team, police force and railway company, management of rescue works, coordination with other rescue organisations at second portal and at rescue train
Emergency coordination at rescue train	Assisted-rescue operations following the instructions and in coordination with the emergency coordinator at the portal

With a tunnel envisioning a rescue concept without rescue train, there is no need for an emergency coordination of the rescue train. For every tunnel, the tasks are specified in consultation with the rescue organisations, and they tend to deviate only slightly from the specifications listed above.

4. REPORTS OF EMERGENCY EXERCISES

In order to acquire new and unbiased insights in the course of emergency exercises, new paths were pursued in the last three years in preparation of these exercises.
It was the declared objective of these exercises to check tunnel safety concepts in a more realistic way than under desktop conditions and to identify weak points in organisational measures.
Subsequently three exercises shall be highlighted out of a multitude of emergency exercises conducted in the last few years, which differ considerably regarding their rescue concepts.

4.1. Exercise No. 1 – derailment of freight train with emission of hazardous substance

During this exercise, the train driver transmitted the following radio message "Practice alarm. This is the driver of the Exercise No. 1 train. I am standing inside the tunnel at km xy and the train was stopped automatically as a result of an emergency breaking. I will check the situation."
Five minutes later the train driver sent another message "Practice alarm. Coach No. 10 is derailed. There is a leakage".

The persons responsible for the voluntary rescue organisations had given their consent to a practice alarm outside their normal working hours yet without knowledge of the exact point in time. The train driver and the staff members of the railway company had not been informed in advance.

Table 2: Tunnel Data Exercise No. 1

Tunnel length	Approx. 5 km
Emergency exits	None
Rescue concept Rescue organisations	Fire brigades at the portals and rescue train with rail wagon for the transport of road-bound rescue vehicles; Rescue train is in the station closest to the portal
Meeting point of emergency coordinators	At a pre-defined portal; There are no designated premises, as rescue organisations have rescue vehicles with adequate communication equipment

The following list shall indicate critical points in time:

- 5 min	First radio message of train driver to traffic control centre, forwarding of message to train operations centre
- 3 min	Tunnel lighting switched on by train driver
Time 0	Emergency call of train driver to traffic control centre, forwarding to train operations centre
+ 2-5 min	Alerting of voluntary fire brigade and of police force by train operations centre
+ 9 min	Switching off and earthing of overhead line by process control centre
+ 11 min	Information on train location and freight from train driver to traffic control centre, forwarding to train operations centre
+ 22 min	Arrival of voluntary fire brigade at portal and at rescue train
+ 30 min	Emergency coordinator of Austrian Federal Railways (ÖBB) on scene, arrival of rescue team and police force at portal, slight delay in contact making
+ 30-45 min	Arrival of approx. 20 vehicles at rescue train site and at portal
+ 55 min	Arrival of rescue train at portal
approx. 1.3 h	Arrival of rescue train at scene of accident

Figure 2: Train operations centre /
rescue train with rail wagon for transport of road-bound rescue vehicles

Important lessons learned from Exercise No. 1:

- The operation control points of the railway company responded efficiently to the sequence of events envisaged in the alarm plans.
- The emergency shutdown and the earthing of the overhead line shall be tested in the course of exercises (the normal shutdown procedure shall not be applied).
- The process of contacting the individual emergency coordinators was a little long winded and calls for an easier identification of the emergency coordinators and for a better definition of the meeting point.
- The communication between the fire brigade and the train operations centre (emergency coordinator of the railway company in the initial phase) is to be improved.
- The staff members of the railway company in the rescue train wore respiratory equipment as well as the same protective equipment as the fire brigade and could not be told apart; a different outfit shall be envisioned.
- The loading and launching of the rescue train took quite some time as one had to wait on the arrival of vehicles and crews as well as on the loading of additional equipment for the management of hazardous materials. This time period is definitely to be reduced.

4.2. Exercise No. 2 – derailment of passenger train

During this exercise, the train driver transmitted the following radio message “Practice alarm. The Exercise No. 2 train is derailed, bring all trains to a halt“.

The commanders of all rescue organisations had previously been informed of this exercise. One of the coaches carried extras sporting various injuries. Yet the train driver and the staff members of the railway company had not been notified in advance.

Table 3: Tunnel Data Exercise No. 2

Tunnel length	Approx. 1.1 km
Emergency exits	Rescue tunnel accessible to vehicles
Rescue concept Rescue organisations	Fire brigades at the portals entering tunnel on a carriageway granting road vehicles access to the tunnel; Use of rescue edit located in the middle of the tunnel
Meeting point of emergency coordinators	At a pre-defined portal; There are no designated premises, as rescue organisations have rescue vehicles with adequate communication equipment

The following list shall indicate critical points in time:

Time 0	Emergency call of train driver to traffic control centre, forwarding of message to train operations centre
+ 4 min	Stopping of train traffic Switching off and earthing of overhead line through separate push button by train operations centre
+ 5-10 min	Alerting of voluntary fire brigade and of police force by train operations centre
+ 8 min	Siren alarm of voluntary fire brigade
+ 15 min	Emergency coordinator of fire brigade makes contact with train operations centre by use of emergency telephone at portal
+ 26 min	Train operations centre grants road vehicles access to the tunnel
+ 36 min	First persons injured are brought to a “safe area”

Figure 3: Emergency coordination at portal / fire-fighting vehicles inside tunnel

Important lessons learned from Exercise No. 2:

- The alerting and arrival of the fire brigade was accomplished in a very short period of time. A shorter period of time seems to be unrealistic if faced with a real incident.
- The time which elapsed until the road vehicles were granted access to the tunnel could further be reduced by additional training.
- For efficient rescue efforts, it ought to be determined which vehicles will in fact be needed inside the tunnel (limited availability of space).

4.3. Exercise No. 3 – traction unit of passenger train on fire

During this exercise, the train driver transmitted the following radio message “Practice alarm. This is the driver of the Exercise No. 3 train. There is smoke emerging from my engine. There is no way of bringing the train to a halt in front of the tunnel. I try to make it through the tunnel.” Then the train came to a standstill with a full service breaking. The train driver was assumed to be unconscious.

The passenger train carried classes with approximately 55 pupils. The pupils’ parents were asked whether their children would be allowed to take part in a disaster control exercise and the respective permissions were granted in writing.

To avert any possible harm, psycho sociologists were asked to accompany these adolescents, and no fire or smoke effects were brought into play.

In order to eliminate any potential danger, all trains were barred from entering the tunnel during the exercise.

The regional managements of the voluntary rescue organisations were informed of unannounced practice alarms. As this practice alarm was staged around mid morning on a week day, the rescue operations did not take part in this exercise. The train driver, the chief conductor and the staff members of the railway company were not informed in advance.

Table 4: Tunnel Data Exercise No. 3

Tunnel length	Approx. 5 km
Emergency exits	Rescue tunnel
Rescue concept Rescue organisations	Fire brigades at the portals and rescue train; Rescue train parked in the train operations centre at a distance of a few 100 m to the portal, the railway company maintains its own stand-by rescue team for the rescue train
Meeting point of emergency coordinators	In the area of the train operations centre; Premises with communication equipment as well as equipment for railway company's rescue team are available

The following list shall indicate critical points in time:

Time 0	Emergency call of train driver to traffic control centre, forwarding of message to train operations centre Train comes to a halt inside the tunnel
+ 2 min	Tunnel lighting activated by train operations centre Alerting of fire brigade
+ 2-5 min	Chief conductor tries to reach train driver via train telephone Chief conductor gets off the train and checks the traction unit
+ 6-12 min	Chief conductor advises passengers of practice alarm using loudspeaker system Chief conductor informs traffic control centre of situation on-board using radio system Passengers are requested to get off the train and walk towards the rear end of the tunnel (shorter distance according to escape-way signs)
+ 12-15 min	Passengers get off the train and follow the escape-way Chief conductor informs train control centre of self-rescue campaign Guidance of passengers through clear and confident instructions
+ 15-18 min	Chief conductor verifies whether all passenger have left the train (including toilets) Chief conductor informs traffic control centre
+ 18 min	Emergency coordinator of railway company arrives at emergency communications centre
+ 25 min	Rescue train is ready for departure
+ 36 min	Chief conductor uses emergency telephone at the portal to inform train operations centre that all passengers have been evacuated from the tunnel

Figure 4: Self-rescue inside tunnel / Rescue train

Important lessons learned from Exercise No. 3:

- The chief conductor responded in a fast, efficient and professional manner. When giving instructions to passengers trying to escape the tunnel, problems occurred when indicating the escape direction, but the assertive response met with a positive perception.
- After approx. 15 minutes all travellers had left the relevant train section and after approx. 30 minutes all travellers had walked the 300 m to the portal.
- The rescue train with the company's own fire brigade team was available at short notice.
- The train operations centre reacted without hesitation and completed the tasks listed in the alarm plans one by one. The communication with passengers inside the tunnel (emergency telephone), fire brigade and traffic control centre was found to be very time consuming.

5. COMPARISON OF SEQUENCE OF EVENTS

The three example exercises presented above are not quite suited to provide a representative overview of a possible time sequence in case of an incident or accident. But many of the exercises performed in Austrian railway tunnels reflect a similar picture.

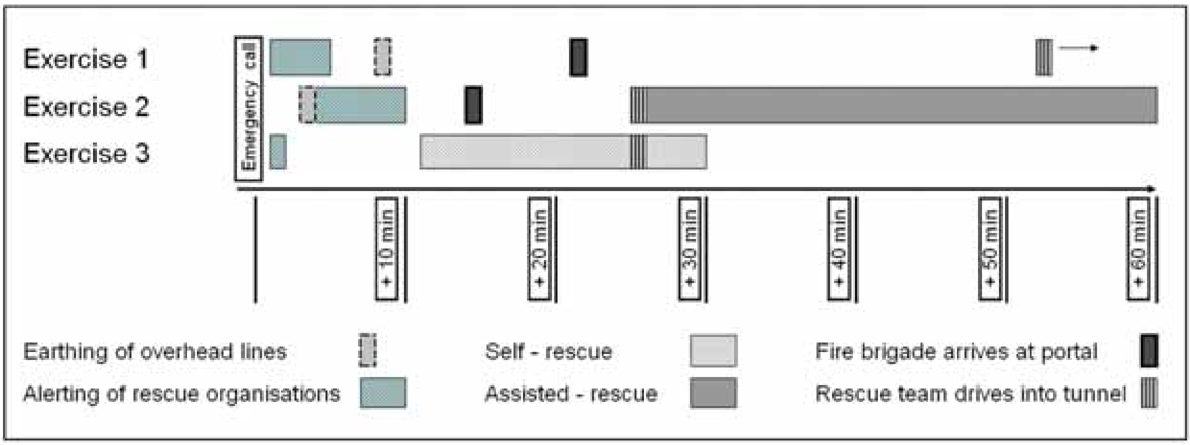

Figure 5: Time Sequence Exercise No. 1 – Exercise No. 3

From the time-sequence point of view, the following conclusions may be drawn based upon the elapsed time periods and the practical experiences made during the exercises, whereby "Time 0" represents the moment at which the train has come to a standstill and an emergency call is received at the train operations centre:

- Within 10 minutes an alert is issued to the rescue organisations, the trains leave the tunnel and the overhead line is earthed
- The instruction advising passengers to perform a self-rescue is given, once the situation inside the train has been clarified, the train staffs has communicated with the traffic control centre and the passengers have been informed on repeated occasions. This sequence may realistically be assumed to take 10 minutes (in case of an acute hazard exposure, a self-initiated rescue effort is likely to get underway).
- After 20 - 30 minutes the first vehicles of the rescue forces arrive either at the portal or at the rescue train.
- After 30 - 60 minutes a rescue train is ready to drive into the tunnel.

6. EXPERIENCES GAINED WITH THE NEW RESCUE CONCEPT "RAILWAY TUNNELS ACCESSIBLE TO ROAD VEHICLES OF RESCUE ORGANISATIONS"

In several new railway tunnels, a new rescue concept has been realised in the last few years, which requires a track which is accessible to road vehicles.
This concept necessitates the following provisions regarding both structure and equipment:

- Access to track area via portal area
- Technical access control in the form of barriers, gates, etc. (permission granted by train operations centre upon shutdown of railway operation and earthing of overhead line)
- Ballast less track system between portal area and portal accessible to road vehicles
- Tunnel accessible to road vehicles over its entire width:
  - Adaptation of noise control elements along slab track
  - Retrofitting of sideways (cable trough covers suited for traffic loads)
  - Surface between tracks accessible to road vehicles

Figure 6: Access area near portal / Accessibility of tunnel by road vehicles

This new system has the following advantages and disadvantages:

- Chances of reducing rescue times inside the tunnel, due to less interaction between railway company and fire brigade
- More flexible use of additional vehicles in case of an emergency
- Reduced dependence on especially trained drivers for rail/road vehicles or on qualified train drivers (respiratory equipment)
- Reduction in permanent costs for emergency stand-by services of railway company
- Use of familiar equipment and vehicles
- In case of smoke emission, additional hazards involved, due to vehicles not being track bound
- More time required for reversing or turning around of vehicles
- Fire brigades enter the tunnel in the absence of skilled railway personnel
- Higher investment costs due to adaptation of permanent way and installation of concrete cable troughs suited for traffic loads
- Safety system of railway company not suited for monitoring of road vehicles
- Hazard of facilities being damaged by road vehicles even in the event of emergency exercises

The experiences gained from the exercises in these tunnels and the feedback received from the relevant rescue organisations and the staff members of the railway company show that this new safety concept literally paves the way for a very fast rescue operation inside the tunnel. It offers the opportunity of additional rescue vehicles entering the tunnel, but it also holds the risk of all kinds of vehicles entering the tunnel - whether they are needed or not.

The turning around of two-axle vehicles in a twin-track tunnel did not take a lot of time. But it remains to be tested whether the rescue concept stands the test of time under reduced visibility conditions due to smoke emission.

7. CONCLUSIONS

Emergency exercises are inevitable to check the efficiency of rescue concepts, emergency concepts, and technical facilities.
Emergency exercises involving rescue organisations are an essential component of the safety concept when it comes to verifying operational and organisational sequences as well as communication lines on a regular basis under hands-on conditions.

7.1. Lessons learned with a view to design

- Emergency exercises reveal additional requirements made on both building structures and equipment components. In this context, special consideration is to be given to the experience gained with respect to user acceptance and error tolerance.
- Emergency exercises confirm the necessity of both the structural and the technical facilities.
- With railway tunnels the interaction of railway companies and rescue organisations is of special importance. This stands in contrast to other emergencies involving rescue organisations, where the emergency response can be planned more independently. These aspects and the knowledge of the parties involved in case of an emergency are already to be taken into account in the design stage.

7.2. Lessons learned with a view to operation

- An efficient communication between the staff members of the railway company and the rescue organisations is the essential precondition for a fast assisted-rescue campaign. Apart from functioning technical facilities, it is decisive that every emergency coordinator (railway company, rescue organisations) is prepared to act on his own initiative without waiting for his counterpart to contact him.
- The train personnel play a key role in detecting and identifying an emergency scenario, in informing the railway passengers, and in launching a self-rescue campaign. An adequate training and sensitization of the railway personnel regarding these issues is thus of great significance to enable the train crew to consult and support the passengers during their self-rescue effort.
- In the initial phase, the traffic operations centre turns into an emergency coordination centre for the railway company as well as into a centre meeting communication and railway operation needs. Staff members working under these conditions are already quite busy and in order to successfully perform their tasks, the safety concept will have to be simple and the main tasks need to be visible at a glance.

AUSTRIAN RISK ANALYSIS FOR ROAD TUNNELS

Development of a new Method for the Risk Assessment of Road Tunnels

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ABSTRACT

In Austria, in the past the assessment of road tunnel safety was based on experience and prescriptive RVS 9.261 guidelines. In the course of updating the Austrian design code for road tunnel ventilation, it was decided to develop a methodology for an integrated quantitative risk analysis. Initially, the main objective was to establish a risk-based decision tool for the specification of important safety requirements of road tunnels (e.g. ventilation system).
For the Austrian Risk Analysis for Road Tunnels TuRisMo a set of different methodical tools are used to analyse the whole system of safety relevant influencing factors; the method consists of two main elements:

- Quantitative frequency analysis: event tree approach for calculating the frequencies of defined accident scenarios
- Quantitative consequence analysis:
  - mechanical accidents: estimation of consequences based on tunnel accident data
  - fire accidents: modelling of consequences by combining a ventilation model with an evacuation simulation model

The risk model covers the personal risks of tunnel users. The result of the risk analysis is the expected value of the societal risk of the tunnel investigated. The respective shares of risk due to mechanical effects, fires and hazardous goods are shown.
Risk evaluation is done by relative comparison

- of risk reducing effects of different safety measures
- of the risk of the tunnel investigated to the risk of a reference tunnel

A tunnel of the same length, type and traffic characteristic, fully complying with the minimum safety requirements as per EU Directive is used as reference case.

Key words: tunnel safety, quantitative risk analysis, risk reducing effects, safety measures

1. BACKGROUND

In Austria, in the past the assessment of road tunnel safety was based on experience and prescriptive RVS 9.261 guidelines. In the course of updating the Austrian design code for road tunnel ventilation, it was decided to develop a methodology for an integrated quantitative risk analysis.
Based on the results of this risk analysis, a simplified method for standard tunnels (without specific characteristics) ought to be defined.
In April 2004, the EU Directive on road tunnel safety was issued. Article 13 of this Directive obliges every member state to develop a method for a risk analysis on a national level. Therefore, the requirements of the EU Directive were implemented in the design process.
The Austrian Risk Model focuses on frequently occurring mechanical accidents and fire accidents with small and medium sized fires. For a more thorough investigation of accidents involving hazardous goods, the DG-QRA model developed by OECD/PIARC shall be used.

2. TuRisMo –TUNNEL RISK MODEL FOR ROAD TUNNELS

2.1. Database of risk analysis

Due to the great number of tunnels in Austria and the extensive collection of data on accidents, the risk analysis is done based on Austrian data and experiences.
Data were collected from accidents with personal injury in tunnels on motorways and expressways for the years 1999 – 2003. In addition, data on accidents with property damage and breakdowns are available for some tunnels e.g. Tauern and Katschberg tunnels.
The following recorded tunnel properties and accident parameters are examined in more detail for the risk analysis:

- Traffic operation: bi-directional or uni-directional traffic
- Traffic volume and operating days
- Tunnel length
- Type of accident (recorded as stipulated in the Austrian code: single-vehicle accidents, accidents in uni-directional traffic, accidents in bi-directional traffic)
- Vehicle involvement
- Accident severity

As an example of the data implemented in the risk analysis, the distribution of accident types in uni-directional or bi-directional tunnels is shown in Table 1:

Table 1: Relative share of accident types in uni-directional and bi-directional road tunnels in Austria (own evaluation board upon [1])

	Bi-directional tunnel	Uni-directional tunnel
Accident type 0 Single car crash	17 %	40 %
Accident type 1 Front-end collision	50 %	59 %
Accident type 2 Head-on collision	33 %	1%

In addition to Austrian data, foreign data sources are used for comparison and completion.
The development of the risk analysis is coordinated with an expert group in Austria, with all members having extensive experience with regard to the risks in road tunnels on account of their activities.

2.2. Methodical approach

2.2.1. <u>General Consideration</u>

The methodical approach consists of two basic elements:

- a quantitative frequency analysis (event tree approach) and
- a quantitative consequence analysis (evaluation of statistical accident data for mechanical accidents and modelling of fire accidents)

The relevant influencing factors are included in the risk model according to their mode of action.
The risk analysis aims to investigate the risk to tunnel users (personal injuries and fatalities); as relevant reference value the societal risk (fatalities per year) of the tunnel is calculated.

The sequence of the risk analysis is shown in Figure 1:

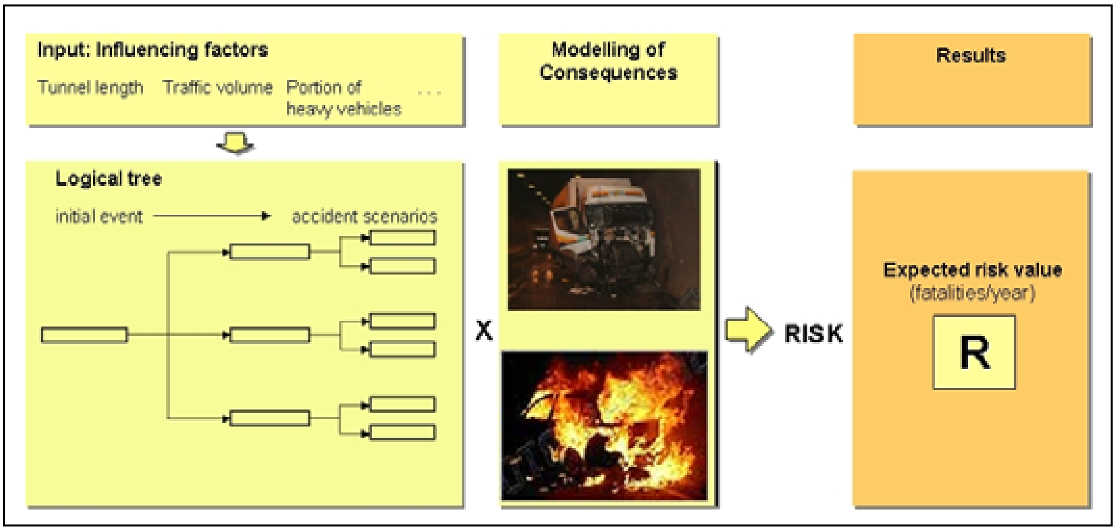

Figure 1: Sequence of risk analysis

2.2.2. Influencing factors

Prior to the development of the methodical approach an expert group identified and laid down the decisive influencing factors for road tunnel risks that should be implemented in the method.
The following main influencing factors and their interrelations were taken into account in the risk analysis:

- traffic volume
- uni-directional or bi-directional traffic
- additional points of conflicts such as ascending and descending ramps
- dangerous goods (amount and composition – general approach only)
- portion of heavy vehicles (> 3.5 tonnes)
- portion of busses
- tunnel length
- ventilation system
- length of escape route to emergency exits
- Operational components (fire detection, etc.)
- longitudinal gradient in tunnel
- longitudinal gradient in front of tunnel
- frequency of traffic jams
- cross section type

2.2.3. Event tree analysis

An event tree analysis is performed to calculate the frequency of defined accident scenarios. The event trees distinguish between accidents (with personal injury) and breakdowns. Starting from an initial event leading to a set of damage scenarios, possibly ensuing damage events are developed through the individual branches of the event tree. These damage scenarios differ significantly from each other as regards type of accident, vehicle involvement, involvement of dangerous goods and influence of fire. Taking into account the framework conditions of the tunnel infrastructure (e.g. distance between emergency exits), the extent of damage is estimated for the respective damage scenario.
The level of detail for an event tree is defined in such a way that the available data material can be used appropriately.

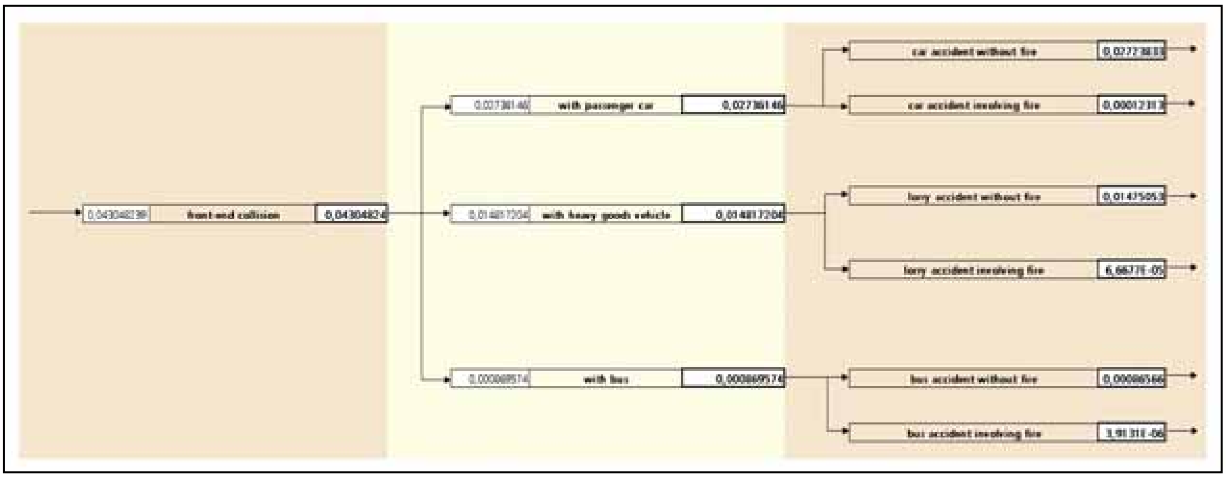

Figure 2: Part of event tree

The individual branches are quantified taking account of the experiences from accidents in Austrian road tunnels. Accident rates for relevant scenarios (vehicle breakdowns with fire, vehicle accidents with personal injury, vehicle accidents with fire) are calculated based on an evaluation of data from 81 Austrian motorway tunnels (60 with uni-directional, 21 with bi-directional traffic) covering the period 1999-2003. The accident rates are modified in dependence of tunnel length and traffic volume.

Table 2: Basic values of accident rates (own evaluation board upon [1])

	Bi-directional tunnel [fatalities/1mio.vehicle-km]	Uni-directional tunnel [fatalities/1mio.vehicle-km]
Accident rate in Austrian road tunnels (on motorways)	0,077	0,112

2.2.4. Consequence analysis

For each damage scenario in the event tree the corresponding extent of damage is estimated.

- Estimation of extent of damage of mechanical accidents

The damage scenarios differ in terms of type of accident and vehicle involvement
The consequences of each damage scenario are estimated based on an evaluation of accident consequence data of 447 tunnel accidents with personal injuries (same database as for frequency calculation).

- Estimation of extent of damage of accidents involving fire

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

They are valid for standard situations. However, the model also makes it possible to investigate non-standard ventilation systems and non-standard situations, but this requires more work.

The smoke release rates of fires are defined and smoke concentrations in dependence on time and location in the tunnel are calculated. The design of the model allows a detailed investigation of the performance of the ventilation system in combination with the corresponding evacuation procedures;

- Basic principle of ventilation model

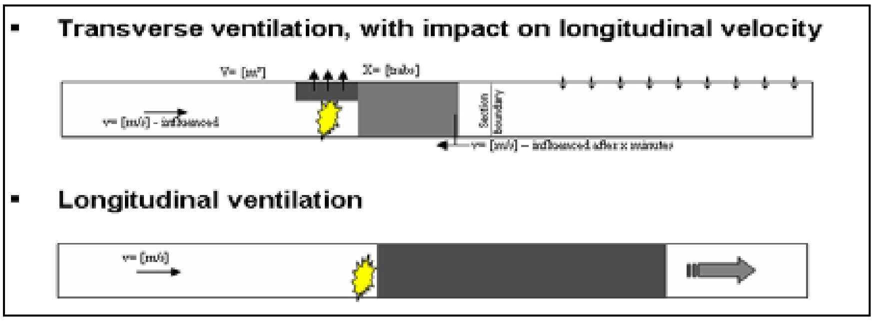

Figure 3: Ventilation systems

<u>Evacuation simulation model:</u>

For the evacuation simulation the software package “buildingExodus 4.0” is used, which takes into account the effects of smoke gases according to the FED model (FED – Fractional Effective Dose) of Purser [2]. The influence of temperature, HCN, CO, CO_2 and lack of O_2 is included. The calculation is done for individual persons with individual characteristics.
In the evacuation simulation model, the location of the accident in the tunnel, the location of the emergency exits, the constellation of the vehicles on both sides of the accident, the propagation of smoke, the reaction of the people and their evacuation in the tunnel towards an emergency exit (a tunnel portal) are taken into account. This approach makes it possible to investigate all influences, which may effect the lapse of time concerning the interaction of propagation of smoke and self rescue, such as

- fire alarm / start of ventilation
- reaction of people
- walking velocity with/without smoke
- walking distances
- congestion effects, etc.

Figures 3 -5 demonstrate the principle of modelling the extent of damage in case of fire, using the example of a bi-directional tunnel with a distance between emergency exits of 1000 m (above) and 250 m (below).

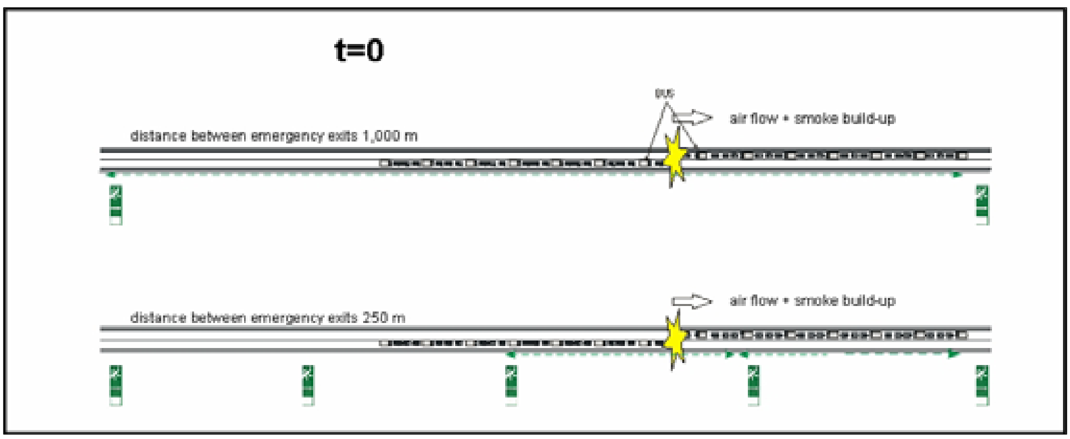

Figure 4: Scenario accident with fire incident – point in time t=0

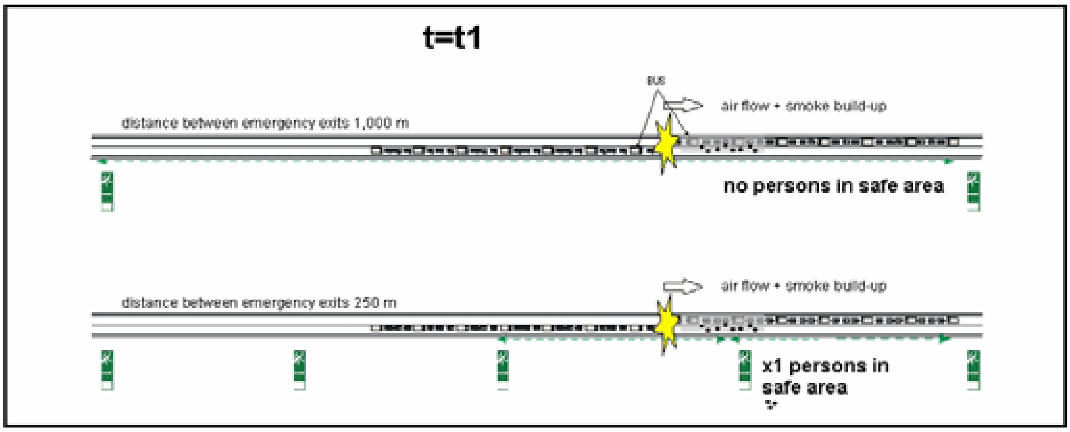

Figure 5: Scenario accident with fire incident – point in time $t=t_1$

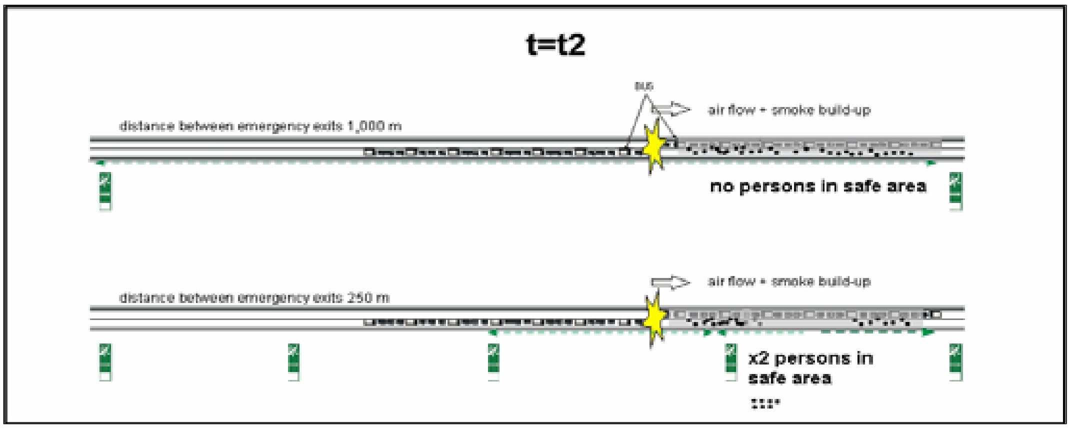

Figure 6: Scenario accident with fire incident – point in time $t=t_2$

The results of the evacuation simulation show, depending on the time elapsed, how many persons reach the “safe area” and how many persons are unable to get to safety due to the given framework conditions (length of escape route, start of evacuation, atmospheric conditions) – see figure 7:

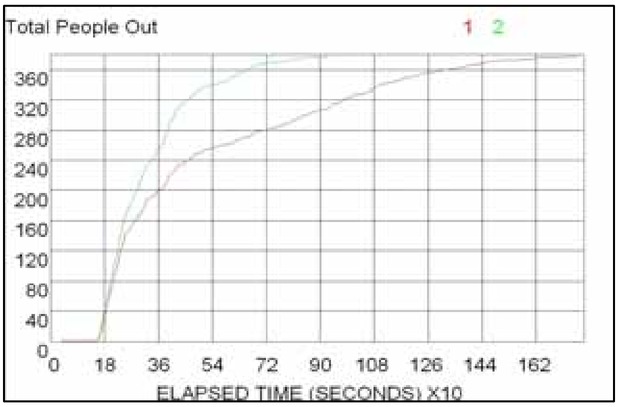

Figure 7: Diagram of the results of an evacuation simulation

Based on these results, various accident locations in the tunnel are investigated, and an expected value of the extent of damage for every damage scenario is calculated; this expected value is implemented in the event tree.
This element of the risk model can be used for the consequence assessment of defined fire scenarios (calculating a risk value) as well as for a detailed scenario investigation.

2.2.5. Risk calculation:

As reference value the expected value of societal risk (fatalities / tunnel and year) is calculated by combining incident frequencies and consequence values for defined scenarios in the event tree; a distinction is made between risks from car accidents with mechanical effects only, from fires and from accidents involving hazardous goods.

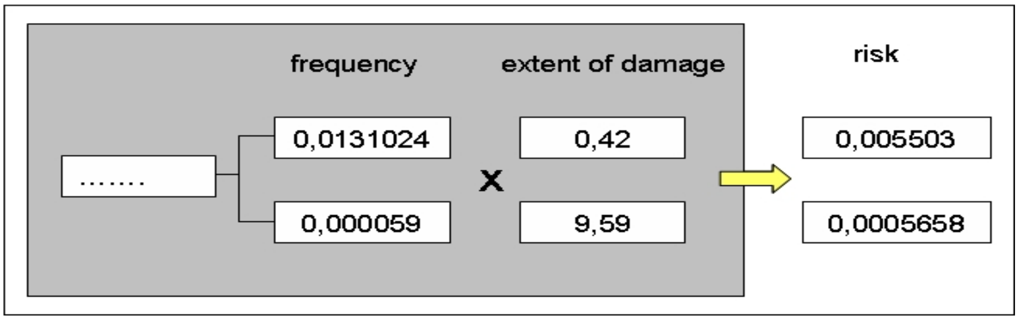

Figure 8: Combination of frequency and extent of damage

2.3. Results of risk analysis and strategy of risk evaluation

In Austria no quantitative risk criteria are defined. The EU Directive defines the minimum safety standard of a tunnel by laying down requirements for tunnel design and tunnel equipment in a prescriptive way. But the EU Directive allows limited derogations for these requirements, on the condition that the same safety level can be achieved by alternative risk reduction measures. For this reason risk evaluation is done by 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, fully complying with the minimum safety requirements as per EU Directive, is used as reference case. The divergences identified can be assessed in terms of risk. Alternative measures to offset the divergences can be evaluated; the risk reducing effects of the different safety measures can be investigated in a similar way. The safety assessment of safety measures can be completed by a cost-effectiveness analysis.

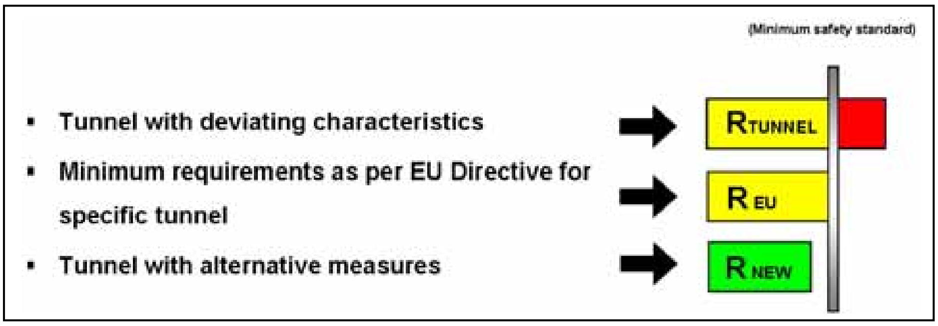

Figure 9: Risk evaluation in accordance with EU Directive (assessment through relative comparison)

3. EXPERIENCE IN PRACTICAL APPLICATION

3.1. Range and limitations of application:

In general the model is applicable to all tunnels with mechanical ventilation; for specific situations (e.g. unconventional ventilation systems) the model can be used, but must be adapted. The advantages of the model are

- the high flexibility of the individual methodical elements, so that it is applicable to almost every tunnel, ventilation or traffic configuration
- the possibility of changing the most relevant input data very easily; thus new information can be implemented quickly in many cases
- its capability to include the effects of almost every important safety relevant influencing factor in a quantitative way; one of its key elements is the modelling of the complex interaction of smoke propagation in the tunnel and the procedure of self rescue in the situation of a fire, which allows the investigation of all influences on the lapse of time within this process
- its simply, clearly understandable and easy comparable results.

The model can be used for a wide field of different applications, such as safety assessment of new or existing tunnels, support of the decision-making process for a selecting safety measures (new tunnels) or upgrading measures (existing tunnels), definition of priorities for upgrading measures, etc.

However, the results of the model (expected value) do not include information about the distribution of different accident consequence classes (such as F-N-curves); therefore the model is not suited to specifically investigate accidents with very low probabilities and very high consequences. Hence, the model is not suitable for a more thorough investigation of the effects of accidents involving hazardous goods.
The method has now been completed and has been successfully adapted to several tunnels of the Austrian highway network.

3.2. View on the simplified method for Austrian codes

In the past, the safety design of road tunnels in Austria was mainly based on experience and prescriptive guidelines such as RVS 9.26 (ventilation), 9.27 (lightning) and 9.28 (operational and safety equipment). The Austrian standards in general fulfil or exceed the minimal safety requirements of the EU Directive 2004/54/EC.
One of these design codes, the RVS 9.261 for tunnel ventilation systems, already contains a very simple risk-related safety evaluation of road tunnels: a "hazard potential" is calculated based on a number of important influence parameters, thus dividing the tunnel into 4 different "hazard classes". The hazard class defines the required safety standard of a tunnel in terms of tunnel design and tunnel equipment.
In the current process of updating RVS 9.261, this method has been reviewed and restructured based on the results of the investigation of a set of characteristic standard tunnels.

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TUNNEL KASTELEC - PLANING, REALISATION, TESTING, EXPERIENCES

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ABSTRACT

Slovenia is among the European states with a considerable number of road tunnels. Two relatively new tunnels are on the road from Ljubljana to the Adriatic seaside: Kastelec and Dekani. Both tunnels have a similar design and therefore the Kastelec tunnel only is introduced here. The length of the tunnel is 2180 m, with a constant gradient of 2.5% towards south and with variable traffic mix. Strong winds of up to 130 km/hr have been recorded in the area and this condition has been emphasized in the design. Plans for the tunnels were made several years ago by the government and they were ultimately built in 2002, opening for traffic in 2004. A longitudinal ventilation system was designed and built with 14 jet fans installed in each tube. In case of a tunnel fire, the non-incident tunnel will be used for rescue. To enhance the ventilation in the incident tunnel, the fans are blowing air in the same direction in the rescue tunnel, while smoke is exhausted from the tunnel with a vehicle fire. The fans in both tunnels are reversible and have the capability of switching from one direction to the other.

Keywords: ventilation design, fire safety,

1. INTRODUCTION

Analysis treats of traffic circumstance at normal traffic and at congestions in instance of one-way traffic in tunnels Kastelec and Dekani. Main accent in study is on simulation of fire in some zones of tunnels at one-way traffic at fire 100 MW. At this are calculated and simulated speed and temperatures of air, surface temperatures of walls, times, retreat from fire zone requires him and time, inclusion of fans requires him. Against this are of remembered also of demand in neighborhood tunnel tube, that he serves for rescuing in case of fire. Finally study is slacked also analysis of necessary fire safety measures, of necessary for ensuring of safety of traffic and of health and lives of participants in traffic.

In first part of analysis are calculated and simulated concentrations of harmful substances (carbon monoxide, nitrogen oxides and concentrations of solid particles) at foreseen traffic circumstances, where is remembered number driven 2000 h^{-1} and 15% share of trucks, namely at various speeds of ride. Results of calculations are showed in tables, and diagrams.

In other part of analysis is done simulation of fire in various zones of tunnel, power 100 MW. Basic calculations are straight so slacked in supplement. In the analysis is remembered above all power of fire 100 MW, because is likelihood 300 MW fire minimal. Results are handed in shape of tables, and for every fire zone especially. Likewise are more in detail treated circumstances of pressure and velocity in neighborhood of tube, which he serves as rescue tunnel in case of fire. Also wind speeds are considered at this.

2. SIMULATION IN TUBE KASTELEC

2.1. Kastelec 1 (left tube)

2.1.1 Situation

On Fig. 1 are showed main dimension and schedule of fans in tunnels Kastelec, including rescue crossing passages, between which is distance cca 400 m. Zone are showed likewise, in which is simulated fire. In left tube is this from first of left zone (KLZ1) to sixth of left zone (KLZ6), in right tube from KRZ1 to KRZ6. Mark means: K - Kastelec, L - left, D – right, Z - zone, and the number.

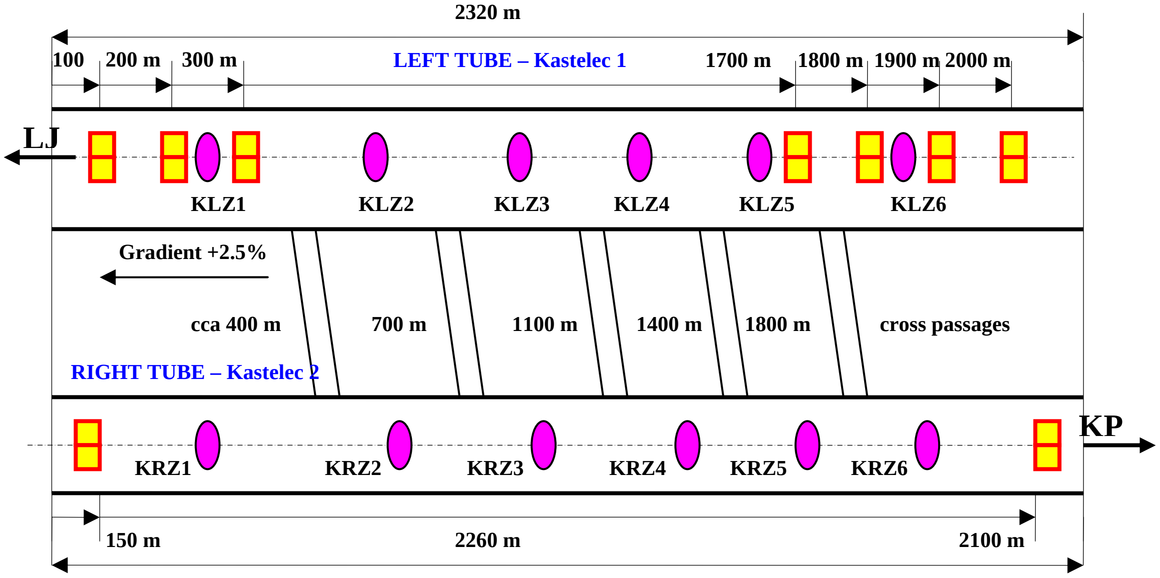

Fig.1: Fans, fire zones and rescue crossing passages

For prognosis of traffic for year 2015 is foreseen maximum density of traffic 2340 h^{-1}, take in account as value 2000 h^{-1} (15% of trucks).

2.1.2. Concentrations

Of windy circumstance at tunnels Kastelec are special. Round meteorological data are 60% days with wind, which speed is smaller from 10 m/s (36 km/h), 85% days with speed smaller from 12 m/s (44 km/h), and 8% days with wind speed over 30 m/s (110 km/h). This wind is very changeable and pushing (Fig. 2). Of speed of air in (m/s), and of concentration of carbon monoxide CO (mg/m^3) and nitrogen oxides NOx (µg/m^3) are simulated for various speed of ride, without of wind, for wind, speed 30 m/s, at included, and at excluded fans.

Fans are estimated because of comparatively large inclination (gradient), above 2.5 % because of fire safety.

We can see, that at driving velocity under 5 km/h the fans are not enough, it is necessary to switch of the engines of vehicles.

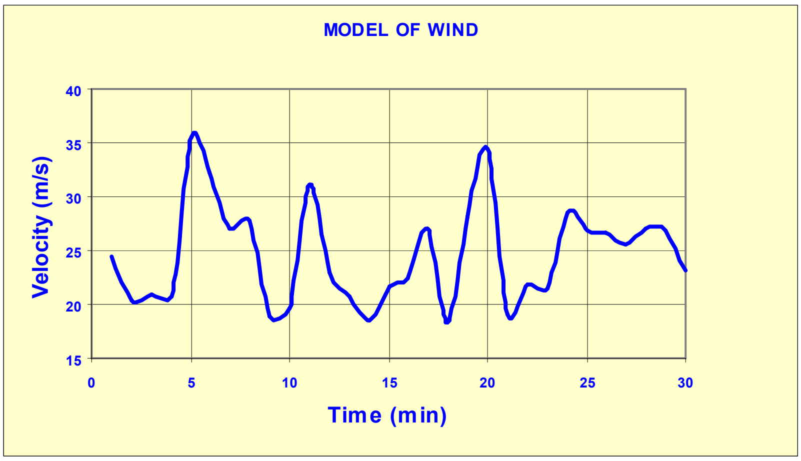

Fig 2: Model of wind (tested!)

Table 1: Concentrations in Kastelec 1

Kastelec 1	No wind			Wind (average maximum)		
v (km/h)	u (m/s)	CO mg/m^3	NOx µg/m^3	u (m/s)	CO mg/m^3	NOx µg/m^3
0 (no fans)	**-0.038**	**2552**	**68990**	**-0.233**	**409.7**	**11119**
0 (fans)	**0.272**	**352.7**	**9578**	**0.141**	**680.9**	**18446**
5 (no wind)	**0.50**	**182.2**	**5789**	**-3.55**	**25.3**	**847.7**
5 (fans)	5.875	15.9	529.2	3.252	27.76	925.4
15 (no fans)	1.90	40.16	1772	4.012	20.5	885.2
15 (fans)	8.525	8.94	433.8	4.285	17.87	816.6
30 (no fans)	3.41	16.44	1206	4.631	14.23	835.6
30 (fans)	9.464	5.893	465.1	4.823	11.61	867.1
60 (fans)	10.02	3.283	777.7	6.35	5.195	1202
80 (no fans)	6.80	4.27	1207	0.997	29.79	8124
80 (fans)	10.65	2.743	794.2	7.32	4.009	1138
100(no fans)	11.30	2.631	788.3	3.04	9.72	2813
100 (fans)	11.32	2.581	784.1	8.22	3.567	1065

3. AIR VELOCITIES

3.1. Velocities in Kastelec 1

We simulated 4 cases see Fig. 3):

Fans no (off) – wind no (off) **Fn Wn**
Fans no (off) – wind no (off) **Fn Wn**
Fans yes (on) – wind yes (on) **Fy Wy**
Fans no (off) – wind yes (off) **Fn Wy**

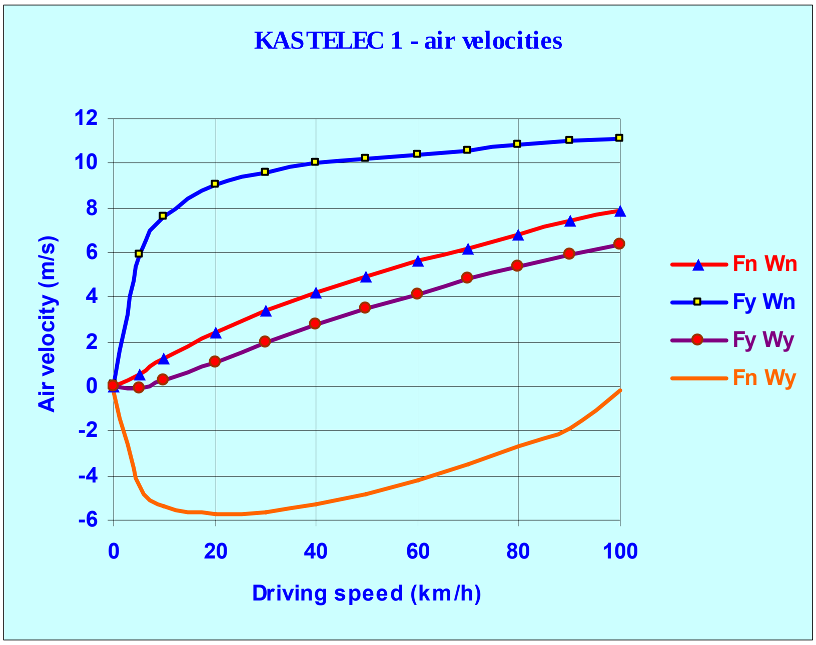

Fig.3: Air velocities in Kastelec 1 (100% traffic)

The air velocity in tunnel is also a function of density of traffic (Fig. 4).

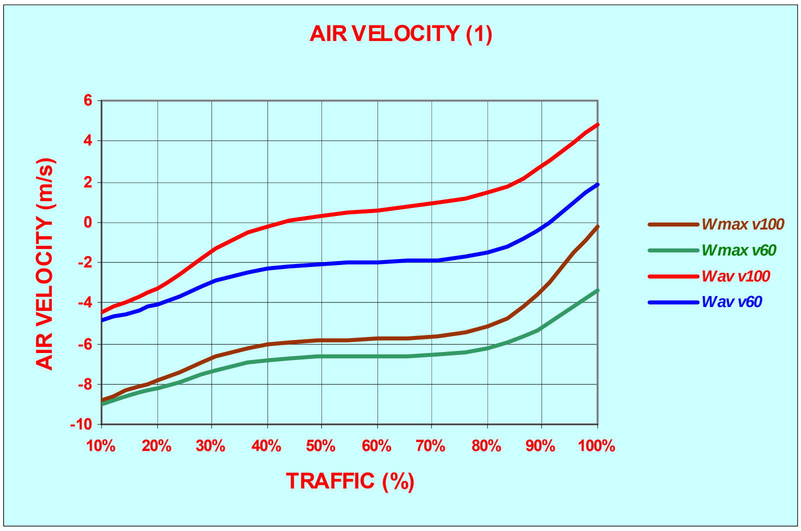

Fig.4: Air velocities in Kastelec 1 (various traffic)

4. FIRE SIMULATION

4.1. Fire in Kastelec 1 – KLZ 5

4.1.1. Generally

In tunnel Kastelec 1 we made simulation of fire 100 MW in 6 examples. Calculation of speed of air is simulated at excluded and at included fans (including time: cca 10 minutes). As example is here showed case of fire in KLZ 5.

4.1.2. Air velocities

Table 2: Air velocities in case of fire (no wind)

	0 (m)	300 (m)	600 (m)	900 (m)	1200 (m)	1500 (m)	1800 (m)	2100 (m)
Off (m/s)	1.30	1.40	1.38	1.40	1.95	3.30	1.20	1.20
On (m/s)	2.30	2.30	2.10	2.00	2.40	4.80	4.60	4.10

At excluded fans is the air speed speed enough low that is not too large cooling off smoke, at included fans are high enough, to cleaning tunnel from smoke.

4.1.3. Air temperatures

Table 3: Air temperatures in case of fire (no wind)

	0 (m)	300 (m)	600 (m)	900 (m)	1200 (m)	1500 (m)	1800 (m)	2100 (m)
Off (m/s)	1.30	1.40	1.38	1.40	1.95	3.30	1.20	1.20
On (m/s)	2.30	2.30	2.10	2.00	2.40	4.80	4.60	4.10

Because of excluded fans are against flash over of fire the temperatures of air several high, however it is important, that speed of air stay low enough. That is why temperatures also several located are. When for cca 12 minutes start up fans, temperature of air is going quickly to lower, however they are alongside tunnel, for difference from before several more highly.

4.2. Rescue tube (Kastelec 2)

4.2.1. Generally

At double tunnels we have in case of fire tube with fire and rescue tube, through which move away participants of incident from tube, where fire is. We must prevent entry of smoke to rescue tube and in her to ensure current of fresh air, which means, that must in rescue tube to ensure overpressure. On this way we prevent also entry of smoke to rescue tube.

This can achieve on two ways:

- classical procedure
- new perfected procedure

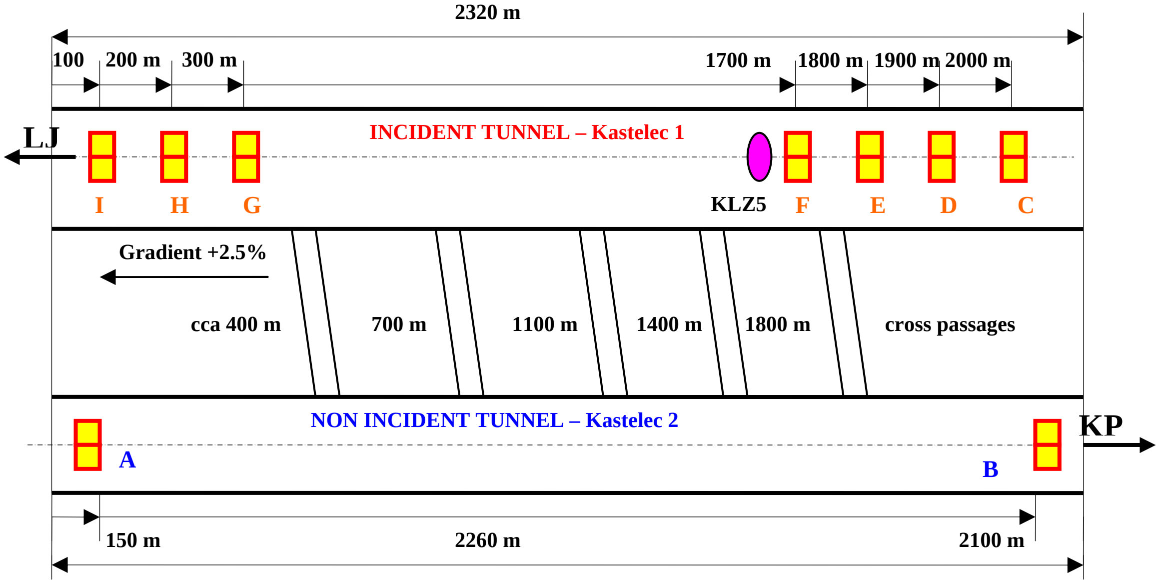

Fig. 5: Fans in case of fire (example for KLZ 5)

<u>Classical procedure</u>

At the beginning of fire, in incident tunnel the air velocity should be 1 ÷ 2 m/s. The fans must be switched of for cca 10 minutes. In non incident tunnel we switch on the couple of fans **A** and **B**. So is in the middle of this tunnel an over pressure:

39 Pa

After 10 ÷ 12 minutes we switch on the fans **C**, **D**, **E**, **F**, **G**, **H** and **I**, in incident tunnel is an under pressure. But it is a danger to come smoke in the non incident tunnel. It depends on form and some other properties of portals, meteorological circumstances,

New improved procedure

At the beginning of fire we switch on the fans **B** in the opposite direction. In non incident tunnel is an over pressure. After 10 minutes we switch on the fans **G**, **H** and **I** in the same direction, as fans **B**. So is an over pressure in non incident tunnel, and an under pressure in incident tunnel. Direction of air movement in both tubes is the same; the smoke can not come in the non incident tunnel.

5. TESTING

5.1. Fire testing

5.1.1. Generally

Goal of found out of test was to find out temperatures and velocities in intersection of tunnel against over flash of fire. This was simulated with prescribed quantity two different fuels. Besides evaluating of process was goal measurement also indirect compare of built-in felt and of warning systems.

Simulation of fire was found out in left tube of tunnel Kastelec on location first niche, where is made also crossing passage for connection between both tubes.

Pools for fuel were placed some meters for niche in middle of tunnel. Two pools were used (round and in shape letter X). In middle over both wares was located construction with four plates namely in plain of intersection of tunnel, as shows Fig. 6.

Fig. 6: Plates with temperature sensors (T1 – T5)

5.1.2. Temperatures

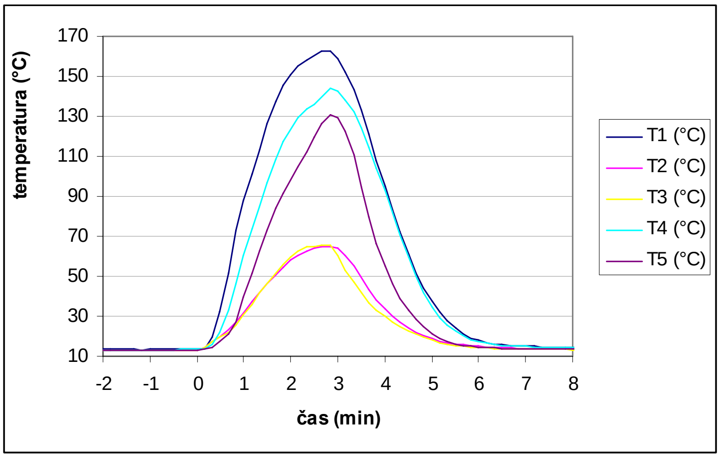

Fig. 7: Temperatures in Kastelec 1

By calculation: T1 = 176 °C

5.1.3. Temperatures measured by IR camera

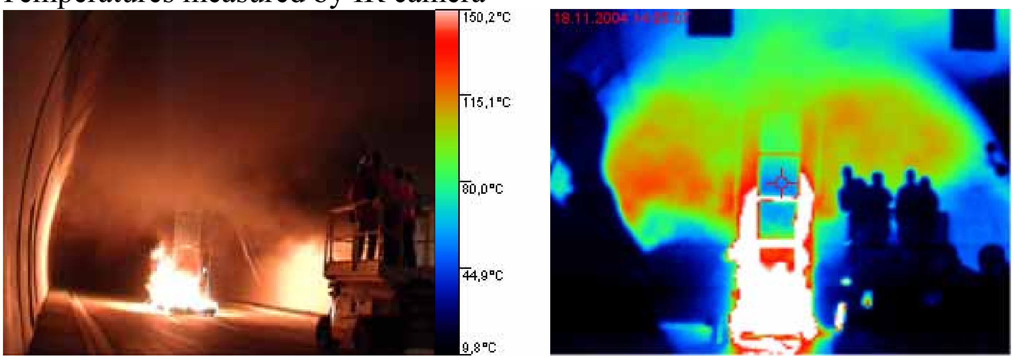

Fig. 8: Thermo grams in Kastelec 1 (example)

5.1.4. Conclusion

Found temperatures and of speed of movement of air can serve for comparison with measured values of built-in felt and theoretical simulation models. For estimating most highly temperature of air in tunnel in case of fire at further tests necessary to accompany also longitudinal temperature gradient. It turns out, that is deviation of flame in connection with air moving. That is why are of temperature in vertical plain over flame more lowly, highest measured temperature is consequence of counter flow of flue gases underneath rim of tunnel.

We estimate against this, that speed of air in intersection of tunnel longitudinal isn't changing essentially. Between fire also didn't find of important changing of speed of air. Essentially are growing up only round start of fans.

6. CONCLUSION

Density of traffic is very changeable so in winter time, in the middle of week, traffic is very rare, in touristy season; guest is at weekends especially exceptionally, even congestions are occurring.

Inclination (ascent and fall) is for high way tunnels relatively large, because amounts ±2.5%, which means, that is between portals cca 60 m of high-altitude difference. Consequence of this is prominent buoyancy.

Both tunnel Kastelec are emphasized very strong north wind (bora), which considerably influences on hydraulic circumstance in tunnel, by ventilation, but also in case of fire and against occurring of fog.

Because of vicinity of port Koper be probably guest traffic of cisterns with gasoline against interior of Slovenia, which in considerable measures influences on fire endangerment of tunnel.

There is danger of occurring of fog in tunnels because of changeable windy and temperature circumstances.
At ventilation distinguish four different instances:
1. Ventilation in normal conditions
2. Ventilation against strong wind
3. Ventilation in case of fire
4. Ventilation to prevent a fog in tunnel

At normal conditions in all tunnels show results of simulation, that in case of congestion fans is not enough. This means, that it must put out car engines in this instance, or to stop traffic. At speed of ride 5 km/h and more fans not even are not necessary. In case of strong wind and at excluded fans at low speeds of ride appears negative speed of air, which is not wrong, because tunnel cleans in inverse direction, and it is concentrations of harmful substances in speed limits.

The drivers must put out engines at congestion of traffic in tunnel, because otherwise tunnel can't be clean. At speeds of driving over 5 km/h tunnel is ventilated alone, either because of piston effect, either because of buoyancy as consequence comparatively ascent (or of fall), either because of wind, or because of activity of fans. In case of strong wind and at excluded fans in some instances appears negative speed of air flow, that he helps with lowering of concentrations of harmful substances straight so, although to opposite direction. Because are all this phenomena between self interwoven, and it is heavy to foresee every situation separately, we must use the automatics. Sensors must find level of concentration of harmful substances, also direction and strength of air flow in tunnel. When level of concentration of harmful substances achieves admissible value, must with fully power include all fans, direction of rotation or direction of air flow must to be harmonious with direction of natural movement of air, irrespective of direction of traffic.

We must stop fans in case of fire at once. In instance, when is not a strong wind, this is enough. If the wind is blowing, must with all power to start up fans against direction of movement of air. In case of strong wind is also in this instance speed of air a bit too high, however acceptable. Round expiry cca 12 minutes must to start up fans with all power, namely in direction of movement of air at stopped fans. With this achieve greater speed of air and greater efficiency at cleaning of tunnel or at extracting smoke from tunnel.

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TUNNEL SAFETY OPERATIONAL PLAN

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INTRODUCTION

Following the catastrophic accidents that occurred in the Mont Blanc and Tauern tunnels, the leading European countries embarked on a series of legislative measures focusing on the problem of safety inside tunnels. Italy was one of the first European states to acknowledge tunnels as a high-risk location for road traffic, and in September 1999 ANAS published Circular No. 7735/99 which looked at the issue of safety inside tunnels from a technical viewpoint. Similarly, in December 1999, the Ministry of Public Works issued Circular 7938 entitled "Road safety inside tunnels with special reference to vehicles transporting hazardous materials". Said circular also ordered tunnel owners or concessionaires to assess and classify the tunnels they were responsible for. In June 2001, the Ministry of Public Works issued a Ministerial Decree regarding "Safety inside road tunnels" which restated the information already contained in Circular No. 7938 and ordered tunnel owners or concessionaires to take the measures needed to modernise tunnel lighting systems in order to comply with the contents of CIE 88-1990. On April 29 2004, the European Parliament adopted Directive 2004/54/EC "Minimum safety requirements for tunnels in the trans-European road network" which all member states must comply with in relation to road tunnel safety. Said directive also hopes that the requirements will gradually be extended to roads not included in the trans-European network. Said document standardises the concept of a safe road tunnel thus putting an end to the individual actions of European countries.

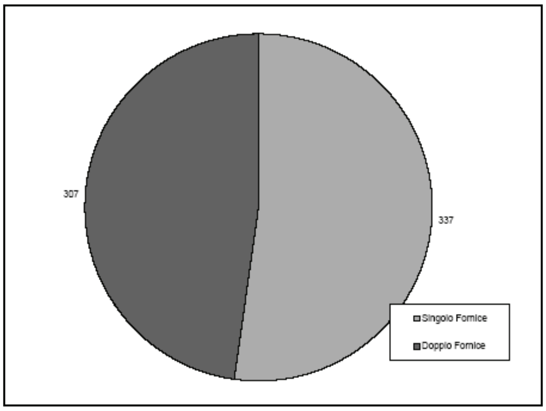
ANAS' Planning Department produced a working instrument – guidelines – which brings together ANAS Circular No. 7735/99, new legislation regarding the geometrical and functional characteristics of roads (Ministerial Decree of November 5 2001) and new planning guidelines regarding road tunnel safety. Said document fully incorporates the European directive's technical contents and sets itself the aim of standardising ANAS planning in relation to road tunnel safety. The key points are:

- Definition of a risk analysis methodology
- Types of action regarding road tunnel safety
- Minimum requirements for road tunnels
- Design criteria for types of action
- Performance characteristics of materials used.

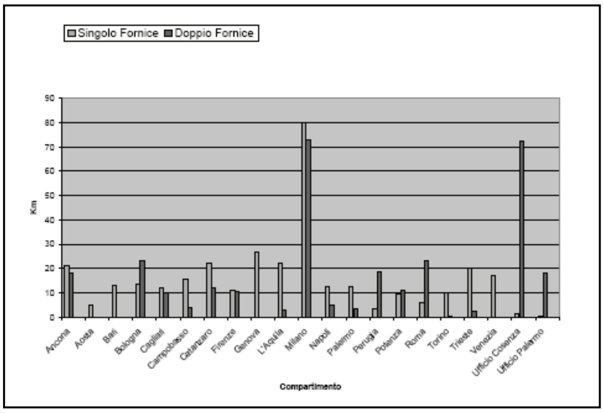
The inclusion of a risk analysis methodology is indicative of the wish to define an instrument which characterises the road tunnel, highlighting risk factors, and which can possibly offer equivalent safety levels or conditions. Specifically, there may be special cases in existing tunnels which cannot be handled using a systematic approach; therefore in these cases *ad hoc* solutions can be obtained, backed up by a specific risk analysis.
The guidelines have received two technical opinions from the Higher Public Works Board and are currently being reviewed in order to take said opinions into consideration.
ANAS also issued Circular No. 33/2005 defining standard sections for the design of new road tunnels, with a view to optimising design and planning.

ANAS NETWORK ROAD TUNNELS

At the present moment in time, considering the new tunnels being built, ANAS is responsible for road tunnels measuring a total 644 kilometres in length.

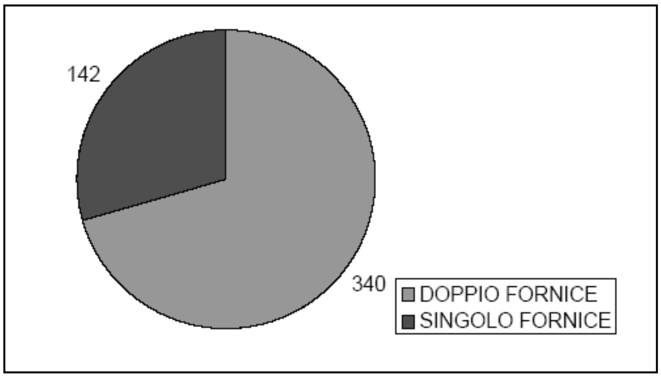


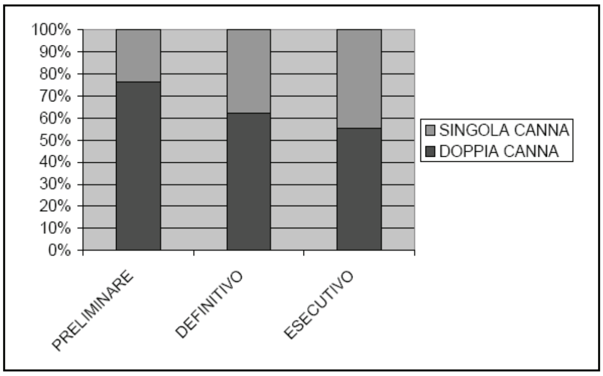
ANAS tunnels: by type of arch



ANAS tunnels: by area

Figures regarding the design of new tunnels in the 2002-2004 periods are of key importance. What stands out most clearly in reference to safety is the major difference between the total kilometres of single and double arch tunnels.





2002-2004 Total length (km) of planned tunnels

2002-2004 Total length (%) of planned tunnels

There are mainly two reasons for the greater number of double arch tunnels currently in the design phase: the application of new geometrical and functional characteristics and the aim of increasing safety in tunnels given that double arch tunnels are intrinsically safer, as can be seen from recent statistical studies.

ANAS ROAD TUNNEL WORKS

The margin of action in newly-built tunnels is wider given that the tunnel system's geometry and architecture have a considerable effect on safety. Double arches, reduction of bends, greater radii of curvature, minimum gradients and entrance positioning are some of the solutions which help increase the level of safety. Furthermore, escape and emergency routes are more easily provided for, while the term "safety regulation" is used for tunnels that have already been built. The focus is placed in particular on all the systems used such as lighting, ventilation, illuminated road signs, SOS system, etc., alongside typical road management measures such as speed reduction, distance between vehicles, regulation of transit of vehicles transporting hazardous goods, etc. Nevertheless infrastructural action which is generally extremely difficult to carry out and expensive is not ruled out.

"Safety regulation"-related activities in existing tunnels mainly concern system engineering, and specifically ventilation, lighting, illuminated road signs, traffic lights, SOS systems, fire prevention (detection and fire fighting), traffic control, CCTV, remote control and command, radio communications systems and surveillance and action stations.
In addition to the aforementioned system-related activities, structural activities are also to be considered for new tunnels (escape routes, smoke extraction wells, entrance-related works, underground plants, etc.) which may prove to be costly and extremely difficult to carry out, but which considerably increase the tunnel's safety level.

TUNNEL SAFETY OPERATIONAL PLAN

ANAS' General Manager set up a commission to represent the main departments concerned with the aim of drafting an operational plan for tunnel safety.
The commission's Chairman is Carlo Bartoli.
The first measure taken by the commission was to examine and authorise (with some additions) the guidelines for safety design in road tunnels measuring more than 500 metres in length, complete with graphs and illustrations.
The procedure regarding the official issue of said guidelines is currently underway; thus there will be a specific reference document for the design of new tunnels measuring more than 500 metres in length.
Said guidelines will also be valid for tunnels in operation measuring more than 500 metres in length. However, complete modernisation of existing tunnels will not be possible due to structural and financial reasons. Therefore the main points of said guidelines provide for the carrying out of a specific risk analysis, on the strength of which a decision can be made regarding the safety features to be installed in each individual tunnel, and a scale of priorities for action to be taken to keep the risk under the set levels.
To this end, experimental risk analysis is being carried out in relation to nine tunnels included in the national road network (seven single arch tunnels and two double arch tunnels).
Subsequently, risk analysis can be carried out in relation to all tunnels measuring more than 500 metres in length. The operational plan for updating safety features in tunnels in operation can only be drafted following said analysis.
At the present moment, the road and motorway network managed directly by ANAS comprises 225 tunnels measuring more than 500 metres in length for a total 302.50 km; 106 of these are double arch tunnels covering a total 122.36 km while 149 are single arch tunnels covering a total 180.14 km.
ANAS tunnels belonging to the TEN cover a total of approximately 185 km while tunnels measuring more than 500 metres in length cover a total of approximately 120 km.

1ST EXTRACT OF OPERATIONAL PLAN TO MODERNISE SAFETY FEATURES IN TUNNELS IN OPERATION

While awaiting data in order to be able to draft the operational plan to modernise safety features in tunnels in operation, the commission nonetheless considered it advisable to draft a first extract of the operational plan, making it possible to carry out modernisation of safety features in a sample selection of tunnels.
The commission felt that the carrying out of a risk analysis for double arch tunnels measuring more than 2000 metres in length was of less importance than the priority concern of measures and choices to be adopted.
Indeed, a higher incidence of risk is to be expected given that they are long tunnels subject to intensive traffic (the double arch offers objective proof of this); on the other hand the factor

linked to escape routes and ventilation is easier to deal with and relatively undemanding from a financial viewpoint.
Therefore, the commission reached the conclusion that it was advisable to fully adopt the suggestions put forward in the aforementioned guidelines for this type of tunnel (long, double arch).
18 tunnels with the aforementioned characteristics were singled out in the national road and motorway network managed directly by ANAS.
The number of tunnels subsequently increased to 27 during inspections carried out by the commission in order to obtain visual knowledge of the situation since shorter tunnels forming part of the same route and located near the main tunnels was included.
This criterion pre-empts and emphasises a general criterion that the commission set as the base for its actions: to give tunnels uniform structural features and systems that are easy to understand for users and which offer a higher level of standardisation for management staff, thus granting a higher level of safety.
The 27 tunnels included in the plan, listed in the enclosed graphs and table below, form part of the following four major routes:

- S.S. 36 “Lake Como and Spluga” (Lombardy)
- E 45 Orte – Cesena (Umbria, Emilia Romagna)
- S.S. 4 “Salaria” (Lazio)
- Sicilian motorway network directly managed by ANAS

No.	ROAD	NAME	LENGTH	YEAR	AREA
1	SS4	Colle Giardino	4440	2004	ROME
2	SS36	Monte Barro	3253	1999	MILAN
3	SS36	Attrav. Lecco	2413	1999	MILAN
4	SS36	San Martino	2035	1999	MILAN
5	SS36	Regoledo	3238	1987	MILAN
6	SS36	Scoglio	2715	1987	MILAN
7	SS36	Dervio	2774	1987	MILAN
8	SS36	Dorio	2108	1987	MILAN
9	SS36	Monte Piazzo	2556	1987-88	MILAN
10	SS3bis	Lago di Quarto	2508	1996	BOLOGNA
11	SS3bis	Roccaccia	1840	1984	BOLOGNA
12	SS36	Fiumelatte	1317	1987	MILAN
13	SS36	Lezzeno	1253	1987	MILAN
14	SS36	Corenno Plinio	757	1987	MILAN
15	A19	Tre Monzelli	1860	1974	SPEC. DEPT. PALERMO
16	A19	Fortolese	1624	1974-75	SPEC. DEPT. PALERMO
17	A19	San Nicola	1440	1974-75	SPEC. DEPT. PALERMO
18	A29 dir	Segesta	1620	1975	SPEC. DEPT. PALERMO
19	SS36	Borbino	1207	1980-87	MILAN
20	SS36	Luzzeno	1158	1980-87	MILAN
21	SS36	Somana	1932	1980-87	MILAN
22	SS36	Corte	1145	1988	MILAN
23	SS3bis	Monte Coronaro	910	1972	BOLOGNA
24	SS4	San Antonio	670	1988	ROME
25	SS3bis	Colle Valenza	699	1964-72	PERUGIA
26	SS3bis	Colle Capretto	1191	1972	PERUGIA
27	SS675	San Pellegrino	1076	1971	PERUGIA
Total length (m)			**49,739**		

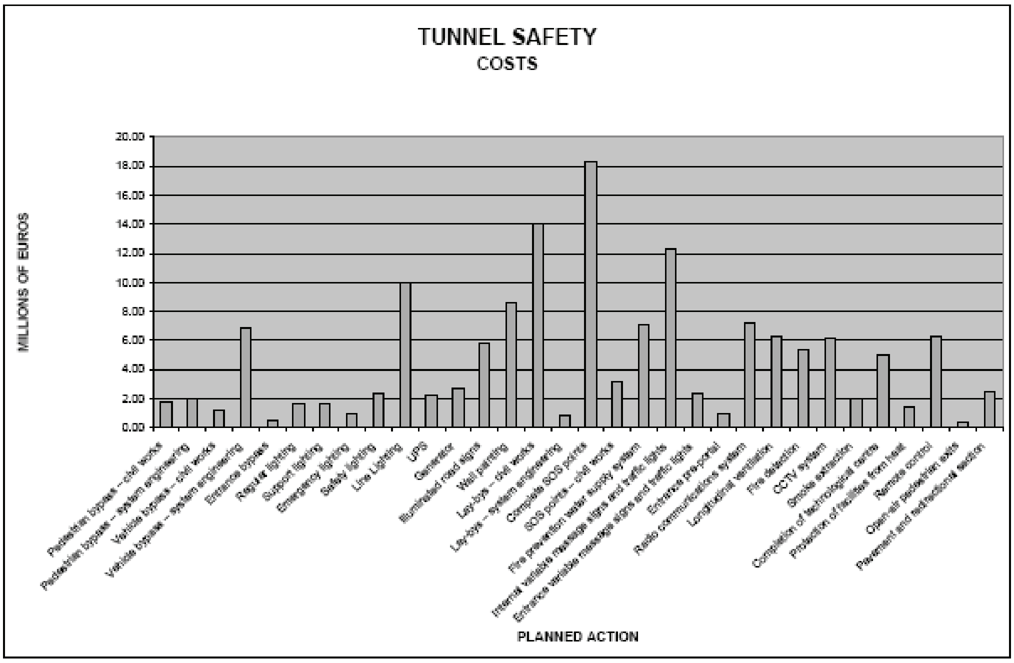
MEASURES TO BE TAKEN

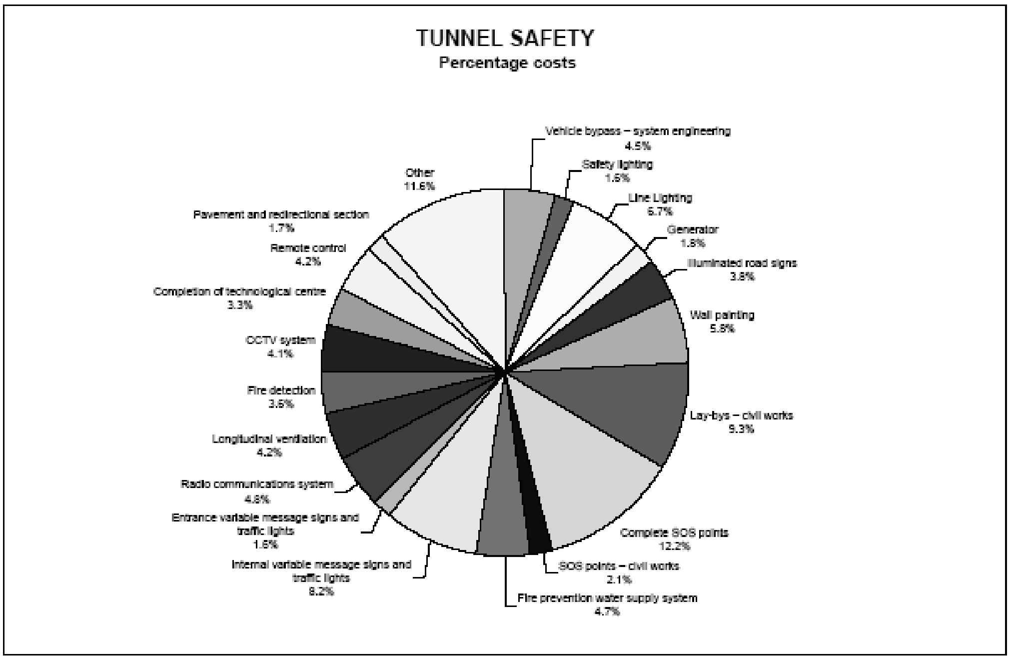
The commission drew up a preliminary list of safety measures contained in the guidelines for safety design in tunnels that are applicable for double arch tunnels of the length in question.
As mentioned above, the commission considered it advisable to adopt all the measures provided for in the guidelines for this type of tunnel.
The necessary technical specifications (at a feasibility level), unit of measure and unitary cost were formulated for each of these measures.
This resulted in the following list:

No.	MEASURES	UNIT OF MEASURE	UNIT OF COST in €	
1	Pedestrian bypass (every 300 metres) – civil works	no.	**A1**	
2	Pedestrian bypass (every 300 metres) – complete lighting and ventilation system engineering	no.	**A2**	
3	Vehicle bypass (every 900 metres) - complete civil works of pedestrian division	no.	**B1**	
4	Vehicle bypass (every 900 metres) - complete lighting and ventilation system engineering	no.	**B2**	
5	Complete entrance bypass	no.	**C**	
6	Regular lighting	lm	**D**	
7	Support lighting	no. entrances	**E**	
8	Regular emergency lighting	lm	**F**	
9	Safety lighting – individual points	no. points	**G**	
10	Safety lighting	lm	**H**	
11	Standby supply – uninterruptible batteries	each	**I1**	
12	Standby supply - generator	each	**I2**	
13	Illuminated instruction and emergency road signs	lm	**L**	
14	Painting of walls	lm	**M**	
15	Lay-bys – civil works	each	**N1**	
16	Lay-bys – complete painting and lighting system engineering	each	**N2**	
17	SOS points (complete)	each	**O**	
18	Creation of points with existing lockers	each	**O1**	
19	Complete water supply system	lm	**P**	
20	Variable message signs and traffic lights (every 300 metres)	each	**Q**	
21	Entrance traffic lights and panels	each	**R**	
22	Pre-portal or anti-recirculation smoke flue (entrances)	each	**S**	
23	Radio communications systems (split cable)	lm	**T**	
24	Complete longitudinal ventilation	lm	**U**	
25	Fire detection (cable)	lm	**V**	
26	Complete CCTV system	lm	**Z**	
27	Smoke extraction	flat rate	**W**	
28	Control centre	flat rate	**X**	
29	Completion of underground technological centre	flat rate	**X1**	
30	Protection of facilities from heat	lm	**Y**	
31	Remote control	lm	**K**	
32	Pedestrian exits from lay-bys with smoke extraction ventilation	no.	**W1**	
33	Raised pavement, redirectional section, parapet with continuous duct and drain	lm	**J**	

Therefore the commission examined the monitoring reports of the tunnels taken into consideration, noting however that data provided by the relative Areas was not sufficient for correct classification.

Hence it was decided to take action in two areas.
On the one hand, action was taken to organise and coordinate a new survey to be completed while carrying out the risk analysis; on the other it was decided to carry out direct inspections of the selected tunnels so that the commission could note the measures needed for each individual tunnel.
Therefore it was possible to obtain new, more flexible classification of the measures to be taken in relation to the specific characteristics of the tunnels which greatly differ one from another due to the fact that they were built in different periods.
Said less rigid approach made it possible to obtain an overall result that was more in line with the real situation, such as to facilitate future planning of action to be taken in each individual tunnel.





PLAN DOCUMENTS

The final study comprises the following:

- 33 files marked by a letter detailing the individual measures with unitary costs and outline of technical specifications;
- 27 files, one for each tunnel detailing the measures to be adopted, quantity and costs with final estimate;
- 1 file summarising all the tunnels and listing the overall costs of modernisation;
- 1 file summarising costs, tunnel by tunnel;
- 1 file summarising the costs for each individual measure;
- 1 file summarising the measures adopted or not adopted in all the tunnels;
- a series of graphs illustrating the measures adopted from a statistical viewpoint.

COMMISSION'S REMARKS

The commission observed that the cost of modernising tunnels is largely in proportion to their length, and obviously also depends on the date of construction and state of maintenance.
The Roccaccia tunnel located on the E 45 is most in need of modernisation.
The most expensive works proved to be structural works (construction of lay-bys – bypasses – escape routes) but these are not so frequently needed, at least not in the tunnels in question.
At the present moment in time, the systems that are most lacking are SOS emergency points and extinguishers, variable message signs and safety lighting (absent in 100% of the tunnels in question).
Some graphs summarising the incidence of individual works are included below.
Lighting is the area which, at the present moment in time, mostly closely complies with the guidelines.

CONCLUSIONS

Drafting of this plan extract has highlighted the importance of carrying out risk analyses of all the tunnels, especially single arch tunnels, as soon as possible along with updating and implementation of monitoring data.
The most important piece of information is undoubtedly confirmation of the considerable financial effort needed to carry out the works in question. However it must be noted that the tunnels in question are the longest and boast the heaviest weight of traffic inside the network and are subject to complete modernisation as set forth in the design guidelines.
A lower economic incidence is to be expected for the other tunnels subsequent to risk analysis.
The commission wants to make it known that after the planned extraordinary works have been carried out, a specific routine maintenance plan must in any case be adopted with a considerable, necessary increase in funding.
Everyday management and routine maintenance activities must be considerably stepped up especially in the event of installation of high-tech, advanced systems.
Lastly, the commission would like to recommend that the tunnels currently being built or modernised strictly comply with the standards set forth in the safety design guidelines and the concepts behind this plan extract, both with regard to structures and system engineering.

PRESSURE LOSSES DUE TO THE LEAKAGE IN THE AIR DUCTS - A SAFETY PROBLEM FOR TUNNEL USERS ?

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ABSTRACT

There is a requirement in Austria to suck off an exhaust volume of at least 120m^3/s at the end of an exhaust duct in case of fire (RVS 9.261). To fulfil this, the leakage volume must be known for a not tight exhaust duct. The paper shows how the leakage volume can be calculated.

1. INTRODUCTION

30 years ago many long motorway tunnels where planed in Austria. For instance: the 6,4 km long Tauerntunnel, the 5,4 km long Katschbergtunnel, the 7 km long Pfändertunnel and the 10 km long Plabutschtunnel. All these tunnels where planed for two tubes. But the traffic amount at that time was low and the car emission was very high. Therefore only one tube was built and equipped with a transverse ventilation system.

The traffic amount was growing in the last 30 years very much. Also the philosophy about the fire in a road tunnel was changed totally after the bad fire disaster in the Mont Blanc and Tauerntunnel. Small exhaust hoods with an area of 0,5m^2 where installed every 12m in the exhaust ducts of these tunnels. The idea was to suck up the smoke in case of fire to the false ceiling and extracted it over a long part of the exhaust duct. The advantage of this solution was thought to have a smoke free bottom zone on the one hand and a not extreme hot smoke in the exhaust duct because of mingling with fresh air on the other hand. Leakage of fresh air into the exhaust duct was therefore no big problem.

But now we think it is better to suck off the smoke directly near the fire place into the exhaust duct through large adjustable exhaust dampers (open area ~12m^2) to avoid smoke propagation in the tunnel. The adjustable smoke dampers are installed every 100m. In normal case of operation all dampers are a little bit open, so that the same amount of exhaust air can be sucked off through each damper. But in case of fire only this damper will be opened fully which is closed by the fire place and all others will be closed. So a concentrated smoke extraction is possible. There is a requirement in the new Design Guidelines Tunnel Ventilation that the exhaust fan must be able to suck off 120m^3/s at last at the end of a long exhaust duct. In this case leakage air which is sucked into the exhaust duct between the fan and the end of the duct has to be minimized or even prevented. If it is not possible to prevent the leakage air in the exhaust duct we have to know it because the flow rate in the exhaust fan will then be enlarged. Thus the power input is higher than in case of a tight exhaust duct. Therefore we have to focus our attention on the calculation on the leakage air.

2. CALCULATION OF THE LEAKAGE AIR

Under the assumption that the air is incompressible, the cross section of the exhaust duct is constant and the area of the leakage strip is constant too over the whole length of the duct we can drive the following differential equation system:

The pressure in the exhaust duct is given by the equation

$$\frac{dp_a}{dx} = -\frac{\lambda_a}{D_a}.\frac{\rho}{2}u_a{}^2 - ka\frac{\rho}{2}\frac{du_a{}^2}{dx} \qquad (1)$$

The velocity in the exhaust duct can be calculated with

$$\frac{du_a}{dx} = \frac{f'}{F_a}\sqrt{\frac{2(p_v - p_a) + \frac{\rho}{2}\left(\frac{F_a}{F_v}\right)^2 u_a{}^2}{1+\xi_a}} \qquad (2)$$

and the pressure in the tunnel follows from

$$\frac{dp_v}{dx} = -\frac{\lambda_v}{D_v}\frac{\rho}{2}u_v{}^2 - k_z\frac{\rho}{2}\frac{du_v{}^2}{dx}) \qquad (3)$$

The connection between u_v and u_a is given by

$$\frac{du_v}{dx} = -\frac{F_a}{F_v}\frac{du_a}{dx} \qquad (4)$$

Here in is

$p_a(x)$	[N/m^2]	pressure in the exhaust duct
x	[m]	coordinate in the exhaust duct
λ_a	[-]	friction coefficient in the exhaust duct
λ_v	[∞]	friction coefficient in the tunnel
D_a	[m]	hydraulic diameter in the exhaust duct
D_v	[m]	hydraulic diameter in the tunnel
ρ	[kg/m^3]	air density
u_a	[m/s]	air velocity in the exhaust duct
u_v	[m/s]	air velocity in the tunnel
v_a	[m/s]	air velocity in the leakage strip
α	[°]	angle under which the leakage streams into the air duct
f′	[m^2/m]	area of the leakage strip
F_a	[m]	cross section of the air duct
F_v	[m]	cross section of the tunnel
p_v	[N/m^2]	pressure in the traffic duct
ξ_a	[-]	resistance coefficient for the entrance of leakage air into the air duct
ξ_v	[-]	resistance coefficient for the entrance in the tunnel
k_a	[-]	is a factor which take into consideration the profile shape of u_a
k_v	[-]	is a factor which take into consideration the profile shape of u_v

3. SOME RESULTS

Figure 1 shows the result from a calculation of the pressure distribution ($x = 0, p_a = -240\ N/m^2$) in the exhaust duct and the tunnel itself when the exhaust duct is tight. The calculation was performed under the assumption that a volume of $120 m^3/s$ is sucked off at the end of the duct. The air velocity in the exhaust duct and in the tunnel is then constant as it can be seen in Figure 2.

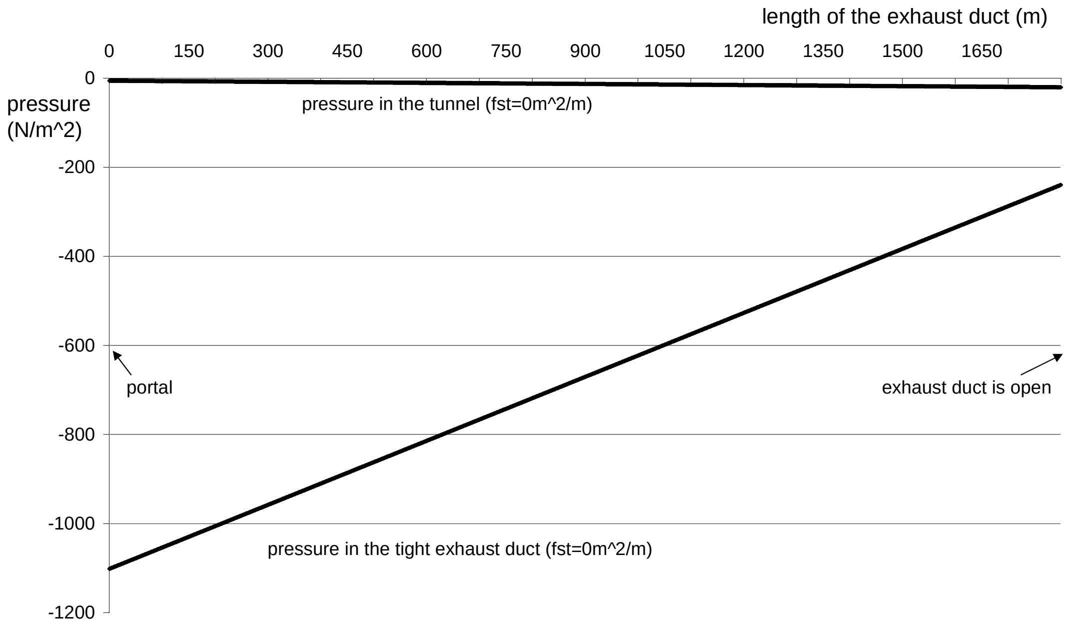

Fig. 1: Pressure distribution in a tight exhaust duct and in the tunnel

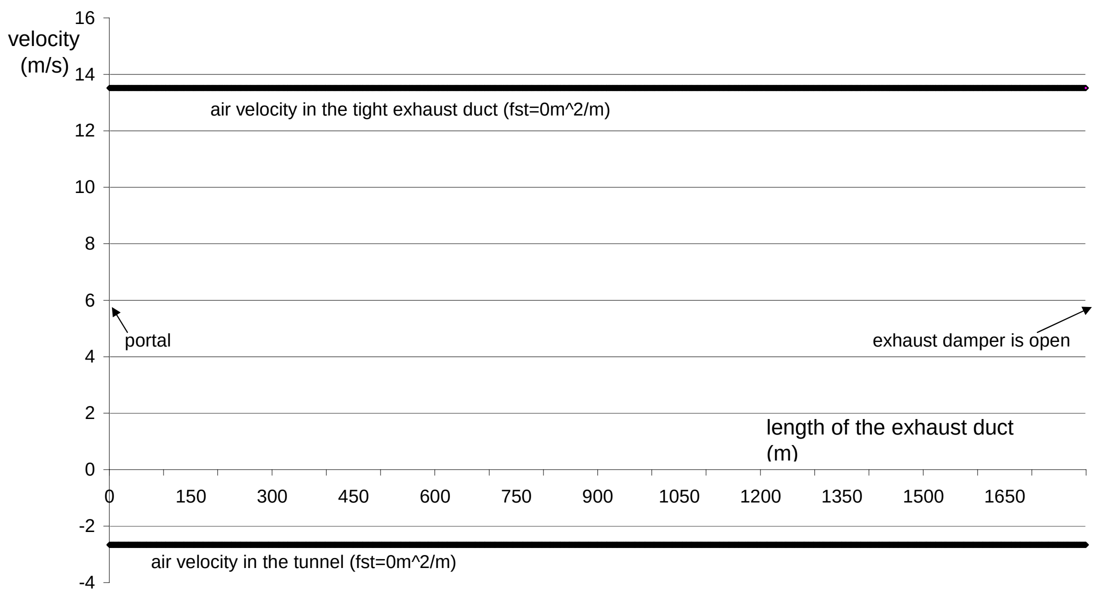

Fig. 2: Velocity distribution in a tight exhaust duct and in the tunnel.

Figure 3 shows the result when the exhaust duct is not tight. ($f'' = 0.001m^2/m$). The pressure distribution starts with the pressure of $-250N/m^2$ near the open exhaust damper at the end of the exhaust duct. It can be seen that pressure in front of the exhaust fan is roughly p=-1800N/m^2 in comparison of p=-1100N/m^2 in a tight duct.

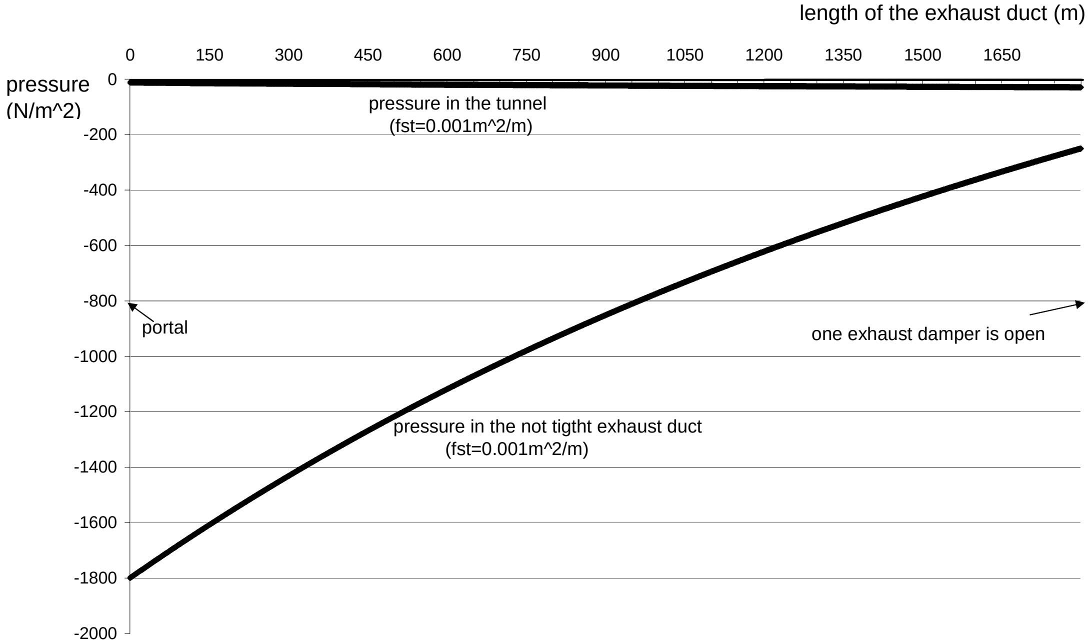

Fig. 3: Pressure in the not tight exhaust duct (fst=0.001m^2/m)

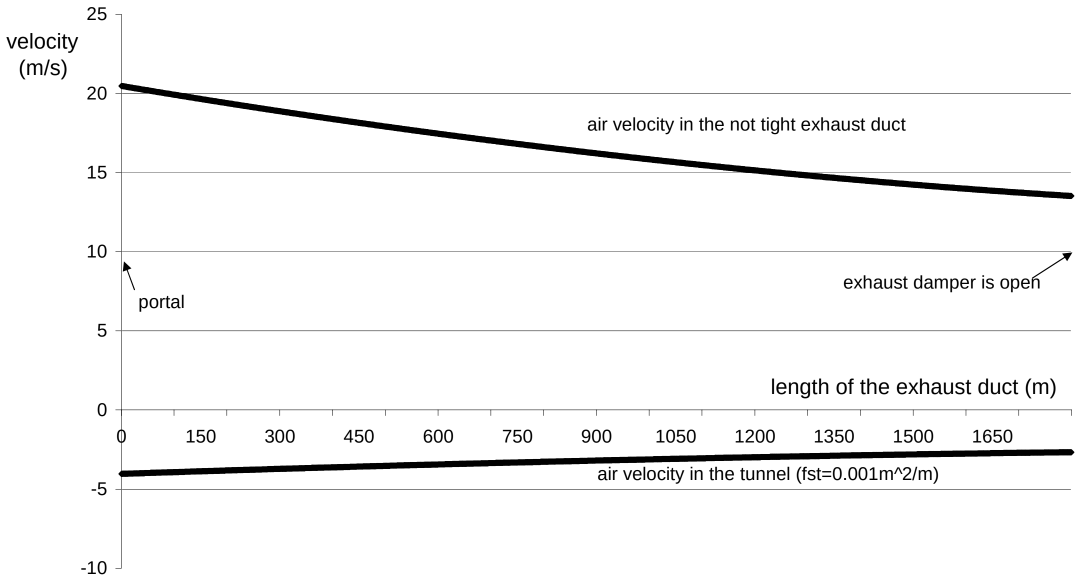

Fig. 4: Velocity in the not tight exhaust duct (fst=0.001m^2/m)

The pressure behind the portal in the tunnel is only a little bit lower than in case of a tight exhaust duct. The air velocity in the exhaust duct is growing from 13.52/s near the open exhaust damper to 20.47/s near the exhaust fan (Fig. 4). So the flow rate in front of the fan is 181.6m^3/s in comparison to 120m^3/s in a tight exhaust duct. If we take only the pressure losses in the exhaust ducts into our power input calculation for the exhaust fan we need 408.7kW ($\eta_{Fan}\sim 0.8$) for the not tight duct and only 165kW for the tight duct to suck off 120m^3/s ($\eta_{Fan}\sim 0.8$) at the end of the exhaust duct.

4. CONCLUSION

The calculation showed that it is important to know the leakage volume that is sucked into the exhaust duct between the open smoke damper and the exhaust fan. The leakage volume and the additional pressure drop in the not tight exhaust duct enlarge the power input of the exhaust fan to suck off $120 m^3/s$ at the end of an exhaust duct very much.

WINDSHIELD FOGGING IN ROAD TUNNELS - FINAL RESULTS

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ABSTRACT

When a car enters a tunnel, the occurrence of water condensation on the outside of the front shield is possible if air temperature and/or humidity in the tunnel are higher than outside. Due to cooling of the tunnel air on the surface of the vehicle, the temperature can fall below the dew point and therefore condensation on the surface occurs. Because of sudden appearance and reduction of the driver's view, this phenomenon presents a remarkable potential for danger.

Gruner Ltd. was assigned from the Swiss Federal Roads Authority with the research program "windshield fogging in road tunnels". Tools for predictions have been developed and by means of surveys with tunnel users, theoretical studies, model calculation and measurements in three affected tunnels, measures have been proposed in order to reduce the appearance of windshield fogging. Beside the suggested measures, the final report contains recommendations which have been made to be included in the Swiss guideline "Ventilation of Road Tunnels".

This paper contains selected results from the measurements and the conclusions out of it. The most important measures to reduce the risk associated with windshield fogging are presented.

Keywords: windshield fogging, ventilation design, tunnel safety

1. INTRODUCTION

The phenomena of sudden windshield fogging are known in many two-way traffic road tunnels. The safety risk due to reduction of the driver's view however is not considered in most of the assessments of the safety level of tunnels even though there have been a couple of accidents indisputably caused by windshield fogging.

The Swiss Federal Office of Roads assigned Gruner Consulting Engineers with a research study which was completed in 2004 [1]. First results have been presented in [2]. This paper focuses mainly on the final results.

2. INVESTIGATIONS

2.1. Surveys

Through a survey of the Cantonal (Provincial) Authorities, it was investigated in which tunnels windshield fogging occurs in Switzerland. The phenomenon is reported to occur in a total of 19 Swiss road tunnels. In 9 of these tunnels regular fog formation on windshields are reported. The survey showed that the fogging hazard in two-way traffic tunnels with a length of over 1400 m is distinctly increased. Additionally, for twin-tube single direction traffic tunnels (one-way traffic tunnels) under renovation, where one tunnel tube is operated as a two-way traffic tunnel, time and again fogging of windshields occur.

The correlation between tunnel length and the potential of danger of windshield fogging can be used as simple instrument to determine the probability of windshield fogging in new and existing tunnels. Figure 1 shows the proportion of tunnels with windshield fogging as a function of tunnel length.

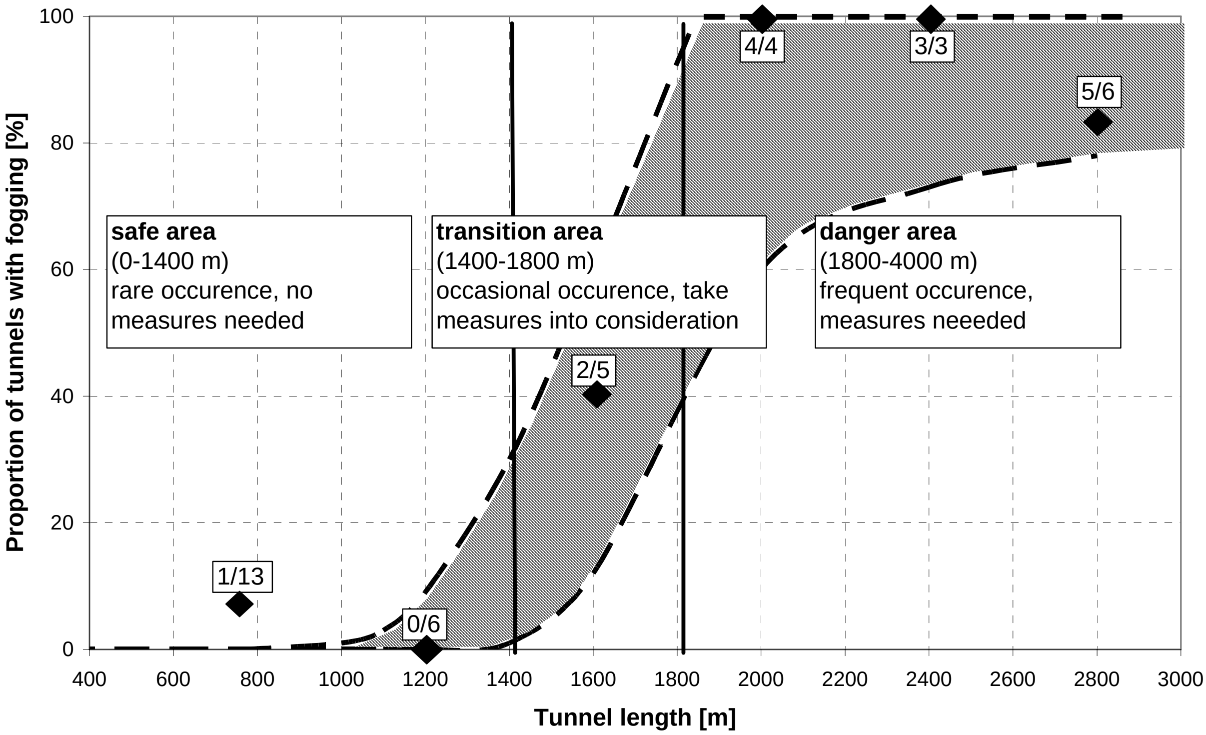

Figure 1: Proportion of concerned tunnels against tunnel length (bi-directional tunnels only)

In the tunnels Vue-des-Alpes (H20, NE, bi-directional traffic, l = 3240 m) and Eggflue (H18, BL, bi-directional traffic, l = 2790 m) a survey of tunnel users was conducted to determine the frequency and intensity of fogged windshields. Obscured windshields were reported on the basis of a three-step scale (light, medium or heavy fogging). Altogether 4770 Vue-des-Alpes as well as 3830 Eggflue tunnel passages were evaluated. The following statements can be deduced:

- In 7% of the tunnel passages (on average) medium or heavy fogging was reported.
- In 92% of the tunnel passages with reported fogging the road surface was wet.
- Fog formation usually occurred shortly after entering the tunnel.

2.2. Measurements

In tunnels Eggflue, Leissigen (A8, BE, bi-directional traffic, l = 2100 m) and Vue-des-Alpes, indoor-air climate measurements were carried out. Besides air temperature and relative humidity, visibility (opacity), air flow velocity and ventilation operation time were additionally recorded. By means of these measurements, it is possible on the one hand to estimate how strongly a tunnel is affected by windshield fogging. On the other hand, the correlation of survey data and measured data allows determining a threshold value for the tunnel dew point temperature above which windshield fogging occurs (see also chapter 3.3 and [2]).

Figure 2 shows results from the climate measurements in the Vue-des-Alpes tunnel. Physically, windshield fogging (on the outside) is possible as soon as the windshield temperature is below the dew point temperature of the outside air. The arrow indicates a corresponding time domain.

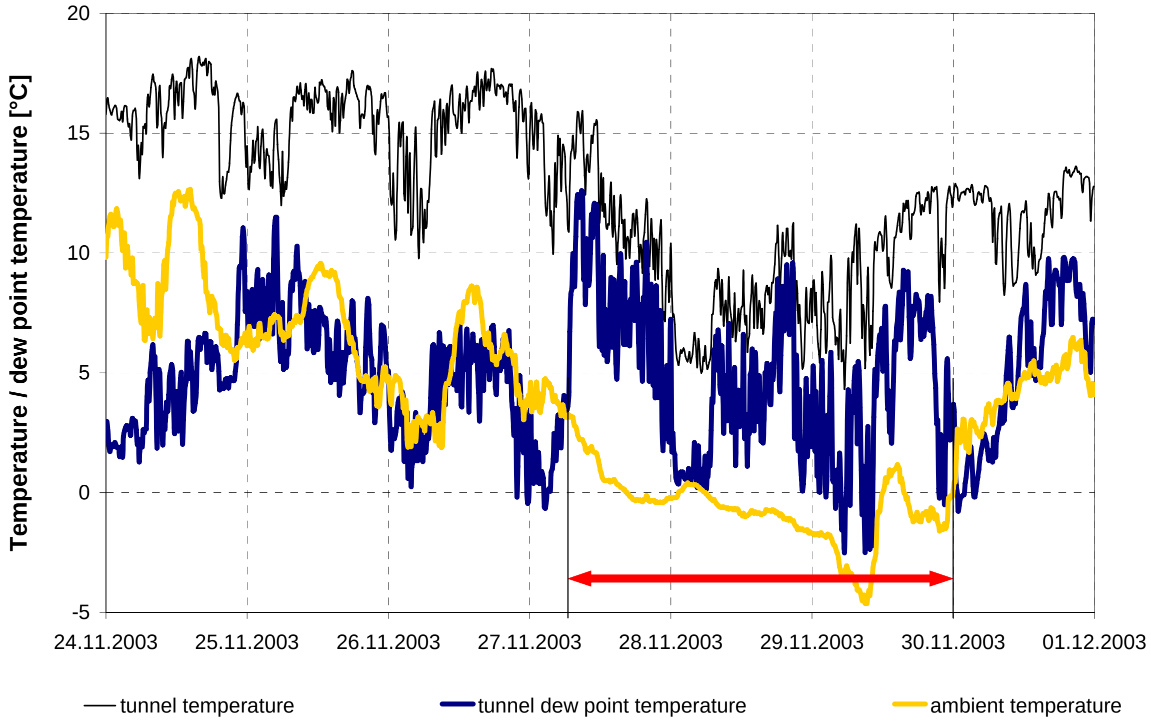

Figure 2: Climate data - the arrow indicates a time domain where the ambient temperature (≈ windshield temperature) is below the dew point temperature in the tunnel.

3. FINDINGS

3.1. Climate

Figure 3 shows the temperature characteristics over one year. Even in summer, the mean tunnel temperatures are - due to heat loss of the vehicles - higher than the ambient temperature.

The following statement can be derived from the measurements and surveys:

- On the basis of stronger emission regulations, or in other words, decreasing noxious emissions from the traffic, a lower air-change rate by the mechanical tunnel ventilation system is to be expected for the future.

Conclusion: Because water ingress into tunnels from automobiles remains approximately constant, an increasing occurrence of windshield fogging is expected.

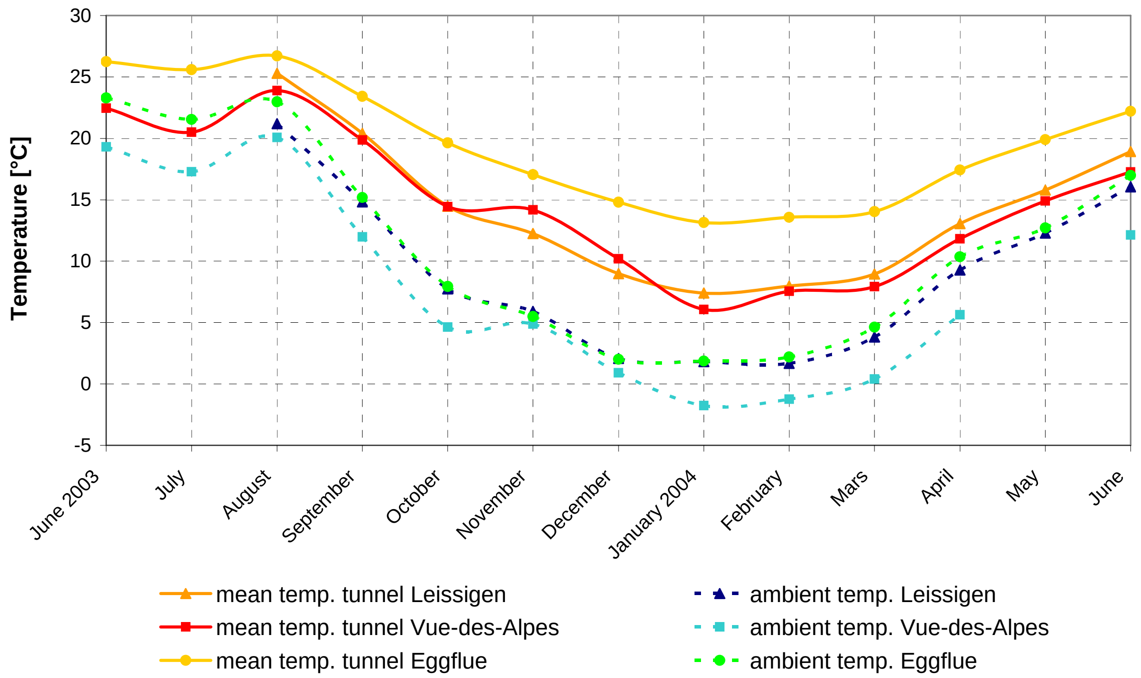

Figure 3: Monthly mean temperatures (ambient and tunnel) for Leissigen, Vue des Alpes, Eggflue[1]. Period: July 2003 to June 2004.

3.2. Ventilation System

The investigation has demonstrated that a tunnel's ventilation system has an impact on the occurrence of windshield fogging.

- When employing a midpoint-extraction ventilation system the dew-point temperature at the tunnel entrance is significantly reduced. This minimizes an abrupt climatic change when entering a tunnel and, as a consequence, reduces the sudden occurrence of windshield fogging. The midpoint-extraction system is well suited to reduce the hazard. Also of critical importance is the correct operation of the dew-point control system.
- With a dew-point controlled semi-transverse ventilation system even with a large expenditure of energy, the fogging hazard can be marginally improved. This system reduces the dew-point temperature at the tunnel entrance just slightly.

Conclusion: Fogged windshields in tunnels are effectively prevented by ventilation systems which aspirate fresh air through both portals. The installation of a dew-point control system is therefore only meaningful when a midpoint-extraction ventilation system (or variable-point extraction system where air is extracted through the plenum above the intermediate ceiling) is implemented. In order to effectively reduce the fogging of windshields, a directional air-flow velocity of greater than 0.5 m/s has to be generated at the tunnel entrance.

[1] For the Vue-des-Alpes tunnel, the temperature is not the average tunnel temperature but the temperature 250 m inside the portal.

3.3. Control Variables for Dew Point Regulation

As control variable, the "supersaturation" of the air in the tunnel [g/m^3] is recommended. Supersaturation is defined as the difference between the absolute humidity in the tunnel and the maximum amount of moisture possible in the tunnel air when the tunnel air is cooled to the outside air temperature. Concerning the threshold value, above which condensate formation occurs, the following statements can be made:

- A comparison of the survey results and the results of measurement shows that with a supersaturation level greater than 3 g/m^3, medium or heavy fogging was reported. With a supersaturation level lower than 0 g/m^3, generally no fogging was reported. In between these two values extends a transition range, in which, depending on circumstances, fogging can occur or not.
- Supersaturation is a good parameter for forecasting the fogging hazard in a tunnel. With a threshold value of approximately 1.5 g/m^3, the best agreement between survey and measurement was achieved. This threshold value was later confirmed by supplementary empirical tests in a wind tunnel.

Conclusion: Supersaturation is proportional to the windshield fogging occurrences in a tunnel and can therefore be used as the dew-point ventilation system control variable. The recommended threshold level is 1.5 g/m^3.

3.4. Windshield Fogging Hazard

On the basis of the data from the tunnels Vue des Alpes and Eggflue and the described threshold value, it can be stated that over a year in 7 % (Eggflue) resp. 9 % (Vue des Alpes) of the time, sudden windshield fogging has to be expected. Figure 4 shows the seasonal variation of the fogging. Fogging occurs mainly during fall and winter.

Conclusion: Windshield fogging presents a significant safety risk for a road tunnel. With the traffic data of the Swiss tunnels where the phenomenon is known, one can estimate that 2000 tunnel users per day are affected by sudden windshield fogging in Switzerland[2].

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[2] Beside the occasional complaints from tunnel users about fogging, there have been a couple of accidents in Switzerland in close coherence with the occurrence of windshield fogging in tunnels.

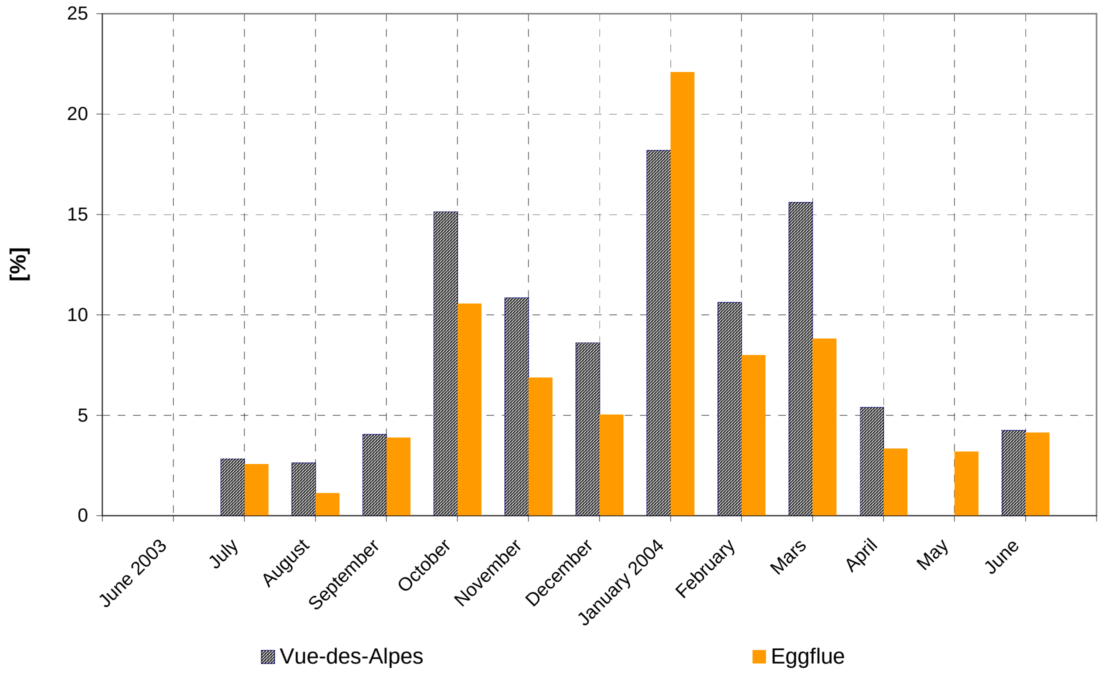

Figure 4: Time slices during which windshield fogging has to be expected based on measured data and a threshold value of 1.5 g/m^3 (Vue-des-Alpes and Eggflue). Period: July 2003 to June 2004.

4. MEASURES

Various measures are suggested in order to reduce the incidence of accidents caused by the sudden fogging of windshields. A measure can reduce the risk through an improved reaction of the tunnel users and/or through a reduction in the occurrence of fogging windshields. The recommended measures are summed up in the following:

Prevention measures

- Information and training of the drivers: Integration of the topic "Abrupt Fogging of Windshields at Road Tunnel Entrances" in the compulsory circulation theory lessons, carry out campaigns through the Swiss Council for Accident Prevention (bfu), as well as informing the population through publication in journals of automobile clubs and other media (e.g. newspapers).
- Warning system: Installation of a static or dynamic warning sign with a warning light in front of the entrance of affected tunnels. The advantage of the dynamic warning system is that the tunnel user would only be warned when climatic measurements indicate a possible fogging hazard. A pilot project for a dynamic warning system was started for an existing tunnel. The costs for the system were estimated to be about 70'000 euro (without integration in the scada-system). Costs for new tunnels are expected to be lower.

Mitigation measures

- Speed reduction: Implement a speed reduction system (e.g. from 80 km/h to 60 km/h) which combines climatic measurement with a dynamic speed-sign system. The effects of this measure are: reduction of the amount of condensation (condensation is linear to the vehicle speed), increasing of the available reaction time for the driver and due to the lower kinetic energy reduced consequences in case of an accident.

Technical measures

- Dew-point Ventilation System: With a dew-point controlled ventilation system the formation of fogging on windshields can be effectively reduced. This is valid, however, only for tunnels with ventilation systems in which outside air flows into the tunnel entrance (midpoint-extraction ventilation system or variable-point extraction system). Ventilation systems with dew-point controlled ventilation have increased energy consumption. The additional costs strongly depend on the specific climate conditions (tunnel and surroundings). In the Leissigen tunnel, the additional power consumption of the ventilation is about 12 %.

5. RECOMMENDATIONS FOR CODES AND STANDARDS

On the strength of the findings, different recommendations and measures for safety standards are suggested for both road tunnels in the planning stage and for tunnels in service.

For one-way traffic tunnels no safety measures are necessary. For bidirectional tunnels longer than 1400 m, measures are to be implemented. The suggested recommendations for Standardization are summarized in the following:

Tunnels in planning stage

- Two-way road tunnels with a length between 1400 m and 1800 m (transition area of fig. 1): A variable-point extraction system (or midpoint-extraction ventilation system) should be preferred to a semi-transverse or longitudinal ventilation system without extraction. Additionally, care must be taken to ensure the installation of dew-point sensors and a dew-point control module in the tunnel ventilation control system at a later time.
- Two-way road tunnels longer than 1800 m (danger area of fig. 1): At the entrance zone of the tunnel, an appropriate ventilation system has to be installed in order to ensure a directional flow of air into each tunnel entrance zone.

Existing tunnels

- Two-way road tunnels (in service) with a length over 1400 m: The time ratio of how often a fogging hazard condition occurs has to be measured. If critical conditions occur more than 4 % of the time during a year[3], then a dew-point controlled ventilation system is to be installed.

It is recommended to integrate the suggested measures into the existing Swiss standard [3]. Because abrupt fogging of windshields does not only present a problem for traffic safety in Switzerland, international coordination of the above guidelines is advisable.

6. CONCLUSIONS

Windshield fogging represents a significant safety risk for two-way traffic tunnels longer than 1400 m. Due to continuous reduction of mechanical air exchange in underground traffic systems caused by the lower vehicle emissions, it is expected that the occurrence of windshield fogging will further increase in the future.

Different measures (organisational/educational and technical) are recommended to reduce the risk due to the sudden appearance of fogging on the windshield. For tunnels with a ventilation

[3] An appropriate mobile measurement and evaluation system has been defined and is already in use.

system which directs the airflow into the tunnel entrance from outside, dew-point controlled ventilation is a technically effective measure and should thus be taken into account in the design of a ventilation system.

In order to reduce the risk associated with windshield fogging as much as possible especially in new tunnels, the research findings should be integrated into the guidelines and standards for tunnels. International coordination of the proposed guidelines is essential.

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NEW REQUIREMENTS FOR AUTOMATIC FIRE DETECTION SYSTEMS IN TUNNELS WITH STATIONARY FIRE FIGHTING EQUIPMENT

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1. ABSTRACT

Automatic fire detection systems have become standard equipment in road tunnels in many European countries in the past. Mainly linear type heat detectors, based on sensitive sensor cables, have been installed.
Other techniques are on the way and are partly used for the detection of smoke, or at least for an early warning of danger.
Requirements for the automatic fire detectors have already been quite hard, but for the activation of stationary fire fighting systems, additional and higher specifications must be fulfilled by those systems.
This paper gives a short overview of the new requirements and presents the tests, which have been performed to prove the ability of one of the most common automatic fire detection systems on the market.

2. FIRE AND SMOKE DETECTION

The detection and localisation of fires along the length of road tunnels is achived by continous monitoring of the ambient temperature with temperature sensitiv sensor cable. Two different techniques are offered on the market: measurement systems based on optical fibres and cable systems with integrated electronic temperature sensors. Both types are well known and not to be described within this paper.

To detect smoke in tunnels and to give an early warning of probable danger, signals from the air quality measure equipment can be used in addition to the linear heat detectors. Video based incident detection systems are more and more able to detect the presence of smoke, beside the recognition of accidents, stopped vehicles, wrong way drivers or persons on the lanes.

3. STATIONARY FIRE FIGHTING EQUIPMENT AND THE REQUIREMENTS

After the tunnel catastrophies of the year 1999, the public as well as the experts have extended their discussion about active stationary fire fighting equipment. A number of suppliers of such technologies have performed practical tests under full scale conditions, for example in the test gallery of Hagerbach in Switzerland or in the Spanish test facility "San Pedro de Anes".
Different to Japan, where sprinkler systems are used in long tunnels since many years, in Europe the installation of water mist systems is the most probable. For this technology, a reliable automatic fire detection system is requested to activate the controlled valves in case of a fire at the right place under all circumstances, with or without human confirmation.

The combination of the electronic linear heat detector LIST with water mist systems has already been successfully done with belt conveying systems in lignite power stations in different countries. Road tunnels, however, have other dimensions and environmental conditions in regard of wind speed are different.

The following requirements for fire detectors are generally valid in tunnels:

- Availabilty and reliability of the fire detection system must be high
- Temperature conditions at the portals are different to those in the middle of a tunnel, which means that the detection system must be adaptable.
- Ventilation can lead to fast changes in temperature, which may not result in false alarms.
- Electro-magnetic disturbances may not influence the detection system
- Subzero temperatures are normal in many countries. Sensors must be reliable at very low temperatures.
- Aggressive exhaust fumes and salts, humidity and fog, dust and dirt, as well as vibration may not influence the functionality of the fire detection system.
- The localisation of a fire must serve the requirements of the ventilation system
- False alarm rate at very low level

If a water mist system shall be activated by the linear detector,

- availability and reliability must be extremely high,
- the localisation of a fire must be guaranteed with a precision of very few meters
- even with the maximum natural air flow
- and with the lowest possible false alarm rate.

Availability and Reliability: in case of a fire, the automatic linear fire detector is probably the only system, which can give the right and necessary information about the fire and its location. Air quality measurement equipment is installed in distances, which are too far for a precise fire place indication. Information through CCTV might be obstructed (stopped truck in front of the concerned camera) or impossible (dark screen due to smoke).
Approved linear fire detection systems like LIST have been certified by authorities, who have tested the systems components on several national and international standards.
The operation must be guaranteed even in case of missing power. So uninterruptable power supplies are mandatory.
Redundant systems will continue the monitoring of a tunnel even if components fail.

Localisation of a fire: the maximum available water for the fire fighting system is limited. Those systems have extinguishing sections of typically 20 to 30 m. After a fire alarm has been released, the concerned fire suppression section will be activated, and normally the both neighboured sections, too.
The demands, for example of the German guideline for tunnels, RABT 2003, to detect a fire with a resolution of 50m , is therefor not sufficient for this application. An activation released by video detection systems fail due to the same reason.
LIST sensor cable systems in tunnels with fire fighting systems have sensors at least every 8m, in Austrian projects, the distance between the sensors is 4m. The place of the sensors is fixed for all time. There is no drift or any other influence, which might result in an indication of a wrong place of the fire.

Air flow: it must be ensured, that the fire will be located with the same precision even at the maximum air flow, which can appear in a tunnel. There are tunnels in mountaineous areas, where the natural air flow can reach 10m/s or even higher. The fast and precise fire detection can be done under these conditions only by reacting on the heat radiation. Convectional heat will affect on the wrong location. Any smoke detection will falsify the fire place, too.

The LIST sensor cable is very sensitive to heat radiation, due to its construction, and gives the exact location of a fire even with high wind speed.

False alarm rate: a fire detector, which gives a remarkable number of false alarms, will cause costs, risks the disregard and will be switched off at last. If a fire suppression system in an operated road tunnel will be released erroneously, the consequences can be awful. Only fire detection systems of good reputation and with good experience are therefor suitable.

A special scenario should be mentioned at this point: a stationary fire fighting system is designed to suppress a fire on a determined location. As real fire events of cars and trucks have shown, vehicles releas smoke before they stop already. Any alarm from a point, which has been already passed by this vehicle, may not be the base of any automatic process, which, once initiated, can't be transferred instantly and automatically to another location

4. THE PROOF OF THE SUITABILITY

The LIST sensor cable system has been involved and has been used in a number of practical full scale fire tests to prove that it meets the a.m. requirements:

In September 2000, tests have been successfully passed in the Austrian Felbertauerntunnel. Fire detection with a precision of 4m has been recorded with a wind speed of 10 m/s.

In September 2003, a full scale of fire tests in the Hagerbach test gallery with a number of real cars and slow starting fire event has proved, that the LIST sensor cable system meets the demands for the special project of the French highway tunnel of the A86 around Paris, where passenger cars will drive on two levels in one tube. This tunnel will be equiped with a water mist system, the installation of the LIST sensor cable has already started.

In October 2003, in the Mona-Lisa-Tunnel in Linz, Austria, a test has been performed with the operational LIST fire detection system, which ensured, that the later installed water mist system will not be activated, if trucks with hot loads (asphalt) will use the tunnel.

Further tests in combination with fire suppressing systems have been performed in the Scheetunnel in Germany, in the Higashyama Tunnel in Japan and again in the Hagerbach test gallery for a series of fire tests.

Fire tests as one part of the acceptance procedure of new tunnels with LIST sensor cables have been passed successfully according to RVS and RABT in many recent projects.

5. CONCLUSION

Reliable automatic fire detection in tunnels has become more important than ever. The recognition of smoke, based for example on video detection, is a sensible supplementation of the current safety equipment in tunnels. A next step of improvement might be the installation of fire suppression systems, with new and higher demands on the automatic fire detectors. Linear heat detection systems have proven that it needs those demands.

SECURITY OF DATA IN AN ETHERNET NETWORK

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ABSTRACT

The Ethernet technology, which dominates the field of data communication in today's office environment, is also playing an ever more important role in traffic automation. The advantages of Ethernet technology lie both in the standardized communication it offers, as well as the seamless infrastructure spanning from the desk in the office or control center to the PLC and sensor in the tunnel.
Ethernet technology means that data is not only available at field level, but also across all areas. As a result of this development, operators are being confronted with questions relating to network security which had previously not been a major issue.
Our challenge is to design a secure network which uses several techniques especially developed for use in the industrial environment.

Keywords: security, safety, industrial firewall, security scenarios

1. INTRODUCTION

Customers around the world count on products from the German based company Hirschmann Automation and Control GmbH, located in Neckartenzlingen close to Stuttgart. Traffic applications such us metros, railways, airports, and road tunnels are all equipped with Hirschmann products. With a 32 percent global market share, Hirschmann is the world's leading supplier of Industrial Ethernet devices, as revealed by a recent survey conducted by the ARC Advisory Group, based in Dedham, USA. Key features of the products are a rugged design, high temperature range and the HIPER-ring, a method for fast reconfiguration of the network if a fault occurs.

In earlier times tunnels were mainly equipped with field buses, remote control systems, and analog video. With Ethernet, different applications and devices now can be controlled over a single high-speed network. Also, special redundancy methods safeguard continuous data transfer.
Along with these advantages, there are new issues to be tackled that must be solved to ensure secure and reliable operation. A high priority issue is security, which is defined by data integrity, authentication, confidentiality, availability, and validity.

For most company employees, the only time they think about the network is when it stops. For other companies, network downtime can cause major financial loss.
For tunnel networks failures can also result in loss of safety.
Therefore we have to ensure that we design secure network systems.

2. TRENDS IN CURRENT TUNNEL NETWORKS

According to a recent study carried out by the ARC Advisory Group in 2005 **[1]**, the number of end devices with Ethernet interfaces supplied for use in automation technology is expected to increase each year by approx. 50%, until 2009. If this trend continues, the vision of field bus systems being replaced completely by Ethernet and IP will become reality.

More and more tunnel applications are based on Ethernet:
PLC, control centers, video surveillance equipment, traffic management, emergency phones, ventilation, air conditioning, lighting, sensors, fire protection, surface condition management,…

The trend is for all isolated systems to merge and be connected to the Internet.

This progression must be backed up by a reliable future-proof security concept.

3. SOURCES OF DANGER

Through the connection of all Ethernet devices which had previously been isolated, to the company-wide network and the Internet, suddenly an almost unlimited number of potential attackers have access to critical networks.

Access to the network for service purposes (Local Access) represents a particular source of danger. In many plants, for example, external employees have unrestricted access to unused Ethernet ports during maintenance or setup work. The situation becomes even more critical if modem connections (remote access) have already been installed for the purpose of remote maintenance of production plants.

A further danger can also be caused by authorized personnel, who could spread dangerous software within the production network. For example, viruses from notebooks used for service purposes could infiltrate into the fundamental network. The root cause of the danger therefore lies in the inner areas of the network.

In the field of automation technology, however, integrated software patch management is not possible in most cases due to different operating systems or software versions within a plant, and the long authorization processes. Many automation systems also lack the necessary performance needed to support local security technologies.

4. SECURITY POLICIES

Faced with this increasingly complex situation, a single unified structured security policy, whose effectiveness can be continually verified, assessed, and improved, is necessary. This is easier said than done. The sheer number of threats and vulnerabilities, and the steps required to minimize risk and fulfill corporate and legal responsibilities can be overwhelming.

Of course there are several standards like BS7799 (ISO/IEC 27001) or ISO/IEC 17799, which establish guidelines and general principles for initiating, implementing, maintaining, and improving security management in an organization.

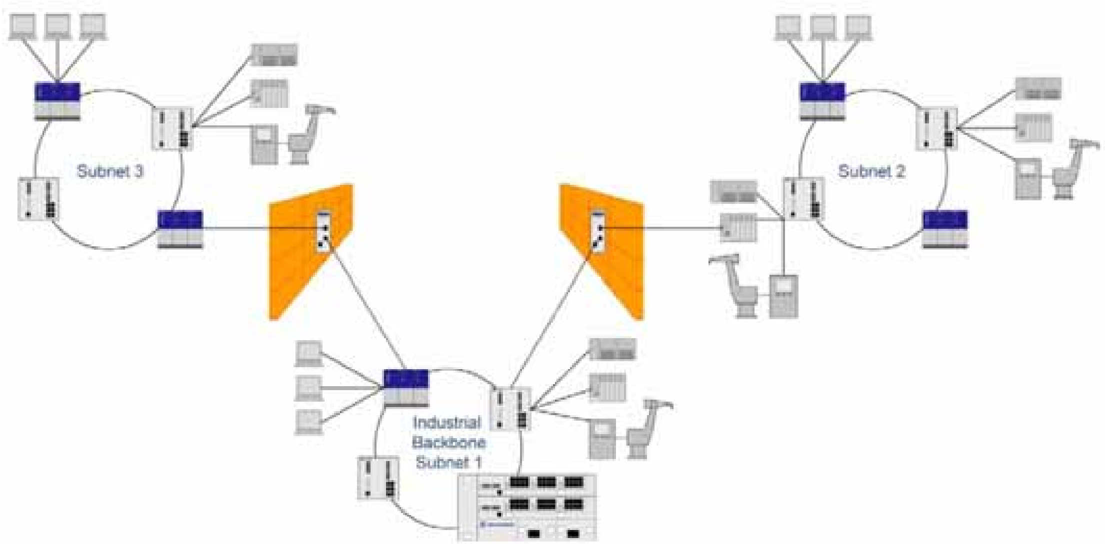
One question remains: How can this be adapted to industrial networks?

5. SOLUTION SCENARIOS

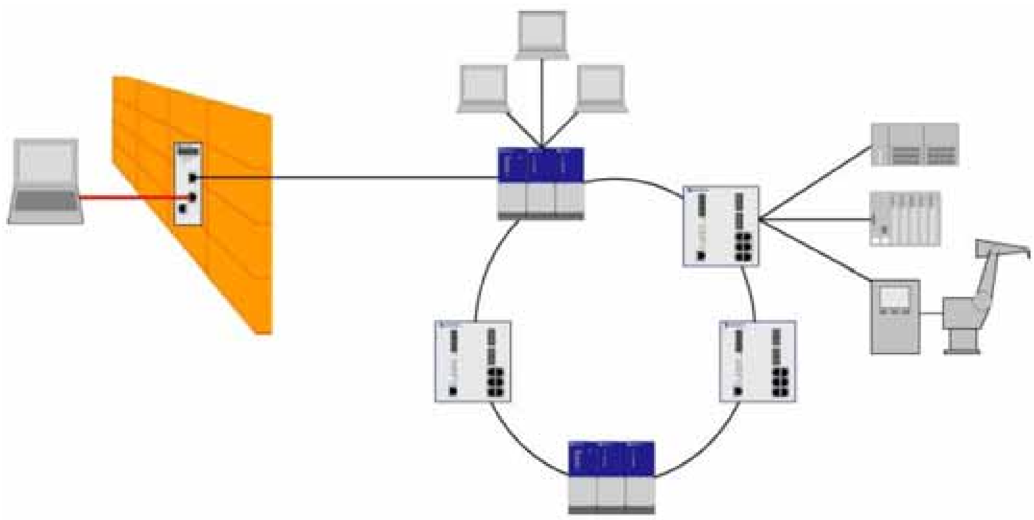
To reduce the security risks mentioned above, the Hirschmann security architecture **[3]** identifies various possible application scenarios:

5.1. Reduce complex networks by subdividing the industrial networks into security compartments or security zones.

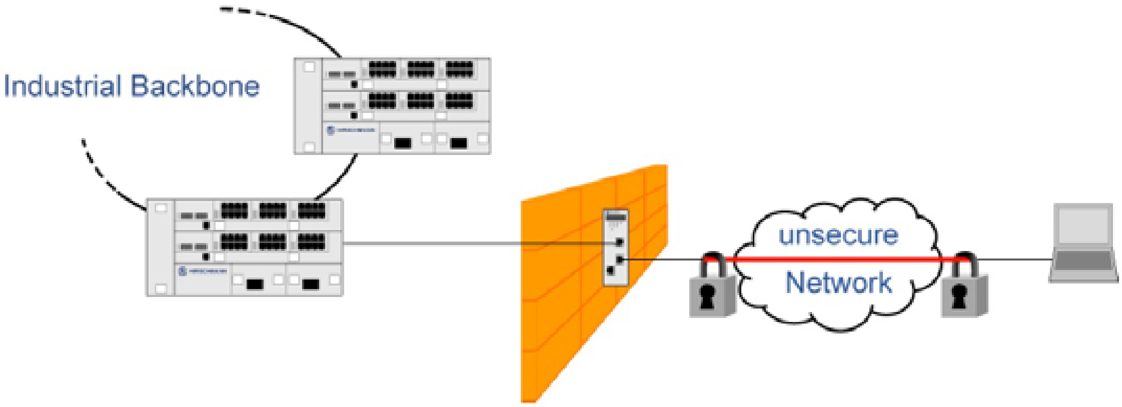
Individual parts of the overall network can be segmented using firewall functionality. For instance the customer's network and tunnel network can be separated.



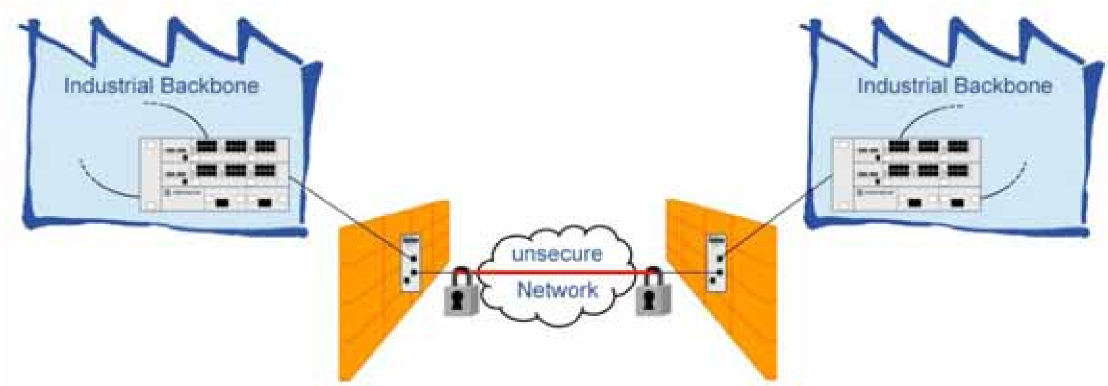
5.2. Establish a secure service port in the network for maintenance work by external or internal service engineers.



5.3. Setup secure access for remote maintenance over the Internet via VPN.



5.4. Use a VPN to connect several network sections via an insecure network.



6. SECURITY DEVICES

Security is like a puzzle – we need different methods to implement a overall reliable security system.

6.1. Industrial Switches

The latest generation of switches offers several important possibilities for security:

Enable/disable access by WEB, Telnet, HiDiscovery
SNMPv3 and Password protection
Secure VLAN
Port Security based on MAC or IP addresses and static MAC addresses
802.1x Port Authentication via RADIUS

6.2. Industrial Firewall (EAGLE from Hirschmann)

The EAGLE product range from Hirschmann offers a security system which is designed especially for use in tough industrial environments and guarantees both communications within tunnel networks, as well as on the interface to super ordinate data networks.

The security appliance offers a firewall with stateful packet inspection engine and VPN (Virtual Private Network) encryption based on hardware. It also includes a Kaspersky virus scanner which enables the end device to be relieved of this highly demanding task. The firewall can be installed on a DIN rail and integrated into existing network structures without extensive configuration. The device also supports redundant network connections in the form of redundant ring-coupling (layer 2) or as a virtual firewall interface (layer 3).

A basic requirement during the planning of networks is an understanding of the permitted communication relationships: Who is allowed to do what and when and where? Unfortunately, the network services and protocols used in various applications or devices are seldom known in the field of production.
For existing equipment, an analysis of the data traffic is usually unavoidable to create sensible rules for the firewall.

7. CONCLUSION

Most companies' employees are unlikely to have the skills, knowledge, and experience to implement a reliable security system.

The best hardware and software security products are only as good as the people who install and configure them. Mistakes at the implementation stage can lead to a false sense of security, as well as additional effort and expense at a later date.

Very important is a regular testing of the security mechanisms, to ensure their continued effectiveness. The people analyzing the effectiveness of the security mechanisms should not be the same people who installed and configured these mechanisms. Testing from outside a corporate network must be done by experts with in-depth knowledge of hacking tools and techniques.

External assistance with implementing security is recommended. Of course many consultancy and service companies offer parts of the puzzle, but then the burden of co-ordination and project management rests with the end customer.

The Hirschmann Competence Center, together with its Partner Network, now offers all consultancy, support, training, and hardware services directly from one source. This one-stop shop assists an organization to reach the goal of creating a security system according to standards such as BS7799, by providing the complete spectrum of security services at every stage of the process.

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SAFE CABLING SYSTEMS IN TUNNELS UNDER FIRE

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ABSTRACT

The paper aims at a detailed analysis of the current know-how in the construction of tunnel cabling systems and shows the impact of fire and heat and the respective measures to be taken. Therefore the results of the test projects EUREKA Firetun and MEMORIAL are scrutinized and evaluated in view of the today's boundary conditions in typical cross sections. It will clearly be shown how the heat distribution is dependant on the cross section and the ventilation system.

Further it will be shown how concrete will protect cables from heat and damage even if the coverage is low and how far open mounted installation channels are endangered.

For typical cabling systems it shall be outlined which requirements and specifications regarding fire and heat resistance are reasonable and required. A short discussion of the applicable norms and standards shall provide further information and decision guidance. It shall be clarified that high safety standards re isolation and fire resistance are not generally required.

1. CABLES IN THE TUNNEL

Cables are accommodated in road tunnels at different places: in lower floor panel troughing systems, containing tubing blocks and pits, on routes at the tunnel cover (lighting, communication, fire protection), on routes behind the wall lining, as well as in pits, ascents, air ducts, traversing and in accessible cable tunnels.

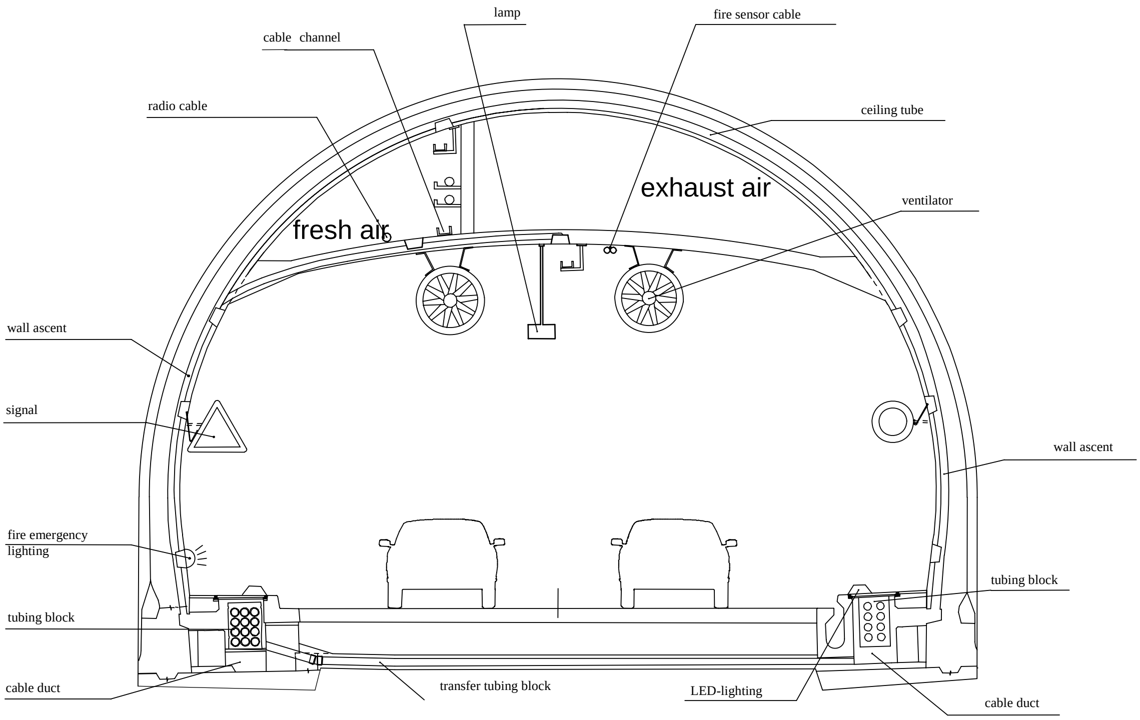

Fig. 1: Cabling systems in typical cross section

The different fire hazard of the cable systems can be judged due to the heat distribution in the case of fire.

2. FIRE IN THE TUNNEL

A fire event in a tunnel is often combined with a rapid temperature rise, connected with a fast propagation of smoke gases. The fire scenario depends on most diverse factors, which are substantial:

- fire load: Passenger vehicles, bus, truck with/without charge
- ventilation system of the tunnel
- air flow conditions at the beginning of the fire

The fire load can reach very high values, in particular if several vehicles are involved. It starts for individual vehicles at 5 MW (passenger vehicle) over 20 MW (bus) up to 100MW (truck). Additionally the air flow (partially affected by the mechanical ventilation) has an impact on the propagation of the hot combustible gases in the tunnel.

3. STANDARD FIRE CURVES

In order to have a uniform basis for technical calculations as well as for practical tests, the temperature gradient is defined by so-called standard fire curves.

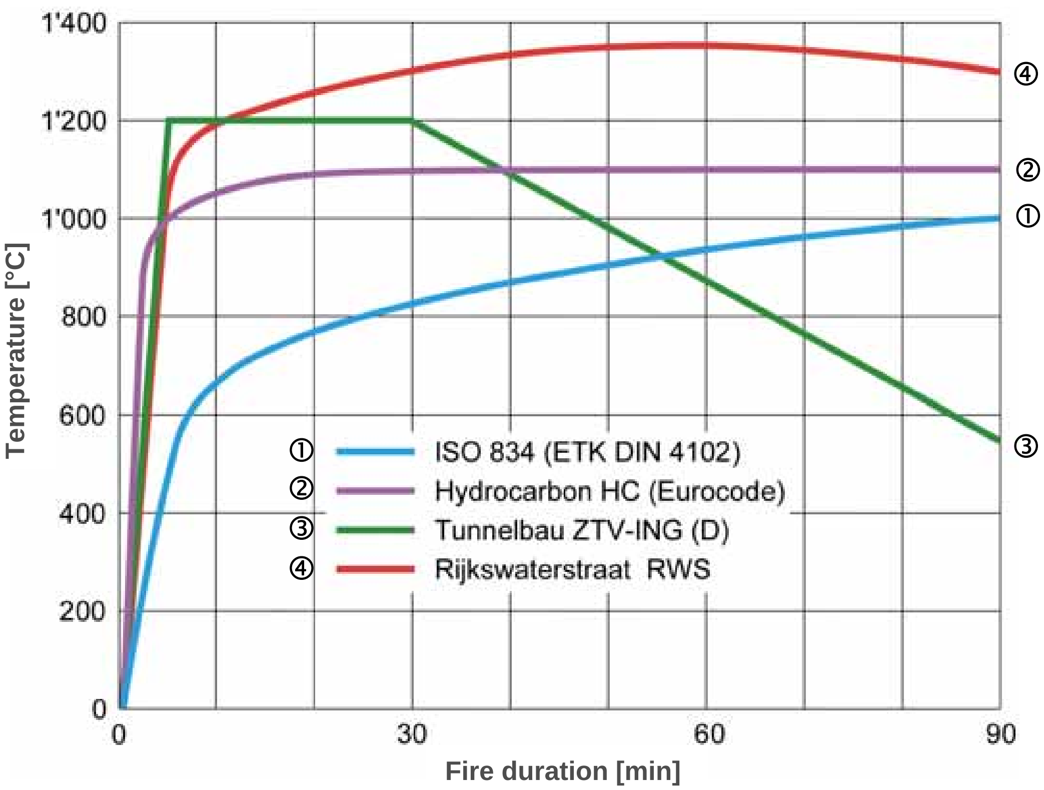

Fig. 2: Standard fire curves

The most common standard fire curve is the ISO standard 834. It forms the basis for the examination of buildings and construction units. The examination of cable systems (cables inclusive fittings and laying systems) is described in the DIN 4102-12 and led to the well-known inspection certificates like e.g. "E30" (function during 30 minutes). However, the ISO standard was developed for above ground structures - not for tunnels -, and has therefore only limited relevance for this special field. Therefore, also the curve of the Netherlands authorities (Rijkswaterstaat) is used, the so-called RWS-curve. The temperatures reach in accordance with this fire curve over 1300 degrees after approximately 50 minutes. However, this curve is internationally not recognized.

4. FIRE TESTS

Some time ago two series of fire tests in tunnels were executed. The results thereof are often consulted for the evaluation of fire risks.

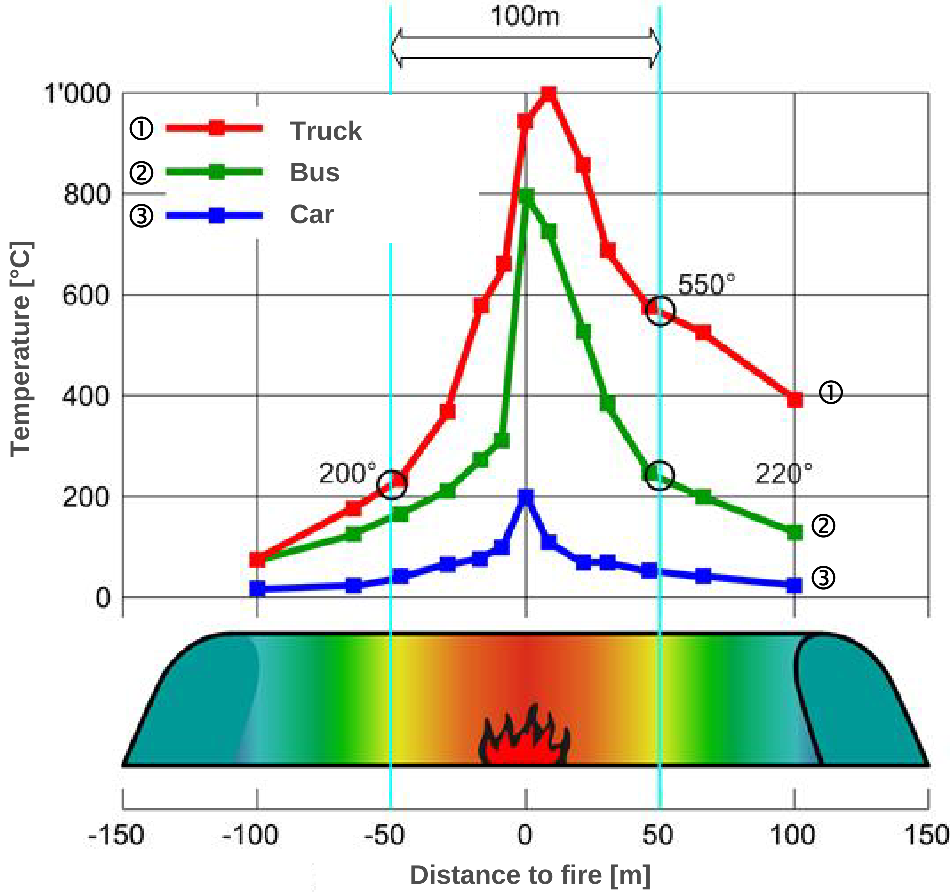

Fig. 3: Maximum temperatures at the ceiling (EUREKA-Project 499 Firetun)

The tests showed very high roof temperatures over the fire source, which were reached after a short time of only 20 minutes. However, the tunnels had a cross-section area of 30 m2 only. This corresponds with about the half of a modern road tunnel with two driving lanes.

5. MEMORIAL TEST USA 1993

The American Memorial tunnel has a 60 m2 cross section and is similar to the Swiss standard; thanks to ventilation systems also the simulation of air flows were possible.

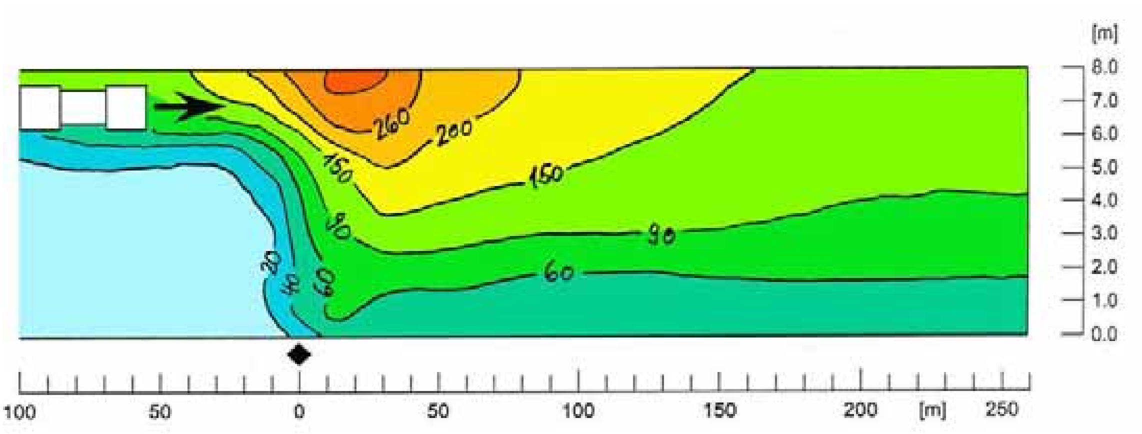

Fig. 4: Memorial Tunnel Fire Ventilation Test Program: 10 minutes after fire start, 20 MW-fire

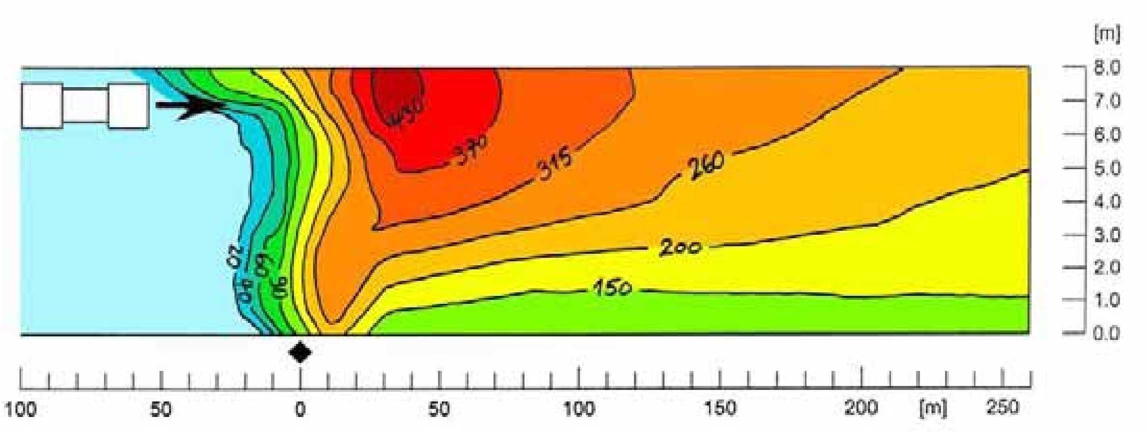

Fig. 5: Memorial Tunnel Fire Ventilation Test Program: 10 minutes after fire start, 50 MW-fire

The comparison with EUREKA shows that with attention of the flow effect and the cross section many lower temperatures are measured. Further, the higher temperatures were measured with relatively high fire loads only.

6. WHICH TEMPERATURES HAVE TO BE EXPECTED?

A critical comparison of the fire curves and the test series leads to the clear result that the temperatures reach generally neither the values of the standardized fire curves, nor those of the EUREKA tests. Very close to the Swiss conditions are the MEMORIAL tests. The Memorial tunnel tests showed clearly that with an efficient smoke exhaust close to the fire source the temperature and smoke propagation can be reduced considerably (in accordance with the new Swiss guidelines for the project engineering of road tunnels the ventilation system must offer the possibility of a local smoke exhaust). The following illustration shows the temperatures which can be expected.

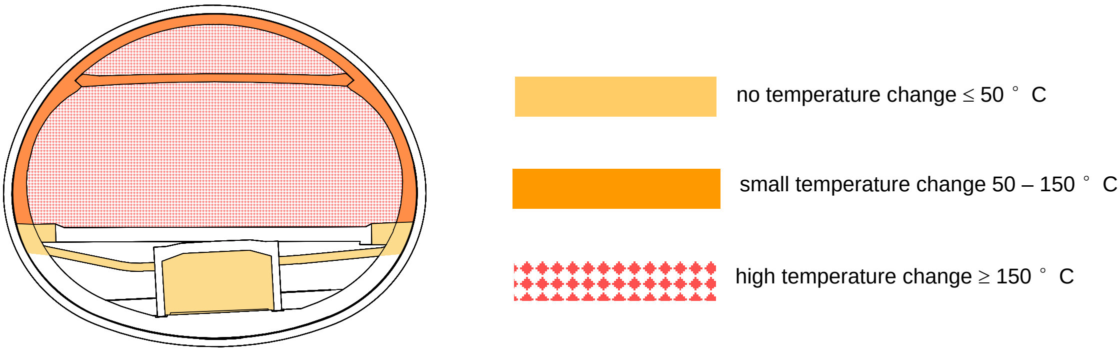

Fig. 6: Temperature zones during fire

7. CABLE UNDER FIRE: STANDARDS

For cable systems the behaviour in case of fire (passive characteristics) as well as the fire resistance (active characteristics) are important to consider. In order to define the appropriate safety level, the standardization situation has to be regarded more closely.

Properties	International	Europe
flame retardant	IEC 60332-1	EN 50265-2-1
halogen free	IEC 60754-1	EN 50267-2-1
no corrosive gases	IEC 60754-2	EN 50267-2-3
low smoke emission	IEC 61034	EN 50268
low flame propagation	IEC 60332-3-24	EN 50266-2-4

Fig. 7: Applicable standards for behaviour in case of fire

For the active characteristics of cables the following standards are relevant. They define the requirements during fire.

Properties	International	Switzerland
Circuit integrity - Fire only - Voltage (<1kV) - Data cable - Fibre optic cable	IEC 60331	--

Fig. 8: Applicable standards for circuit integrity

The system circuit integrity of cable systems is mostly the most important issue. Thus the system function can be guaranteed during fires for a certain period. In the extensive standardization work DIN 4102 the system circuit integrity is treated for electrical cable systems in the part 12. The standard comprises the entire cabling system, i.e. cable inclusive carrying system. However, it is applicable only to low-voltage cables (< 1 kV), thus not to high-voltage cables and also not to fibre optic cables. System circuit integrity classes are defined (in minutes): E30, E60, E90.
Furthermore, the requirements can be divided in three groups:

Require-ments Group	Requirements	IEC-Standard	Halogen free and flame retardant cables (FE 0)	Circuit integrity (≥ FE 5)	Circuit integrity (E30 - E90)
Function	Circuit integrity	DIN 4102-12	--	--	X
Isolation	Circuit integrity	IEC 60331-11	--	--	X
Material	flame retardant	IEC 60332-1	X	X	X
	halogen free	IEC 60754-1	X	X	X
	no corrosive gases	IEC 60754-2	X	X	X
	low smoke emission	IEC 61034	X	X	X
	low flame propagation	IEC 60332-3-24	--	X	X

Fig. 9: Requirements groups

8. RECOMMENDED CABLE SAFETY CLASS

Safety cable systems cause extra costs; it is therefore worthwhile to regard conditions:

Basic Requirements	Higher Requirements	Additional cost	
cables:		**1.5 mm^2**	**16 mm^2**
FE 0	FE 180 (E 30)	60 - 100%	30 - 50%
FE 5	FE 180 (E 30)	20 - 40%	10 - 20%
FE 180	E 30	0%	0%
Installation material			
no fire protection	E 30	60 - 100%	
Cable trough			
Material: without fire protection	E 30	60 - 100%	
Installation: without fire protection	E 30	20 - 30%	

Fig. 10: Additional cost for circuit integrity cables

In which cases are these extra costs justified? Generally, halogen-free and flame-retardant cables are mandatory for a tunnel. Also safety cables, which offer a protection against the consequences and the propagation of a fire. Safety cables with system circuit integrity are recommended if temperature and availability risk are relevant, e.g. installation cables in the tunnel cross section: Lighting, ventilation, signing. Cable systems in tubing blocks or in pipes with sufficient concrete cover (> 10 cm) usually require no system circuit integrity, since they are sufficiently protected by their specific situation. Safety relevant cables have to be considered especially, e.g. cables for uninterrupted power supplies (UPS): They should at least have the same system circuit integrity as the overall system they belong to.

9. CONCLUDING REMARK

Fire accidents in road tunnels result often in high temperatures due to the limited cross section. The temperatures indicated in the standards always describe the values maximally arising during a fire event; however, these values have to be expected only within the upper tunnel area. At the lower level the temperatures are significantly lower. Due to safety considerations, the general demand for system circuit integrity cannot be justified for cable systems in accordance with DIN 4101-12, since the risk reduction is only marginal in many cases. However, each project must separately be regarded due to the object-specific conditions.

SAFE DECISIONS THROUGH NETWORK BASED VISUALISATION

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ABSTRACT

This paper explains how the proper visualization solution can help reduce response times and make collaborative decisions in the fastest and safest manner.

To reduce response times, the key is flexibility in display solutions. For example, an operator's response time to a situation can be greatly reduced if the display system had the ability to highlight an event in larger and varied formats, mix data and video to provide proper context, and to be able to do this in an integrated and automated fashion with higher level applications through an Application Programming Interface - API.

In addition with proper displays, the end users also save operational costs on power and cooling requirements versus conventional monitor stacks. Operational costs are also reduced by the use of a unique integrated universal decoder which allows the user to save both the space and capital cost of the decoders as well as provide freedom for the user to choose other suppliers.

In helping to make better decisions, ergonomics are key. Consider trying to share with someone else what you see on your PC screen. Would it not be better if everyone can see what you see with just a simple tilt of the head? Size does matter!

These points will be graphically explained by use of the Rijkswaterstat (RWS) case study illustrating how such display systems can be used to help manage tunnels and bridges.

1. INTRODUCTION

The traditional security system displays are usually based around monitor stacks and PCs running specific sensor applications. These systems are often not integrated and rely often on human judgement and active surveillance to associate various disparate events to evaluate the actual threat. For example, if a tunnel sensor warns of fire at a specific location, it is up to the human experience to visually locate which monitor in the stack shows the associated location of the sensor, view it to verify that there is indeed a fire and then act accordingly. While this is sufficient, the implied knowledge of the correlation (sensor ID to camera ID to position of monitor in the stack), the ability to properly discern the often small images on monitor stacks, and to react in time takes much training and is not very scalable to larger systems. How many such correlations can one keep in one's head before one need to refer elsewhere (thus reducing reaction time)? Consider, if the sensor failed to register, then the only way the operator would detect the fire is if he or she would be actively scanning the monitor stacks (which is not practical when the monitors exceed 16).

Therefore, in this simple example, an integrated system where the alarm trigger can automatically bring up the proper camera at the proper size and overlay the sensor system outputs alongside the appropriate video would save much time. Further more with proper networking capabilities and size of display, this visualization system will allow others to also collaborate in making the decisions to help manage the situation. For example, a more senior operator (being able to see what the sensors and videos are showing) may be able to intervene before a junior one shuts down a tunnel due to misinterpreting a malfunctioning sensor reporting fire.

2. SAFE DECISIONS THROUGH NETWORK BASED VISUALISATION

As described in the introduction section, a flexible display system would replace the typical monitor stack – often made up of multiple CRT displays. A display system such as that offered by BARCO not only provides the required flexibility by way of mixed formats but also reduces the operational costs.

Figure 1: Control rooms from Yesterday, Today and Tomorrow

Its added size and flexibility allows it limitless scalability of multiple sources and the ability to simultaneously view them on screen. This provides the necessary ergonomics to support joint decision making.

In addition, an open universal decoder platform enables the user to distribute information to and from multiple remote locations and at the same time reduce hardware and even cable infrastructure – both increased flexibility and cost savings.

In a typical Tunnel Control Room there are many processes to monitor and manage – sensor data, traffic flow, power management, video images etc. These many and varied data types can result in extensive cabling infrastructure.

Due to the disparate information visualisation is often independent – pc's for computer data based information; specialised static Mimic displays for the road way view and separate video monitors for CCTV.

This non integrated approach relies heavily on the operator to manage these disparate systems in a far from ergonomic way.

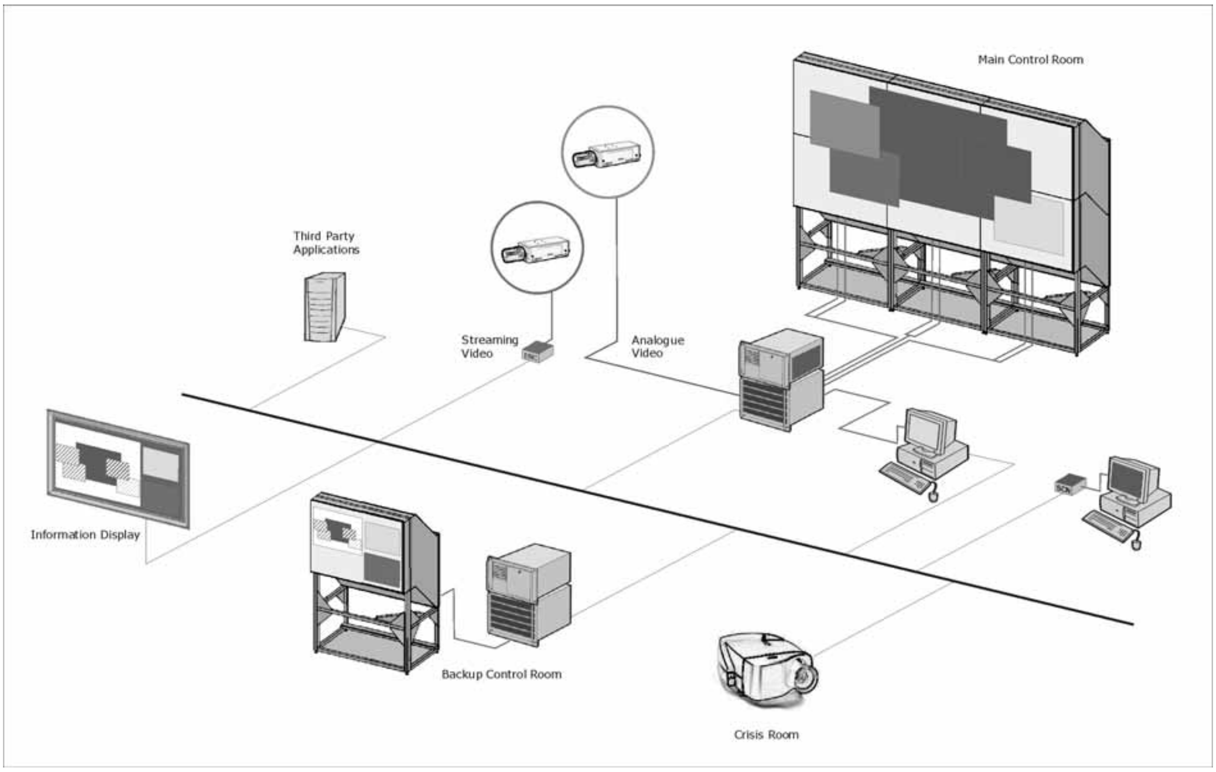

Figure 2: Modern system architecture

An excellent example of how Barco's Networked Visualisation can provide real benefits is the application in the Netherlands by the Dutch Department of Transport – RWS.

They are directly responsible for the efficient flow of traffic not just road ways but also water. The region in question includes the port of Rotterdam one of the largest and busiest ports in the world.

The requirement was to manage the highways including tunnels and also the canal bridges in the South West of the Netherlands.

Historically the process had been managed by independent control points situated at key locations, such as tunnel entrances and bridges. This though was a non integrated approach with limited scope to interact – i.e. if a swing bridge is opened and the traffic cues ideally a diversion would be provided.

The customer need was to centralise the tunnel and bridge management to save cost of running remote locations and to enable integrated and intelligent management of the complete traffic system.

The requirement was to manage 600 video feeds from all over the region. In certain locations audio links were also required. A Gigabit Ethernet Fibre Optic Ring Network provides the back bone – much of which already existed. An analogue system could be used but this would result in high dedicated cabling costs. This network enables the transmission of video, data and audio from remote locations to a central control. The use of a single central control centre required the implementation of a back up capability to ensure planning for the unexpected. This was covered by use of the existing regional control rooms.

Network Visualisation enabled the collation of the multiple source feeds back to not only the Central Control but also the regional back up centres.

By using IP streaming inputs to handle the camera feeds in multicast mode – video can be viewed at single or multiple locations simultaneously. Sensor data can be collated via the network and shared as required.

Due to the 'Cause and Effect' nature of such a system – i.e. opening one bridge can have a knock on effect to traffic in adjacent tunnels – it was key that operators had the ability to collaborate and view data from multiple sources.

Barco's Network Visualisation solution included nine display walls to manage the tunnels and three display walls to manage the bridges. Each 'Personal Wall' – essentially an operator location primarily manages a fixed zone, however the system enables multiple sources to be viewed and compared simultaneously when required so that the fastest and safest decisions can be made. Each operator has the ability to view all information on their display wall if required. The displays are large enough for supervisors to also view without having to crowd around the display. Further the intelligence of the system triggers alarms prompting the operator and where necessary automatically updating display layouts to present the most relevant information to the operator. This integrated approach was further enhanced by the use of Barco's API, enabling a fully automated solution.

Operators are now able to direct the most appropriate services to any particular incident and indeed to manage multiple incidences at once and make the fastest and safest decisions due to the ability to share all information between operators – true collaboration.

It should be noted therefore that such display systems are not only helpful for security operations but operations of the overall system in general.

3. CONCLUSION - SAFE DECISIONS THROUGH NETWORK BASED VISUALISATION

Barco’s Networked Visualisation, utilises network enabled displays to enable complete flexibility in terms of displaying mass data across multiple displays as well as multiple sites.

The use of larger high resolution displays ensures the best ergonomics for group decision making and the simultaneous view of multiple video and or data applications results in faster decision making.

Hardware accelerated decoding provides enhanced performance when displaying large quantities of video inputs with full scalability on screen.

This solution also protects the users’ investments in technologies by supporting both analogue and digital signals on the same platform. This allows for the migration from Analogue based solutions to IP seamlessly. Further integration via use of the API provides process integration to allow the users to automate and correlate alarm events to reduce their response times.

Although not specifically discussed, with networked based capabilities, the sharing of information across multiple networked control rooms allows for situational awareness for all, anytime, anywhere.

Barco’s Networked Visualization solution will reduce operator response times and helps make collaborative decisions in the fastest and safest manner.

THE IMPACT OF PRESSURE AND SUCTION WAVES ON INSTALLED COMPONENTS, WITH PARTICULAR REFERENCE TO ENCLOSURES IN RAILWAY TUNNELS

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ABSTRACT

Environmental conditions in tunnels, which under certain circumstances can be extreme, place heavy demands on installed components. Enclosures, in particular, which are intended to protect other components from these environmental influences, have to be designed to be capable of coping with these conditions. This is the only way that the safety of the installed components and ultimately the safety of the tunnel can be improved. Considering each of the requirements in isolation is inadequate, however. Optimized holistic concepts are required. The effects of the environmental conditions to enclosures are considered as well as methods of resolution.

Keywords: Enclosure design, tunnel application, environmental conditions

1. INTRODUCTION

Tunnels are currently being planned and built in many different countries, both for road and rail traffic. They are being built, firstly, because of modern-day requirements for fast connections, and, secondly, because the space is simply not available to provide ideal routes using conventional means of construction. Hence, the biggest tunnel projects are currently to be found in the Alpine countries. At the same time, however, tunnels are also being built in countries which would not normally be associated with them at first thought, such as in the Netherlands.

Longer tunnels, smaller tunnel cross-sections and higher traveling speeds place higher requirements on both the materials and components involved. To be able to work safely and reliably, the active components in particular have to be protected from all harmful environmental influences. The more effectively these components are protected from such influences, the greater safety of the tunnel.

Standard enclosures are often unable to meet these requirements.

At first consideration it might be assumed that the very fact that the components are installed in a tunnel would mean that they are well protected from all major weather influences. However, this view is deceptive, as closer scrutiny of the conditions in tunnels makes clear. Given that environmental conditions in railway tunnels are far more extreme than in any other types of tunnel, it is this type of tunnel which is the focus of this examination.

2. ENVIRONMENTAL CONDITIONS IN TUNNELS

2.1. Climatic conditions

Climatic conditions in tunnels vary considerably depending on the length and nature of the tunnel. At the portals and the entry and exit areas it can be assumed that the climatic conditions are the same as in the open air. Deep inside tunnels through rock, on the other hand, conditions can be expected to be totally different. Here the air temperature will be between 35 – 40 °C and the level of air humidity will be high. In addition, it can also be expected that mountain water and/or condensation water will be dripping from overhead. The presence of salts brought into the tunnel from outside can also lead to the formation of aggressive media, and the concentration of these salts increases over time because there is no rain to wash them away.

The following table (Table 1) provides a summary of some of the typical climatic conditions which have to be accounted for:

Table 1: Typical climate conditions

	EN 50125-3 Railway application	ETS 300019-1-4 Non-weatherprotected locations	e.g. Customer specification
Temperature	-55 … +40 °C	-45 … +45 °C	-15 … +35 °C
Temperature change	0.5°C/min up to 20°C in total	0.5°C/min	± 30 K every 30 min
Air humidity	15 - 100%	8 - 100%	30 - 100%
Salts	+	+	+
Condensation water/mountain water	+	+	+

These climatic conditions provide a good basis for corrosion of all kinds. It is precisely these environmental conditions which often make higher quality, non-corrosive materials essential. In addition to treated sheet steel and aluminium, use is also made of stainless steels such as 1.4301 (V2A) or 1.4571 (V4A).

2.2. Mechanical conditions

In addition to the climatic conditions, a whole host of mechanical influences also have to be taken into consideration (see also Table 2).

- Falling rocks
- Dust
- Iron dust
- Concrete dust
- Rail rust
- Brake abrasion
- Vibrations
- Impacts

Table 2: Typical mechanical conditions

	EN 50125-3 Railway application	ETS 300019-1-4 Non-weatherprotected locations	e.g. Customer specification
Pressure pulse	± 5 kPa @ 0.5-1 kPa/s	---	± 5 kPa
Sand	30-1000 mg/m³	300 mg/m³	++
Dust	0.5-15 mg/m³ 15-40 mg/(m²h)	5 mg/m³ 20 mg/(m²h)	++
Windpressure	1300 N/m² @ 45.6 m/s	50 m/s	1500 N/m²
Vibration	2,3 m/s^2_{eff} 5-2000 Hz	3 mm @ 2-9 Hz 10 m/s² @ 9-200 Hz	1 m/s² 40-120 Hz
Shock	20 m/s² @ 11 ms	250 m/s² @ 6 ms	---

Particular attention should be given to the dynamic fluctuations in air pressure. These should never be underestimated.
When a train travels through a tunnel it has a piston effect which generates a pressure wave ahead of it and a suction wave behind it (see Figure 1).

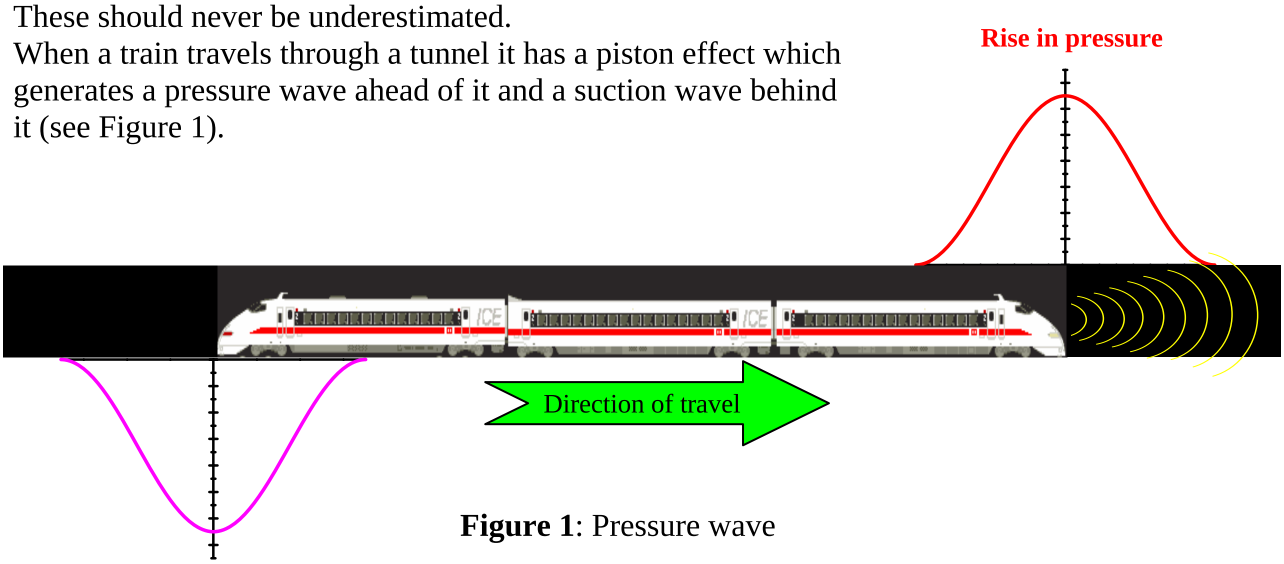

Figure 1: Pressure wave

The level of the pressure wave depends on the speed of the train v, the cross-section of the tunnel A and the type of tunnel construction (single rail or multi-rail). What is important for the design of the enclosures and the dynamic response are the times during which the pressure is at its most extreme.
For speeds of 300 km/s = 83 m/s and an enclosure width of 1m, the time for the train to pass by the enclosure is 12 ms.

In reality, however, the actual change in pressure does not happen so fast. Measurements taken in a number of tunnels have demonstrated that the change in pressure from a maximum to minimum takes a number of seconds (8 seconds in Figure 2)

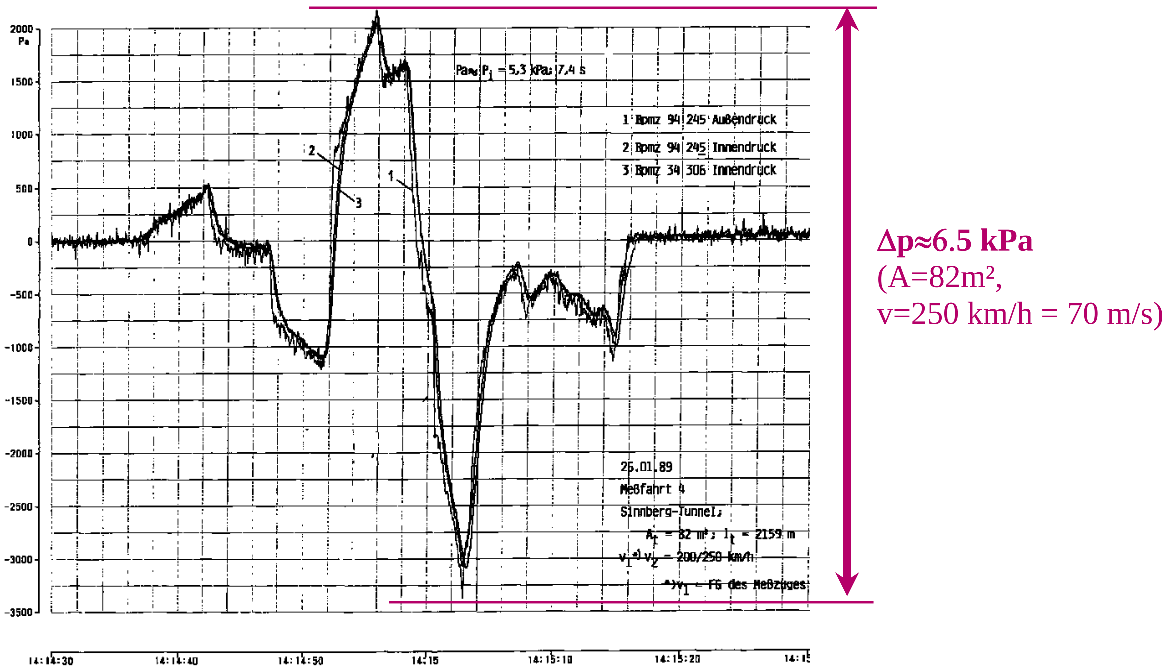

Figure 2: Measurements recorded in an ICE tunnel in 1989

Measurements recorded in the Simplon tunnel (train speed v=140 km/h, pressure drop within 12 sec.) indicated that the typical pattern of air pressure development is as shown in Figure 3.

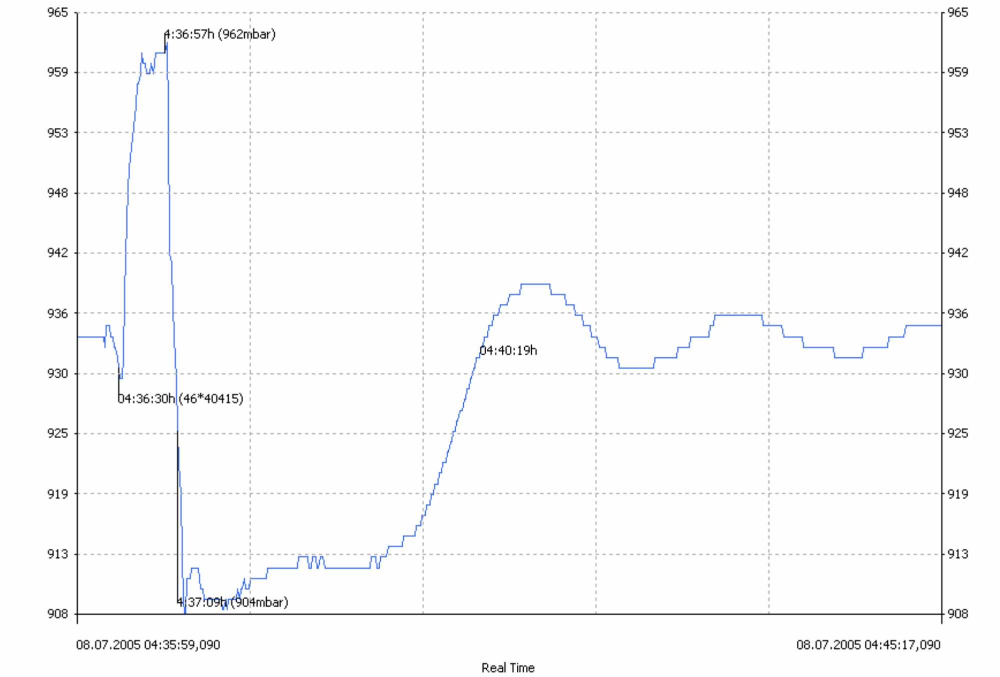

Figure 3: Measurements recorded in the Simplon tunnel (Switzerland) in July 2005

Hence, the dynamic load on the enclosures is not a momentary surge, therefore, but a rapid change in pressure.

3. REQUIREMENTS OF ENCLOSURES

3.1. Requirements in relation to environmental conditions

The environmental conditions described in section 2 lead to a range of requirements to be met by the enclosures if they are to provide adequate protection for the installed components.

Protection from dust and water:	Protection category IP65 or higher (in accordance with EN 60529)
Climate control:	Compliance with minimum or maximum temperatures for inside for the components in the enclosure (e.g. +5…+40 °C)
Resistance to pressure:	±6.5 kPa (new requirement is ±10 kPa – see section 3.2)
Service life:	25-30 years for passive components with a maintenance plan 10-12 years for active components with a maintenance plan

The special challenges here do not lie in trying to meet each of the requirements in isolation, but meeting them in combination. This means, for example, that the enclosure has to remain dust-tight even while the pressure is changing.

3.2. New requirements in terms of resistance to pressure

Smaller tunnel cross-sections and high train speeds result in more severe conditions in respect of resistance to pressure. Whereas just a few years the maximum alternating load was still considered to be no more than ±5 kPa, it has now been raised to ±6.5 kPa, with some of the latest invitations for tenders even demanding ±10 kPa.

To illustrate what this means for an enclosure, where the typical size is 800 x 2000 mm² (width x height) and the alternating pressure is 10 kPa = 10000 N/m², the door has to be able to withstand a pressure of ±16000 N (which equates to a weight of 1.6 tons!).
Are these new requirements justified or exaggerated?
It is possible to check these new requirements on an approximate basis using empirical evidence in the railway tunnels where pressure differences of ±5kPa occur.

Assumptions:

- Influence of a 10% reduction in the tunnel cross-section.

  Assuming an isentropic change of state, the laws of gases (equation (1)) can be used as the basis for estimating the increase in pressure.
  This produces a factor for the increase in pressure caused by the reduction in the cross-section as shown in equation (2):

$$\mathbf{p \cdot V^{\chi} = const.} \tag{1}$$

$$\frac{\mathbf{p_1}}{\mathbf{p_0}} = \left(\frac{\mathbf{V_0}}{\mathbf{V_1}}\right)^{\chi_{\mathbf{Air}}} = \mathbf{1{,}11^{1{,}4} = 1{,}157} \tag{2}$$

  where p is the pressure, V the Volume and χ the adiabatic exponent.

- An increase in travelling speed from 220 km/h to 300 km/h (83 m/s).

  If the dynamic pressure (equation (3)) is taken into account for the increase in the travelling speed, the resultant factor is as follows (equation (4)):

$$\mathbf{p_{dyn}} = \tfrac{1}{2} \cdot \rho \cdot \mathbf{v}^2 \tag{3}$$

$$\frac{\mathbf{p_1}}{\mathbf{p_0}} = \left(\frac{\mathbf{300\frac{km}{h}}}{\mathbf{220\frac{km}{h}}}\right)^2 = \mathbf{1{,}86} \tag{4}$$

  where p is the dynamic pressure, ρ is the density of air and v is the speed.

The new pressure load is therefore calculated as follows:

$$\mathbf{p_1} = (\mathbf{1{,}157 + 1{,}86}) \cdot \mathbf{p_0} = \mathbf{2{,}15 \cdot 5\frac{kN}{m^2} \approx 10{,}75\frac{kN}{m^2}} \tag{5}$$

Hence, the new requirements of ±10 kPa are realistic for high speed trains in tunnels with reduced cross sections.

4. ALTERNATIVE SOLUTIONS

4.1. Design approaches

A number of alternative design approaches come into consideration for ensuring that the enclosures meet the specified requirements.

A) <u>Reinforcements</u>
One alternative is to reinforce the enclosure in such a way that it would withstand the pressure loads under all circumstances while meeting all the other requirements such as protection from dust at the same time (see Figure 4). However, it has to be appreciated that the enclosure will certainly be more expensive if this approach is taken, because of the costs of the additional reinforcement.

Figure 4: Reinforcement of enclosures

B) Pressure compensation

The effort and expense of reinforcements can be eliminated if the enclosure can be provided with a means of pressure compensation. These days it is even possible to obtain pressure compensation solutions which are also dust-proof and waterproof at the same time. However, a major disadvantage of these is that they allow air humidity (water vapour) to penetrate the enclosure unhindered. The installed components must be suitable for relative humidities of up to 100%.
Humidity penetrating the enclosure then becomes critical if a cooling unit is used for the air-conditioning in the enclosure. This is because the humid air can condense in the cooling unit, leading to more humid air coming into the enclosure (even reinforcing the process because of the pressure difference) and thus even more condensation water inside the enclosure. Good solutions are necessary to get the condensated water out of the enclosure due to the requirements of section 2!

C) Seals

Where seals are used for the doors and walls there are also a number of different options available. Rubber strip seals provide a very tight seal, such that the enclosures are very tightly sealed and the differences in pressure are maintained for a long time. However, the disadvantage of these is the sealing joint, because it has to be glued once the seal has been fitted. The alternative is to use PU foam seals which can be foamed-in without a seam. These seals have properties which permit faster pressure compensation without any loss of sealing effectiveness against dust.

Figure 5: Sealing preventing dust coming into the enclosure (after 15 years tunnel application)

D) Lock systems

What is important in lock systems is that the locking points are not too far apart. For an enclosure of 2 m in height, for example, three locking points will be insufficient under pressure.

Under pressure the door can deform between the locking points, such that it is then no longer effectively sealed. In addition, a further problem with insufficient locking points is that the mechanical load on the individual locks may become too strong, meaning that failure is inevitable. The latest locking systems now also permit the top and bottom edges of the doors to be locked as well so that the door can now be secured all the way around (on the fourth edge by the hinges).

Figure 6: Locking system for three sides

E) Accessories

The aforementioned requirements also apply to all other accessories such as cooling units, cable entry elements, indicator instruments, etc., with contacts to the outside.

4.2. Verification

Once the concept has been developed the product should then be verified, ideally before completion of the design engineering phase. This is possible at an early stage with the aid of computations using finite element methods, for example. These can be used to look into both individual aspects and complete solutions. The following four illustrations (Figures 7 – 10) provide examples of calculation results. A pressure load of -10 kPa is put to the enclosure in Figure 7. The non-reinforced door will bend to the outside, displacements and forces will be to high for that door and the hinges (Figure 8).

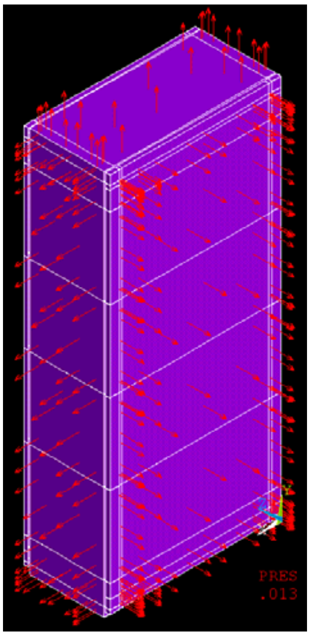

Figure 7: Pressure load

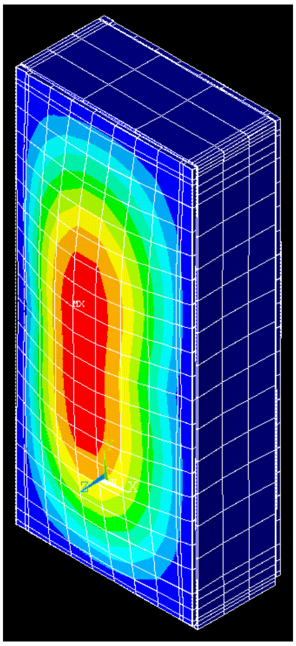

Figure 8: Displacement of a non-reinforced door

After installing a reinforcement frame onto the door (Figure 9) the result of a new calculation show smaller displacements and forces to the door (Figure 10).

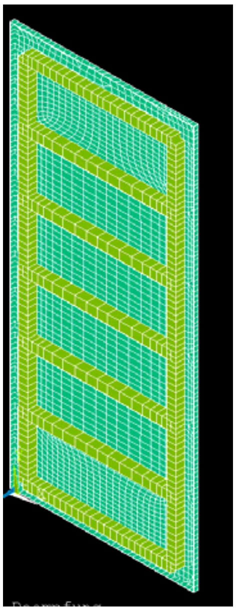

Figure 9: Reinforcement frame

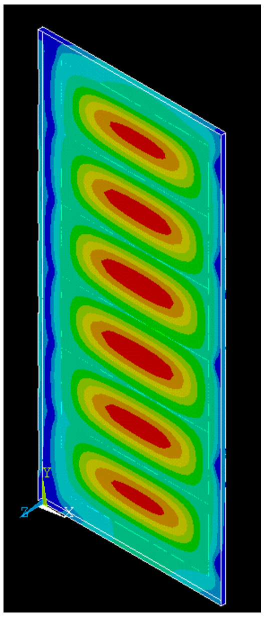

Figure 10: Deformation in a reinforced door

However, in addition to theoretical considerations and computations it is also imperative that suitable tests are performed on prototypes. One reason for this is that in many cases not all of the components of the enclosure are depicted in the theoretical models and the models themselves involve necessary simplifications.

Since special tests of this kind, such as pressure tests, are not covered by any standards, manufacturers have to rely on their own creativity to develop and carry out their own tests. The alternative is to commission a suitable institute to carry out the development work and supervision – at a cost.

Figure 11 shows a measuring arrangement for carrying out alternating pressure tests involving 200,000 pressure changes of 0-5000-0 Pa. This arrangement has a corresponding upstream control unit and data logger for performing and analysing the tests. Figure 11 also shows several pressure load cycles from this test.

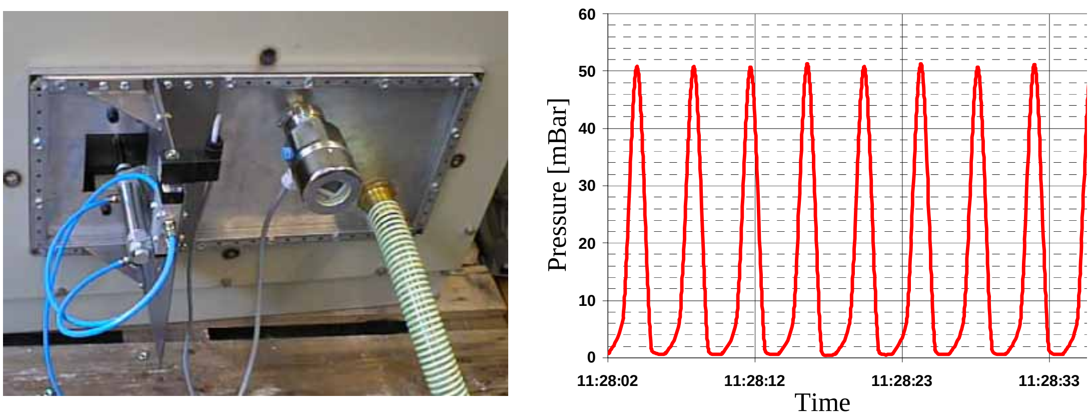

Figure 11: Pressure test set-up and measured data for +5 kPa

According to the new pressure requirements a new test has been developed to simulate pressure cycles of the enclosure with pressure differences of ±10 kPa (see Figure 12). For 200,000 cycles this test takes 25 days (24 hours).


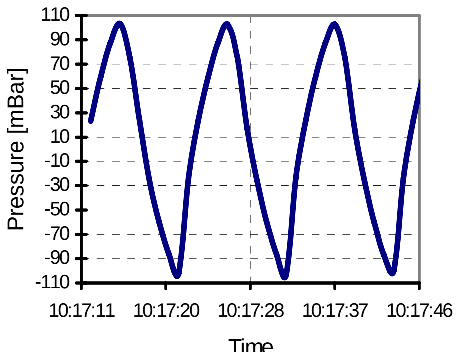

Figure 12: Pressure test and measured data for ±10 kPa

The test also permits theoretical computations to be checked, which guarantees that the computation parameters and boundary values specified in the finite element calculations are more reliable. Figure 13 shows such a check during a pressure test on a non-reinforced door. The door displacement at 20mbar underpressure is 30 mm (800 mm wide door in this instance)!

Figure 13: Displacement of a non-reinforced door at 20mbar underpressure

5. SUMMARY

It has been demonstrated that the diverse high requirements made of enclosures cannot be treated in isolation but have to be brought together in a single concept in order to achieve maximum safety and reliability for all components involved. From a rough calculation it is apparent that the latest new requirements regarding pressure differences are realistic. In addition to theoretical computations of loads, tests are absolutely imperative because not all details can be accounted for in models.
Overall there is a requirement for optimized, suitable climate control solutions and simple and efficient maintenance solutions which are specifically designed for an integrated concept. Given the diversity of components that customers want installing and the wide variations in power losses involved it will always be impossible to develop a standardized enclosure solution. Nevertheless, service-proven solutions can always be used as the initial point of reference, at least, for the development of something new.

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FIRES IN ROAD TUNNELS IN EUROPE – IMPACT ON TUNNEL SAFETY IN GERMANY

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ABSTRACT

Based on new findings from the devastating fires in tunnels in some Alpine tunnels in 1999 and 2001, the requirements to the safety of road tunnels were fundamentally revised and supplemented. The national bodies of rules and regulations were revised accordingly for this purpose and were introduced in Germany with the RABT 2003 as a standard for tunnels that were to be newly built in the area of federal highway roads. The federal states of Germany have largely taken over these regulations for state and county roads and have recommended their use for communal roads as well. On a European level, the EC directive 2004/54 (EC tunnel guideline) was decided upon by the European parliament, in which the minimum requirements on the safety for tunnels in the Trans-European Road Network (TERN) are laid down. The EC directive was converted to national law with the introduction of RABT 2006. Already in 2002 the Federal Ministry of Transport, Building and Urban Affairs concerned introduced an extensive retrofitting program for road tunnels in Germany to adapt existing tunnels to the new safety standard as quickly as possible. The main part of the retrofitting program will be finalized by 2010. On the one hand, a short term immediate program was implemented and a long term extensive retrofitting program for the more complex measures was agreed on to speed up effective measures for the increase on tunnel safety in existing road tunnels. A considerable part of the measures could already be finalized. Maintaining records of the body of rules and regulations at a high level will continue to be guaranteed by the initiation and financing of national research projects on tunnel safety on the part of the government in connection with the international research activities going on at present.

1. INTRODUCTION

After the devastating accidents caused by fire in 1999 in the Montblanc tunnel and in the Tauern tunnel as well as in 2001 in the Gotthard tunnel, the subject of tunnel safety has become particularly high priority both on a specialist as well as on a political level. There had to be acknowledgment of the fact that, in spite of modern equipment and operating systems the possibility for tunnel users to save themselves in the case of such extreme accidents - in the first few minutes after the occurrence of a fire - are not sufficient. Recovery by others also did not go too well in all cases and there is room for improvement here as well.

The consequence of this was a variety of activities on a national and international level where current experiences were exchanged and new research results were introduced. Although the safety standard in Germany is already relatively high when compared internationally, all measures were once again put to the test and possibilities for improvements were worked out. The results have meanwhile been included in the body of rules and regulations and are being continuously implemented within the framework of extensive retrofitting programs in existing tunnels as well. The financial scope of the retrofitting program is approx. 300 Mio. €, and about 25 % covers structural measures and 75% operational retrofitting measures. The retrofitting program will be largely completed by the year 2010. The requirements according to the new EC tunnel directive will be exceeded in many cases in the process, which, however can be justified, particularly with respect to the high traffic loads in German road tunnels.

2. NUMBER OF TUNNELS

The number of tunnels along the federal highway roads on the effective date of 31st December 2004 was a total of 202 tunnels with a total length of 191 km (Figure 1). The total number including the road tunnels in federal state, county and communal roads is 310 tunnels with a total tube length of 250 km. The aging pattern shows, that the number of tunnels compared to other structures in the German road network is still relatively new and has increased disproportionately in the past 15 years in particular. Thus, the number of road tunnels on federal highway roads has more than doubled between 1992 and 2004 alone. The reasons for this are, on the one hand, increased requirements to noise protection and protection of the country side that can only be realised in sections by covering the roads, as well as, on the other hand, the often cramped conditions at by-passes which increasingly require routes with tunnels.
About 53 % of road tunnels on federal highway roads are tunnels with only one tube that are operated with bidirectional traffic. There is a need for retrofitting according to requirements here, particularly in the case of longer tunnels with a high traffic load, to optimise the ventilation systems, for example and to improve the possibilities for saving yourself using additional escape routes.

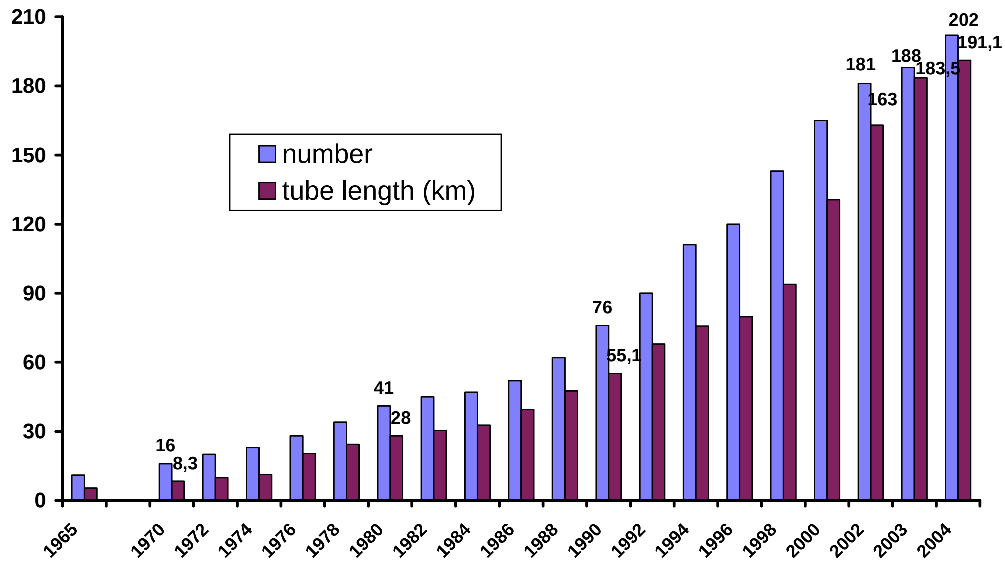

Figure 1: Number and tube length of main road tunnels in Germany

3. EC TUNNEL DIRECTIVE AND RABT

Safety requirements to road tunnels refer both to structural measures as well as to the operational fitting of the tunnel in particular. The structural requirements with respect to dimensioning, design and structural fire protection, for example, are regulated in the "Zusätzliche Technische Vertragsbedingungen und Richtlinien für Ingenieurbauten (ZTV-ING)" Part 5, tunnel construction; operational requirements with respect to ventilation and lighting, escape possibilities and safety equipment, for example, are compiled in the "Richtlinien für die Ausstattung und den Betrieb von Straßentunneln (RABT)". The usual fittings according to RABT are shown in Figure 2.

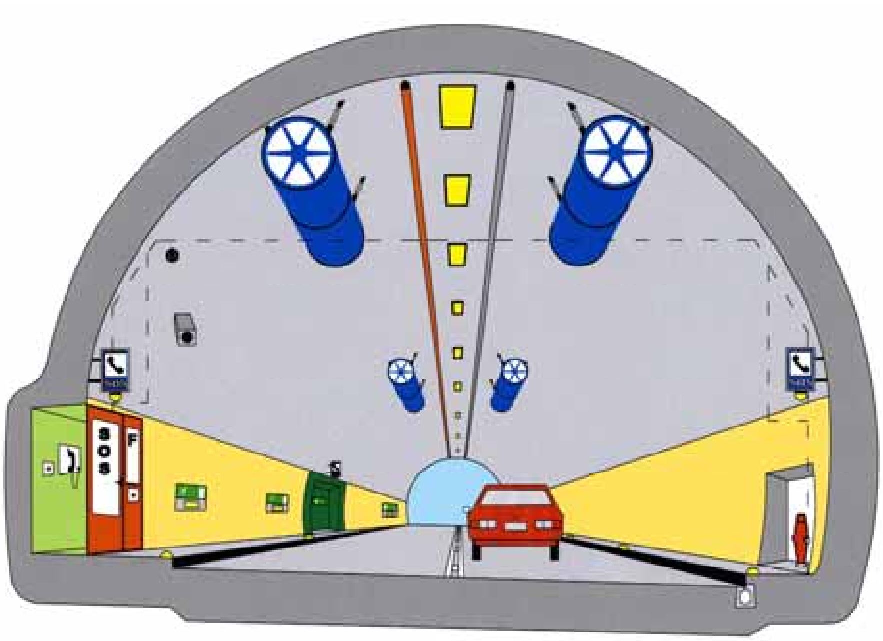

Figure 2: Equipment in road tunnels in Germany

The 2003 edition of RABT already took into account the latest findings and measures with respect to safety, which were a result of the intensive discussion amongst experts after the fires in tunnels. The level of the requirements is over and above the EC tunnel directive in many points. RABT 2003 started with the main objective of personal security, for which the operational and structural measures have to be laid down first. The extent of safety measures mainly depends on the length of the tunnel. Apart from this, the proportion of heavy traffic can be essential for individual components, for example, when determining the strength of the fire concerned.
According to the indications in the EC tunnel directive, it was to be converted to national law by May 2006. This took place in Germany by recording RABT 2003, for which, apart from minor adaptations to the safety requirements, it was mainly additions to administrative and organisational regulations as well as documentation, registration and reporting duties that were required. An important point in this case is that the requirements of the EC directive were not only converted for the German road tunnels belonging to TERN, but for all tunnels in the federal highway road area. The conversion of the EC directive is now available in an updated form as the 2006 edition of RABT.

4. MEASURES FOR SAFETY RETROFITTING

At first the road administrations of the federal states, that design, construct and operate federal highway roads within the framework of contract management for the government, were requested, to subject all tunnels to an appropriate testing to obtain as complete an overview as possible on the extent of necessary safety equipping of existing road tunnels. The RABT 2003 catalogue of requirements was important for this purpose. The necessary measures for this were differentiated according to structural and operational retrofitting. An initial cost estimate had to be given for the measures at the same time, which must be indicated more accurately later for a larger scope using corresponding design documents.

The following points had to be checked, amongst others, for a possible structural retrofitting:

- distance of emergency exits
- position of escape galleries
- position of lay-bys
- crossing of the central reserve outside each portal
- drainage system, slot gutter
- fire extinguishing line, hydrants
- water supply at the portals
- support basin for disruptive incidents
- position of intermediate ceilings
- installation of emergency cabins

The following points also had to be checked, amongst others, for a possible operational retrofitting:

- ventilation system, fire ventilation
- normal lighting, evacuation lighting
- current supply, emergency power supply
- emergency stations at the entrances/exits
- emergency cabins in the tunnel
- video monitoring system
- fire detection
- fire-fighting equipment
- radio broadcasting for emergency services
- function of loudspeaker system
- traffic engineering equipment
- road signs in front of and inside the tunnel
- escape route signs
- lane indicator system

Apart from the enquiry for the requirement for structural and operational retrofitting measures, organisational measures were also requested. This included

- the availability of alarm and evacuation plans
- execution of regular practices and
- monitoring by control centres.

When testing the required measures and the conversion that has already started at the same time in some states, it very soon became clear that the safety facilities in tunnels in particular, that are of significance for the tunnel users to be able to save themselves, must be formed in a uniform manner in all tunnels. However, since RABT 2003 did not give sufficient specifications for all points for this purpose, guidelines for a uniform appearance of the tunnels with reference to the facilities relevant to users were worked out immediately. These refer, amongst other things, to the

- designing of escape route markings
- designing of self-illuminating guide markings on emergency walkways with alternative use as escape route markings in the case of fire,
- colour coordinated design and marking of emergency exits (Figure 3) and
- colour coordination of the emergency cabins.

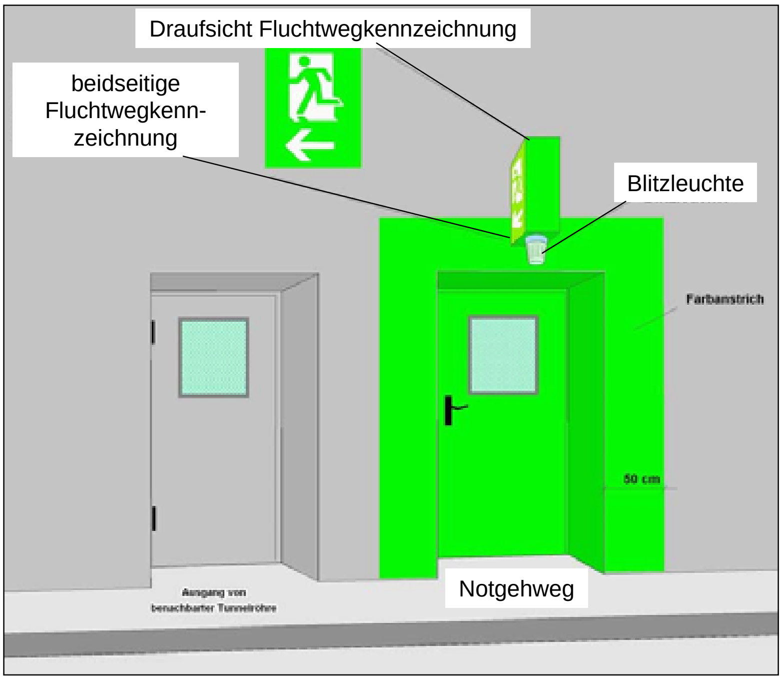

Figure 3: Design and marking of emergency exits

These uniform design guidelines have meanwhile been introduced in the area of federal highway roads and were included in RABT 2006.

5. MEASURES

An initial evaluation of the necessary measures was carried out by the Federal Highway Research Institute on behalf of the Federal Ministry for Transport, Building and Urban Affairs based on the check lists to prepare a list of priorities with a corresponding weightage. The retrofitting programs covering several years could be then be compiled from this list of priorities after agreement with the road administrations of the states.
The project specific list of measures soon showed that particularly for older tunnels, for the preparation and conversion of the measures, partly extensive experts' opinions were necessary, for which the processing would take a considerable amount of time. The financial and personal capacity of the respective road administrations also had to be considered for the majority of projects in the individual states. For this reason, two retrofitting programs were developed:
An immediate program with measures of a smaller scope, but which already contribute to a clear increase in the safety in tunnels and improve the possibilities for tunnel users to save themselves, in particular.
The actual retrofitting program with extensive measures, which partly covers an extensive modernisation of the entire tunnel equipment or includes larger structural measures that can often only be carried out with complete closing of the tunnel tube.
Immediate measures should preferably be carried out in still relatively new tunnels with fewer requirements for retrofitting or in tunnels where extensive retrofitting is only planned in a few years due the laborious preliminary investigations. The main objective is the improvement of personal security by the following measures, amongst others:

- Improvement in the recognition of technical failures, e.g. through a concentrated acquisition of traffic data connected to traffic influencing units and video technology
- More effective automatic closing of tunnels in the case of accidents through the additional installation of barriers at tunnel entrances

- Optimisation of the recognition and localisation of fires through the further development of detection systems
- Improved ventilation and measures for smoke to escape faster from the tunnel tubes
- Faster and more specific information to the tunnel users thorough flawless reception of traffic radio and improvements to loudspeaker technology
- Improvements to the escape route systems by reduction of the intervals between the emergency exits and by building additional rescue corridors.
- Clearer marking of the escape routes through uniform pictograms connected to fire emergency lighting and lane indicator systems.

A large number of immediate measures could be carried out meanwhile and numerous extensive retrofitting could be completed. With the ambitious objective of completing the main tunnel retrofitting program by the year 2010 Germany would have finished tunnel retrofitting even before the deadline given in the EC tunnel directive.

Apart from this, national research projects are being financed at present using government funds for research to clarify individual issues on measures for tunnel safety. This includes, amongst others:

- Detection of fires and accidents in road tunnels – Comparative investigations
- Experiments with fires in road tunnels – Standardisation of execution and evaluation
- Assessment of safety in road tunnels
- Design of emergency exits in road tunnels
- Fire reaction of tunnel wall coatings
- Safety of Lives in Tunnels (SOLIT) (promoted by the BMBF)

As in the case of the results of the international research projects and activities (e.g. PIARC) currently under way, the results of the above mentioned activities will also be taken into consideration when maintaining records of the relevant bodies of rules and regulations and thus guarantee a safety standard in tunnels on federal highway roads corresponding to the present state-of-the-art in future as well.

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EQUIPMENT FOR OPERATION AND SAFETY IN HIGHWAY TUNNELS

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ABSTRACT

ASFiNAG **plans, builds, maintains and levies** the Austrian motorways and freeways. Currently ASFiNAG operates a road network of around 2045 km in length. Around 140km of special toll sections are on this road network, for example the Bosruck, Gleinalm, Arlberg and Tauern tunnels. A further 290km of motorways and freeways are currently in planning and construction. Considering all tunnels on the road network 130 tunnel facilities with a total length of around 285km are currently in operation. This corresponds to the distance from Vienna to Salzburg on the A1 West-motorway. Safety in motorway and freeway tunnels takes a very high priority in the ASFiNAG group due to this high proportion of tunnels in the total road network.
The catastrophes in 1999 (Mont Blanc and Tauern tunnel) have clearly demonstrated that tunnel safety should have been raised at the time. Proposals for improving tunnel safety have been prepared by various expert commissions and incorporated into the national guidelines. The implementation of these recommendations and guidelines and of the Road Tunnel Safety Act is one of the highest aims of the ASFiNAG group for ensuring the highest possible safety standards in all motorway and freeways tunnels. Decisive improvements to the operating and safety equipment in the tunnels have been achieved in emergency installations, for example, emergency call installations, escape/emergency services routes, lay-by niches, video monitoring etc.
The résumé of recent years clearly shows that the safety level in the Austrian motorway and freeways tunnels has clearly been raised due to an ambitious ASFiNAG tunnel safety investment programme.

1. INTRODUCTION

Tunnel safety has been significantly improved due to technical developments in recent years. This development drive was triggered by the tragic events of 1999. The topic of tunnel safety has been of high significance in the population since these events.
All operating and safety installations of the road tunnels have the raising of safety levels as their aim, so that maximum safety can be ensured for the tunnel users over the longest possible period in the event of emergency (e.g. fire).

2. OVERVIEW OF THE CURRENT EQUIPMENT STANDARDS FOR NEW TUNNEL CONSTRUCTION AND MODERNISATION

Major constructional and electromechanical installations which significantly influence the safety level and behaviour of the road users are:

- Emergency call installations in the tunnel and tunnel entrance area
- Construction and equipping of the fire fighting niches for the emergency services
- Design of the escape and emergency services routes

- Marking of the escape and emergency services routes
- Installations in the tunnel traffic areas
- Construction and installations of the lay-by niches
- Video monitoring
- Design of the tunnel entrance areas

This presentation will not go into further detail on further relevant safety installations such as ventilation, illumination, radio, etc.

2.1. Emergency call installations in the tunnel and tunnel entrance area

All emergency call installations in the tunnel are positioned in walkable and illuminated niches. The emergency niches are situated at intervals of around 250m in the tunnel on the right hand side seen from the driving direction. (Intervals between the emergency call niches were reduced to 125m due to the stipulations of the EU directive and of the Road Tunnel Safety Act.) A compact standing element including raceway, illumination, an outward opening door with safety glass and a fire extinguisher section is located in the structural niches. Opening of the doors is monitored by door contacts. The walkable emergency niche is equipped with a robust handset for making emergency calls. The functionality of the emergency installation is signalled to the emergency callers through an operation and malfunction display. The two fire extinguishers can be taken from the fire extinguisher section on the outside of the emergency cabin. Removal of the fire extinguishers is contact monitored and triggers a fire alarm upon removal. Furthermore, two hand hazard signals for SOS and fire reports are provided on the outside of the emergency cabin. The marking of the emergency niches in the tunnel traffic areas is carried out using internally illuminated emergency signs.

Emergency installations in the entrance areas are housed in closed cabins; the equipment is similar to that of the niches in the tunnel.

Figure 1: Emergency call installations in the tunnel and in the entrance areas

2.2. Construction and equipment of the fire fighting niches for the emergency services

All equipment items for fire fighting in the tunnel are housed in walkable and illuminated fire fighting niches for the fire service. The fire fighting niches are situated at intervals of around 125m in the tunnel opposite the emergency call niches. The equipment of the fire fighting niches is to be agreed with the local fire services. The fire fighting niches must however be at least equipped pursuant to the specifications of the Road Construction Guidelines and Regulations with a hydrant (B+C outlet with rigid coupling), B+C adapters, coupling tool, two hand fire extinguishers, and with at least 40m hoses in the areas of lay-by niches.

Figure 2: Fire fighting niches for the emergency services

2.3. Design of the escape and emergency services routes

Escape and emergency services routes are crossways in the neighbouring tunnel tubes or connections to the outside. Various types of crossways are differentiated in Austria. There are drivable crossways at every lay-by niche at intervals of around 1000m. Furthermore, there are crossways at intervals of 500m, which are only drivable with special vehicles of the emergency services and walkable crossways.
For connections to the outside, there is also a differentiation between drivable connections and walkable connections.
All escape and emergency services routes are separated from tunnel traffic areas by gates and doors and lit with the same luminance as in the tunnel roadways. Escape route orientation and signs lights lead to these escape routes.

Figure 3: Design of the escape and emergency services routes

2.4. Marking of the escape and emergency services routes

Marking of the escape and emergency services routes is carried out using internally illuminated escape route signs and escape route orientation lights. Escape route orientations lights are mounted at intervals of 50m at 1m height over the raised shoulder. Escape route orientation signs are mounted opposite these lights at intervals of 25m.

Figure 4: Marking of the escape and emergency services routes

2.5. Installations in the tunnel traffic areas

The most important installations in the tunnel traffic areas are installations for the traffic directing and monitoring. These are traffic light signal equipment, lane marker signals, traffic signs, directing installations, video monitoring, etc. The illumination, information equipment (loudspeaker systems and tunnel radio), emergency call installations, extinguisher installations and automatic fire alarm equipment represent also important installations for increasing safety in the tunnel traffic areas.

Figure 5: Installations in the tunnel traffic areas

2.6. Equipment and installations in the lay-by niches

Lay-by niches are provided every 1000m in the tunnel. The lay-by areas are around 40m in length and 3m in width. The illumination level in the lay-by niches is clearly higher than that of the roadways, whereby these areas are clearly highlighted in the tunnel. Important operating and safety installations such as yaw/pitch/zoom cameras, wall hydrants, loudspeaker systems, fire fighting niches, emergency call niches etc. are fitted in the area of the lay-by niches. Distance indicators to the portals are provided on the tunnel walls in the lay-by niches.

Figure 6: Equipment and installations in the lay-by niches

2.7. Video monitoring

Systems for automatic video monitoring and video detection raise the safety level of a tunnel significantly due to the short detection times. The entire roadways and critical areas such as emergency niches, lay-by niches, escape /emergency services routes and portal areas are monitored. Monitoring is performed in critical areas with yaw/pitch and zoom cameras. All images from all cameras are evaluated and transmitted to the tunnel monitoring-centre.

2.8. Design of the tunnel entrance area

Measures for safe traffic direction and better information of the road users are provided in the area of the tunnel entrance areas. Measures for safe traffic routing are for example traffic direction installations, traffic lights, dynamic information signs, setup of a speed reduction funnel etc. Optimal design of and protective measures for the tunnel entrance areas significantly contribute to increasing tunnel safety.

Figure 7: Design of the tunnel entrance area

SUMMARY

The résumé of recent years clearly shows that due to an ambitious ASFiNAG tunnel safety investment programme (around €210 million in 2006) the safety level in the Austrian motorway and freeway tunnels has been clearly raised since 1999. The tendencies in tunnel safety in coming years are for example reduction of the intervals of escape and emergency services routes, retrofitting with wall hydrants, centralisation of tunnel monitoring etc. The developments in tunnel safety should however not only be limited to systems for detection, combating and minimisation of effects. Targeted information programmes and education of the road users in correct behaviour in road tunnels should definitely be performed in coming years to be able to bring about a further improvement of safety levels.

THE EUROPEAN TUNNEL TEST IN THE SCOPE OF THE EUROTAP PROJECT

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ABSTRACT

The EuroTAP project (European Tunnel Assessment Programme) is the latest of a total of eight research and network projects for tunnel safety conducted under the aegis of the European Commission. The project is being implemented in the period from 2005 to 2007, under the guidance of the ADAC and eleven other European automobile associations.
The primary objective of the project is to raise awareness amongst drivers of correct driving behaviour in tunnels, together with the awareness of tunnel operators and rescue services with regard to the status and requirements of tunnel safety.
The project comprised the implementation of 150 tunnel tests throughout Europe, providing drivers with information regarding correct behaviour and safety facilities in tunnels (leaflet, video, tunnel info sheet) together with a concluding audit containing a retrospective of nine years of tunnel tests, with developments and innovative solutions for the improvement of safety in European road tunnels.
The focal point of the article will cover the preparation and implementation of tunnel tests performed by Deutsche Montan Technologie GmbH since 1999. This will focus in particular upon the general conditions for the tunnel tests, the methodology and assessment, taking account of the European tunnel guidelines; as well as the presentation of significant findings.

Keywords: tunnel test, risk, safety, inspection, methodology

1. INTRODUCTION

Tunnels are important elements of our transportation systems. They reduce distances, represent stable connections free from the influence of seasonal and weather conditions and relieve urban areas of noise, exhaust fumes and dust.

In a united Europe the significance of passenger and freight transport on roads is increasing in importance. But what about the safety of these transportation routes, in particular in tunnels?

Following the catastrophic fire in the Mont Blanc Tunnel on 23 March 1999, this question was also posed by the ADAC. The ADAC saw the fire as a motive to inspect and assess the safety status of European road tunnels for car drivers. The tests were directed in particular at tunnels on European holiday routes with lengths of 1.5 km and above.

Test partner from the very beginning was Deutsche Montan Technologie GmbH. Together with the ADAC, a checklist was drafted in 1999, covering the most significant safety measures. This checklist was drafted on the basis of the RABT, with the status of 1994. For the purpose of the assessment the safety measures were divided up into individual categories, which were incorporated into the overall findings with a variety of different weightings. Using this formula, all 20 tunnels were assessed in 1999, regardless of their very different risk potential.

The procedure was selected in a manner that ensured collation of all relevant data and information in the course of an on-site appointment with the tunnel operator, with the tunnel and control centre inspected and individual facilities inspected. The data was subsequently evaluated and assembled in the form of a report. The draft report was submitted to the ADAC on 28 May 1999. On 29 May 1999 the next catastrophe occurred in the Tauern Tunnel, which had been tested exactly 14 days previously.

Of the 20 tunnels tested, 5 were awarded a grade of "good", 6 with "acceptable", 5 with "poor" and 3 with "very poor". The Elbtunnel in Hamburg refused to take part in the tunnel test in 1999.

The principal deficiencies were inadequate facilities for self rescue, a consequence of a lack of emergency exits and/or inadequate smoke extraction in case of fire, together with a lack of fire detection systems, long approach routes for fire services and no regular emergency drills.

The discussions conducted with the operators also indicated "weaknesses" in test methodology. In particular, no comparability of results is possible without additional consideration of the risk potential. In this manner, tunnels with a low traffic volume, such as the Felbertauern Tunnel or the Great St. Bernhard Tunnel received assessments that were too negative.

In the following years the methodology was continuously reworked and both checklist and assessment updated. This was performed primarily by integrating additional national regulations and guidelines, conducting discussions with tunnel operators and national and international expert commissions (UN ECE, PIARC, CEDR) and, of course, utilising the experience gained from the previous tests. Organisational changes arose, in particular, due to the involvement of an additional 11 automobile clubs from 10 countries and, in 2005, with the launch of the European EuroTAP project.

2. THE EUROTAP PROJECT

The EuroTAP project consists largely of four focal points. The first of these is the testing of 150 road tunnels with a minimum length of 1 km, lying primarily on the trans-European road network or significant holiday routes. The second point covers the development, drafting and marketing of a leaflet on "Safe Driving in Road Tunnels“, which is to be distributed throughout Europe with a print run of approximately 2.7 million copies. The development of 150 tunnel info sheets for the websites of automobile clubs is the third point. In this manner, in the course of holiday route planning, motorists can obtain the most significant safety information concerning the 150 tested tunnels (number of tubes, frequencies of traffic radio, speed limits and distances between lay-bys, emergency exits, emergency phones and fire extinguishers). The concluding tunnel audit is intended to provide a retrospective look at nine years of tunnel tests, as well as displaying findings and experiences gained through the implementation of the tests, along with innovative solutions for the improvement of safety in road tunnels.

Consequently, this project is directed at a variety of target groups. The focal points named are an indication that this is a European project aimed primarily at motorists themselves. A variety of media is utilised to reach a broad public, providing information both regarding test results and the correct behaviour to be followed in tunnels, as well as safety facilities. An additional target group is that of the tunnel operators: the test results and comparison at European level provide them with an overview of the safety status, with the additional benefit of using positive experience to improve the safety of their tunnels. The findings and results can also be utilised by politicians and decision makers at national and European level to standardise regulations and provide financial funding for the improvement of tunnel safety.

3. GENERAL CONDITIONS FOR THE TUNNEL TEST

The aforementioned focal points form the basis for the aims of the test. On the one hand, the purpose is to familiarise motorists with the subject of tunnel safety, on the other hand, to inform tunnel operators and politicians of the status quo with regard to safety. Consumer protection and expert information factors must therefore be considered in particular when processing results and findings. A further aspect is the comparability of findings. This begins with the drafting of a standardised, objective assessment benchmark, taking into account the requirements of a range of national regulations and the EU directive [1] together with a corresponding classification of tunnels, and continues with the illustration of the findings.

An important prerequisite for the test is the willingness of the tunnel operator to co-operate. This incorporates both the prompt and professional transfer of the respective information and data as well as the implementation of a tunnel inspection without significant or long-lasting restrictions on traffic, and without risk to the persons participating in the inspection.

Significant boundary conditions also include the timetable and budget. According to this, a time period of approximately two days is available per tunnel for the preparation, implementation and evaluation of the test. Test implementation is limited to a time window of approximately four weeks, in which multiple testers are incorporated simultaneously. Basing the methodology of the tunnel tests on the risk analysis promoted by the EU directive is not possible with regard to time or cost factors. Despite this, the procedure at least serves the approximate purpose of an inspection.

These general conditions dictate that a special procedure for collecting and assessing data must be established. The procedural method and methodology will be illustrated in more detail in the following sections.

4. PROCEDURE

Each test phase begins with the selection of the tunnel. The most significant criteria continue to be the significance for European or regional holiday traffic, together with length of tunnel, which, following the implementation of the EU directive, [1] should be at least 1 km. Suggestions from the automobile clubs are discussed and jointly agreed upon. Every year, tunnels that have already been tested are tested again in order to assess the effect of the modernisation measures.

The operators of the tested tunnels are generally approached several weeks prior to the beginning of the test, in order to determine their willingness to be tested. Following this, the operators are sent data sheets for the recording of initial relevant data, with these provided to the respective tester at the latest a number of days prior to the test. Following this, an on-site appointment is arranged by the ADAC with the tunnel operator, in which the tester makes an inspection of the tunnel. Depending on complexity and length of the tunnel, this appointment generally takes from 4 to 6 hours. The following procedure is fundamentally foreseen:

- Introduction to tunnel operator
- Discussion of the data and information provided by the operator
- Drive through the tunnel in the presence of the operator, with stops at relevant points (portals, lay-bys or emergency lane, emergency exits, ventilation station, operation building etc.) in order to collect visual impressions and conduct random inspections of safety facilities (e.g. emergency telephones, hydrants, fire extinguishers, accessibility of emergency exits and escape routes) together with the completion of the overall data sheet.
- Inspection of the tunnel control centre
- Discussion with the operator regarding safety matters and to record retrofitting and modernisation measures planned for the tunnel.
  The operator receives prior notice of which documents are to be inspected or made available during the discussion.
- During the drive through the tunnel, important safety facilities are documented photographically. In addition, photos of both tunnel portals are taken for the presentation of the findings on the internet.

5. METHODOLOGY

5.1. Basis

The assessment criteria contained in the data sheets are based on the state-of-the-art and national regulations in Europe, together with the EU directive regarding minimum requirements for the safety of tunnels in the trans-European road network [1]. These assessment criteria, along with the evaluation benchmark, are examined and updated on an annual basis. At the present time, the regulations covered are largely those of Germany [2], Austria [3-6], France [7], Great Britain [8] and Switzerland [9-12].

5.2. Risk potential

In the ADAC tunnel test the assessment of the risk potential is made in both qualitative and quantitative form, building upon the experience gathered in the previous tunnel tests, together with further national approaches to the classification of tunnels. In this, the following parameters are allocated different weightings:

- Traffic performance per year
  (derived from traffic volume and length of tunnel) — 0 to 8 risk points
- Traffic performance of HGV per day and tunnel tube — 0 to 8 risk points
- Type of traffic (unidirectional or bidirectional traffic) — 1 or 8 risk points
- Traffic volume (vehicles per day and traffic lane) — 0 to 5 risk points
- Transport of dangerous goods — 0 to 5 risk points
- Maximum longitudinal slope — 0 to 3 risk points
- Additional hazards, such as gateways,
  crossings in the tunnel or downstream areas,
  long stretches of uphill and downhill gradients prior to the tunnel
  together with the possibility of flooding of the tunnel — 0 to 3 risk points

The risk points of the stated parameters are added together and evaluated as follows:

Very low risk	1...9 risk points
Low risk	10...14 risk points
Medium risk	15...21 risk points
High risk	22...28 risk points
Very high risk	more than 28 risk points

In the overall evaluation the tunnels receive a "bonus", graduated according to risk potential. I.e., tunnels with medium or low risk potential do not need to meet the same safety requirements (safety potential) as tunnels with a high risk potential. This is realised via the so-called risk rating factor.
This risk contemplation is based upon the following considerations:

- With increasing traffic performance there is a rise in the frequency of accidents and fire incidents. This can be confirmed in particular via the evaluation of the accident statistics of the tunnels inspected to date.
- With increasing HGV share or number of HGVs the likelihood of a significant fire increases. Combined with the misconduct of tunnel users or incorrect decisions on the part of tunnel safety staff, the consequence may be a major catastrophe (see Mont Blanc Tunnel, Tauern Tunnel and Gotthard Tunnel).
- The longitudinal gradient of the tunnel influences smoke diffusion in the tunnel. The greater the longitudinal gradient, the stronger the thermal buoyancy of the fumes and the larger the smoke diffusion zone, in particular until the ventilation becomes effective. In addition, longer stretches with a strong longitudinal gradient may result in overheating of brakes

and engines, in particular for HGVs, thus increasing the likelihood of fire. The influence of the longitudinal gradient on the regularity of breakdowns and accidents has been proven in corresponding investigations [13].

- Type of traffic (unidirectional or bidirectional) and traffic status (slow moving traffic/ congestion in the tunnel, daily or seldom) have an effect on the escape and rescue situation, together with the choice of ventilation system. With unidirectional traffic and without congestion in the entire tunnel, vehicles behind the fire site can leave the tunnel safely and people located in front of the fire site may be protected via smoke extraction in the direction of traffic.
  In the case of bidirectional traffic or congested unidirectional traffic, vehicles may be located both sides of the fire site and cannot easily leave the tunnel. Here there are increased requirements placed upon ventilation systems (suitable smoke extraction) and escape route planning.
  In addition, with bidirectional traffic the risk of severe accidents (e.g. head-on collisions) is increased, as occurred in 2001, in particular in the Gleinalm- und Amberg-Tunnel in Austria.
- The involvement of a dangerous goods transport in a fire incident may lead to a catastrophe due to the high fire load and the creation of a highly toxic atmosphere (see Caldecott-Tunnel, California 1982, with seven fatalities). The unlimited transportation of dangerous goods and high number of HGVs increases the likelihood of a large-scale fire (catastrophe).

5.3. Safety potential

During the tunnel test points are issued for the safety potential of a tunnel, graded according to the significance of individual measures (total number of points = 100 %), with the points divided into the following eight categories as follows:

Tunnel system	14.0 %
Lighting and power supply	7.6 %
Traffic and traffic control	15.9 %
Communication	11.0 %
Escape and rescue routes	13.4 %
Fire protection	18.6 %
Ventilation	11.6 %
Emergency management	7.9 %

Safety potential is consequently the sum of the evaluations of the individual measures. In each category approximately 15 to 30 individual measures are recorded and evaluated. The maximum number of possible points for each measure varies, ranging from 5 points for the tunnel sign at the portal to 60 points for the distance of emergency exits.
Physical dimensions such as width, distance, volume or time are evaluate in numeric form. There is an interpolation between an upper and a lower threshold. The upper threshold is generally derived from the strictest requirements of national standards. The lower threshold is either specified to incorporate the requirements of the EU directive or on the basis of an engineering assessment. Where the upper threshold is met, the respective maximum number of points is allocated. No points are allocated for the lowest threshold. For example, with the distance between lay-bys the upper threshold is reached at 600 m, assessed at 40 points, the lower threshold is specified at 1400 m, taking into account the requirement of 1000 m as per the EU directive [1]. A tunnel with a distance between lay-bys of 800 m would consequently be awarded 30 points.

Further criteria are evaluated by means of a yes-no decision. I.e., where the criteria is met (Yes) the maximum number of points are awarded, where the criteria is not met, (No) no points are awarded.

Evaluation also takes into consideration the fact that the safety measures of the individual categories complement each other, partially compensate each other or may be more or less autonomous of one another. In order for the existing connection between safety measures to be adequately assessed, in Table 1 the eight categories are allocated to the four safety pillars Prevention, Detection, Self-rescue and mitigation.

Table 1: Allocation of categories to the safety pillars

Category	Prevention	Detection	Self-rescue	Mitigation
Tunnel system	X			
Lighting and power supply	X			
Traffic and traffic control	X	X		X
Communication		O	O	X
Escape and rescue routes			X	O
Fire protection	O	X		X
Ventilation	O		X	
Emergency management	O			X

The symbol "X“ characterises significant criteria and the symbol "O“ subordinated criteria.

For the preventive measures a relatively low combination of individual categories is seen. For example, there is a connection between the brightness of the tunnel walls and/or road surface and the lighting level, or between the lane width and the permissible speed.
The connection of the measures of detection and control of events is primarily seen as a logical or inevitable chain, beginning with various means of detection of events and the automatic activation of safety systems, as well as enabling adequate monitoring, control and information via a control centre and securing the incorporation of emergency services (fire brigade, rescue service, police etc.).
The strongest connection exists within and between the categories of escape and rescue routes and ventilation. A particular importance here is held by the traffic status (bidirectional traffic and frequency of congestion) for the selection of a ventilation system, the control and monitoring of smoke removal and the allocation of emergency exits.
The connections illustrated have an influence on the overall results of a tunnel via the so-called K.O. criteria. The background to these observations is the fact that specific deficits cannot be compensated for by random other measures, e.g. the lack of emergency exits cannot be balanced out by good lighting or a stable power supply. A tunnel with a positive assessment should indicate positive evaluations in all eight categories, where possible, or at the least no "very poor" result. The occurrence of a "very poor“ result in one or more categories is the basis of the K.O. criteria.

5.4. Calculation of the overall result

The value resulting from the addition of the safety potential of the individual categories initially represents a reference value for safety. In addition, the overall result also takes account of risk potential and the risk rating factor. The risk rating factor varies between 0.6 (for one risk point) and 1.0 (from 29 risk points) (c.f. Figure 1).
The overall evaluation for each tunnel is calculated on the following basis:

Result (basis value) = safety potential / risk rating factor

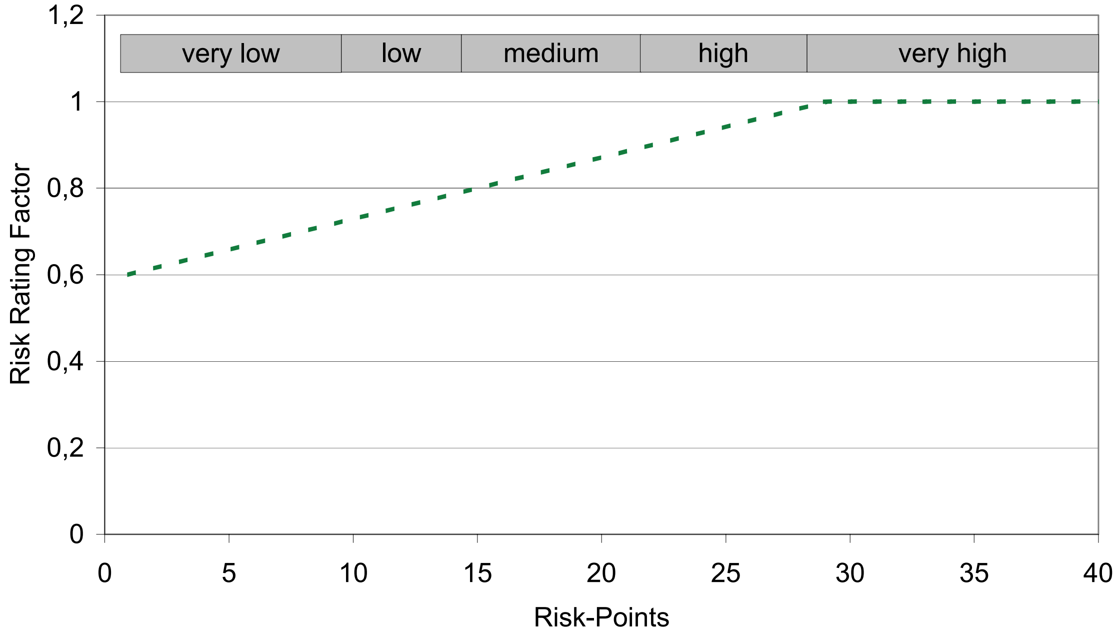


Figure 1: Evaluation of risk rating factor

In this manner, tunnels with fewer than 29 risk points receive a bonus, graduated according to the existing risk potential. For example, tunnels with a medium risk potential of 15 risk points receive a bonus of 20 % or with 21 risk points a bonus of only approximately 13 %.
The following benchmark is used as a basis for the grading of the result:

"very good"	≥ 90 %
"good"	≥ 80 %
"acceptable"	≥ 70 %
"poor"	≥ 60 %
"very poor"	< 60 %

In this the results "very good", "good" and "acceptable" represent positive assessments and the results "poor" and "very poor" negative assessments.

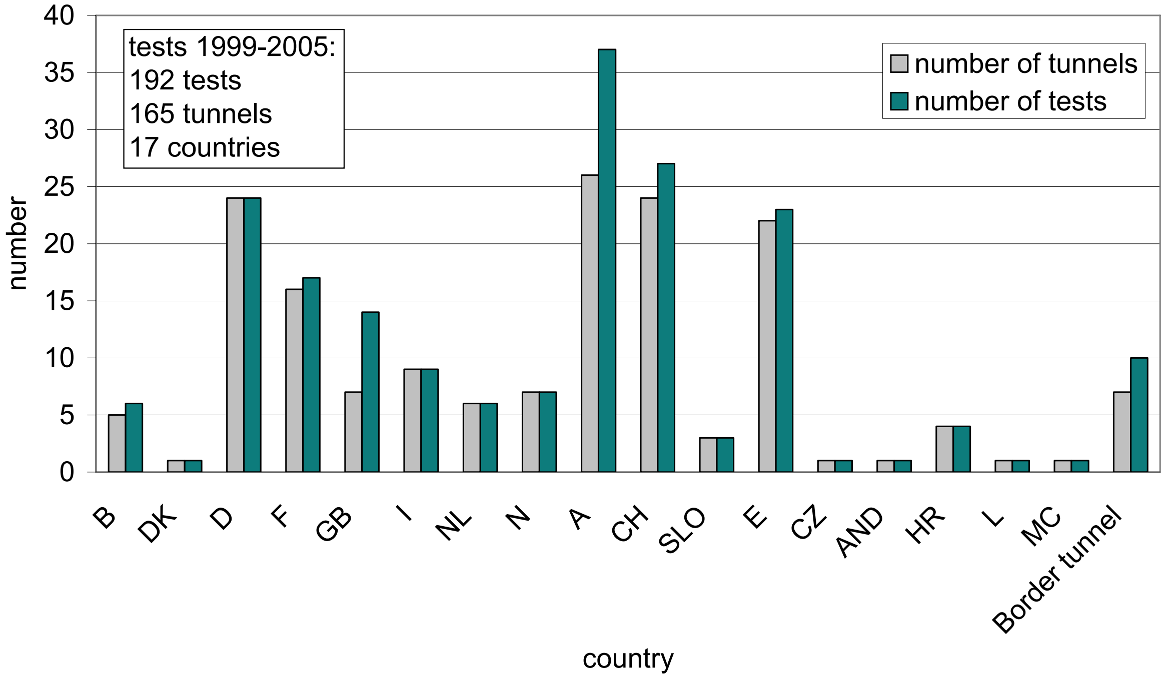
Example for the calculation of the basic result:
Safety potential = 67.5 %
Medium risk potential with 18 points → risk rating factor = 0.843
Result (base value) = 67.5 % / 0.843 = 80.1 % → rated "good"

A correction of the result in the form of a "downgrading" should be made following a very poor rating of one or more categories. In the evaluation of the K.O. criteria the different weightings of the individual categories, degree of connection of categories (allocation to the four safety pillars) and the degree of "non-fulfilment" of the category must be taken into consideration. The degree of connection is only significant where more than one category is rated as "very poor" and where these categories are allocated to one or different safety pillars. With regard to the degree of "non-fulfilment" a category should be differentiated between tunnels that scarcely meet any parameters in this category - consequently receiving 0 or only very few % points - and tunnels that fulfil a number of parameters but nonetheless, for example with 59 %, still achieve only a "very poor" result.

6. RESULTS

6.1. Statistical evaluation

In the years 1999 to 2005 a total of 192 tests were conducted in 165 tunnels. The distribution of the tests over the 17 participating countries can be seen in Figure 2. Seven border tunnels were also tested.



The length of the tunnels inspected was between 0.7 km and 24.5 km. The daily traffic volume was a minimum of 350 vehicles per day and a maximum of approximately 220000 vehicles per day. Traffic performances of 0.9 to 150 million vehicle-kilometre were calculated. The percentage of HGV stood at between 0 and 60 %. 56 tunnels with bidirectional traffic and 109 tunnels with unidirectional traffic were tested. The oldest tunnel inspected entered into service in 1897.

As per the risk classification specified in section 5.2, only 2 tunnels have to date been awarded "very high“, 47 tunnels "high“, 87 tunnels "medium“, 28 tunnels "low“ and one tunnel a "very low“ risk potential.

With regard to the results, 35 tunnels were rated "very good“, 50 tunnels "good“, 56 tunnels "acceptable“, 29 tunnels "poor“ and 22 tunnels "very poor“. However, these results fail to take account of altered rating benchmarks and criteria.

6.2. National differences and common deficiencies

In addition to "age-related" differences, the inspected tunnels also indicate significant national differences in safety concepts. The differences recorded in the intervals of safety facilities are contained in Table 2.

Table 2: Intervals between safety facilities in the inspected tunnels

Country	Lay-bys	Emergency exits	Emergency phones	Fire extin-guishers	Hydrants
Austria	400...1200 m	100...8300 m	212...250 m	106...250 m	100...365 m
Belgium	250...600 m	200...250 m	50...175 m	50 m	50 m
Switzerland	600...1500 m	200...3000	125...250 m	125...250 m	50...180 m
Germany	600...1100 m	60...1000 m	75...600 m	60...180 m	80...300 m
Spain	600...1200 m	200...4000 m	100...350 m	25...350 m	50...130 m
France	600...1500 m	200...1500 m	150...300 m	150...300 m	100...300 m
Great Britain	1100 m	250...1500 m	50 m	50 m	50 m
Italy	600...1140	400...800 m	300...1140m	50...1140 m	50...75 m
Norway	300...500 m	300 m	100...500 m	50...250 m	300 m
Netherlands	-	50...200 m	30...90 m	30...90 m	30...90 m

If preventive measures are taken into account, Austria and Croatia, in particular, still have single-tube motorway tunnels, whereby second tubes are either planned or under construction for numerous tunnels. In Switzerland, France, Italy and The Netherlands, in particular, numerous tunnels are not equipped with lay-bys or emergency lanes. All tunnels have end-to-end lighting systems with adaptation lighting in the entrance area. Only a few, older tunnels had a poor level of lighting. Surveillance from a permanently-manned point (tunnel control centre or other) did not exist in a number of Italian tunnels. Video control systems are often not evident in Italy and Norway, but also in older tunnels in Germany, Great Britain and Switzerland.

Differences are also present with regard to the detection of incidents and the information and warning of tunnel users. Automatic fire detection systems are often lacking in tunnels in France, Norway, Spain, Italy, Great Britain and The Netherlands. This deficit is partially compensated, at least in France, Norway, Spain and The Netherlands by a video control system with automatic incident detection. Possibilities to communicate via traffic radio and loudspeaker are commonly poor in Spain and Italy, but also in older tunnels in Germany, France and Great Britain.

Mitigation measures often indicate a lack of emergency and rescue operation plans in Italy, as well as in older German tunnels. Deficits in the regular staging of emergency drills are commonly found in tunnels in Spain, Italy, Great Britain and Switzerland. Fire fighting water supply is often lacking in Italian, Spanish and Norwegian tunnels.

Self-rescue measures are often inadequate in single-tube tunnels due to a lack of emergency exits. This is at least partially compensated by effective ventilation systems with smoke extraction via remote controlled flaps. With twin-tubed tunnels in Italy existing cross cuts are often not indicated as emergency exits or are situated at intervals that are too large, a number of tunnels lack a mechanical ventilation system.

7. OUTLOOK

In the years 2006 and 2007 the tunnel test is to be continued with the inspection of a further 100 tunnels. In 2007 the tunnel audit will conclude the EuroTAP project.

It is also foreseen that the methodology of the tunnel test will be used as a comparison for the results of risk analyses. For this purpose, a number of tunnels with characteristics or results as varied as possible will be selected.

In numerous countries, the coming years will see the implementation of a number of modernisation projects for existing tunnel facilities. Inspections of tunnels that have not yet been tested, or retests of tunnels previously tested are planned to be continued beyond 2007, with the goal of both providing evidence of a satisfactory level of safety, as well as delivering information to the users of tunnels.

LITERATURE:

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3 RVS 9.281 Projektierungsrichtlinien, Betriebs- und Sicherheitseinrichtungen, Bauliche Anlagen, 2002 (Österreich)

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13 Road safety in tunnels. PIARC Committee on Road Tunnels, ref. 05.04.B, 1995

COMPARATIVE ANALYSIS OF ROAD SAFETY IN TUNNELS

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ABSTRACT

The probability of an accident 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 severity of injuries sustained is significantly higher than on open stretches of motorways. In a tunnel the risk of being killed in a traffic accident is twice as high as on open stretches of motorways. Traffic safety is significantly higher in tunnels with uni-directional traffic than in tunnels with bi-directional traffic. In tunnels with bi-directional traffic the probability of being killed in a traffic accident is 2.3 times as high as in tunnels with uni-directional traffic. Both in tunnels with bi-directional traffic and in tunnels with uni-directional 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, uni-directional, bi-directional

1. INTRODUCTION

In recent years, a number of spectacular traffic accidents occurred in tunnels, which triggered debates about the safety of road tunnels. Every year, an average of 88 accidents in motorway and expressway tunnels occurs in Austria which causes an average of 13 fatalities, 37 severe injuries and 108 minor injuries. The macroeconomic costs amount to a total of EUR 13 million. The study "Comparative Analysis of Safety in Tunnels" of the Austrian Road Safety Board by order of the Federal Ministry of Transport, Innovation and Technology (Robatsch K., Nussbaumer C., 2005) explores the traffic safety of road tunnels on motorways and expressways compared with safety on other types of roads and also compares traffic safety in tunnels carrying bi-directional traffic with safety in tunnels with unidirectional traffic.

The first part of the study represents a continuation of the study „Tunnels with bi-directional and uni-directional traffic" (Robatsch, Nussbaumer, 2004). This study dealing with accidents occurring in Austrian tunnels between the years 1999 and 2001 is now completed by the present study dealing with accidents occurring in 2002 and 2003. In the second part accidents in tunnels are evaluated by point of origin, cause and fault. Based on the results of this study, recommendations are made on measures aimed at raising safety in road tunnels.

2. SAFETY IN TUNNELS VERSUS SAFETY ON OTHER TYPES OF ROADS

A variety of relative accident rates and the distance travelled in all of the tunnels studied are compared with the corresponding figures for motorways, expressways and federal roads on open sections.

In tunnels, the accident rate and the casualty rate are significantly lower than on motorways, expressways, and federal roads. A comparison of accident cost rates shows tunnels ahead of motorways, but behind expressways and federal roads.

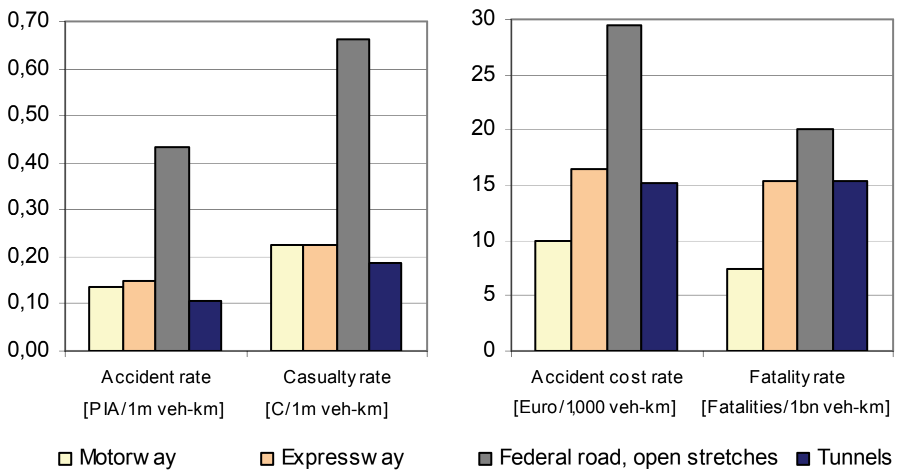

Figure 1: Relative accident rates for tunnels and other types of roads (1999-2003)

The probability of an accident occurring and the probability of being injured or killed is lower in tunnels than on motorways and expressways. However, the risk of being killed in a traffic accident is twice as high in tunnels as on motorways.

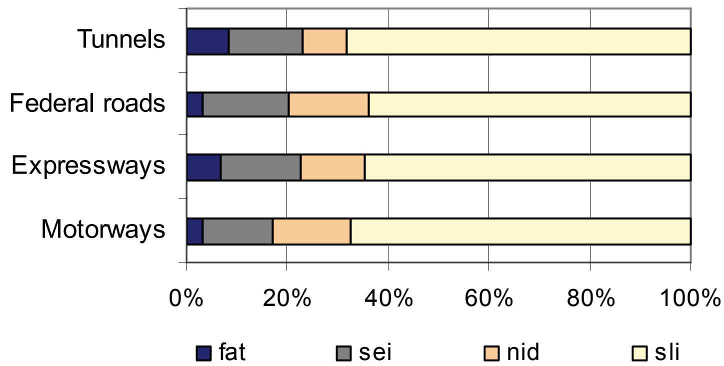

Figure 2: Severity[1] of casualties in tunnels versus other types of roads (1999-2003)

In tunnels, the severity of casualties is significantly higher than on motorways, expressways and federal roads. While 3.3% of those injured on motorways die, the fatality rate in tunnels is substantially higher at 8.2%. The number of persons killed relative to all casualties is by far the highest in tunnels.

3. SAFETY IN TUNNELS WITH UNI- AND BI-DIRECTIONAL TRAFFIC

This chapter compares accident rates occurring in the studied tunnels with unidirectional and bi-directional traffic on motorways and expressways. The length of a tunnel has a very substantial influence on relative accident rates. Particularly tunnels of less than one kilometre length have very high accident rates. As the share of short tunnels varies greatly, a comparison of safety is not possible. 71% of all tunnels with unidirectional traffic (78) and 10% of all tunnels with bi-directional traffic (2) are shorter than one kilometre. The question of whether tunnels with bi-directional traffic or tunnels with unidirectional traffic are safer arisen, only with regard to longer tunnels, as short tunnels are usually built as twin tube tunnels. For these and for statistical reasons it seems meaningful to compare only tunnels of a length of one kilometre and more.

[1] Fat = fatalities, sei = severely injured, nid = severity of injury not identifiable, sli = slightly injured.

Table 1: Number, length and traffic intensity of tunnels of more than one kilometre length with bi-directional and unidirectional traffic (status 2003)

	Tunnels with bi-directional traffic	Tunnels with unidirectional traffic
Number of tunnels studied	18	32
Total length [km]	86,214	64,307
Average length [km]	4,790	2,010
Traffic intensity [ADT]	14.569	12.154

In the calculations below, 18 tunnels with bi-directional traffic are compared with 32 tunnels carrying unidirectional traffic. On average, tunnels with bi-directional traffic that are longer than one kilometre are 2.4 times as long as tunnels with unidirectional traffic. At 14,569 vehicles per day, the average traffic intensity in tunnels with bi-directional traffic is slightly higher than in tunnels with uni-directional traffic, which carry 12,154 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. In addition to the absolute accident figures and the relative accident rates it is helpful to also include the severity of casualties. The calculations below comprise accident rates, accident cost rates, casualty rates and fatality rates for accidents in tunnels with bi-directional and unidirectional traffic.

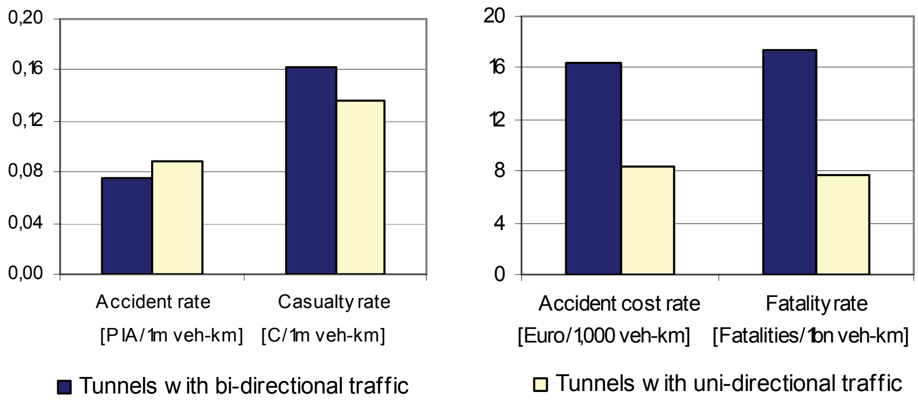

Figure 3: Relative accident rate for tunnels of over 1 kilometre length with bi-directional traffic and tunnels with unidirectional traffic (1999-2003)

In tunnels with bi-directional traffic, the accident rate - at 0.076 accidents per one million vehicle-kilometres - is slightly higher than in tunnels with uni-directional traffic, where the corresponding rate is 0.088 accidents per one million vehicle-kilometres.

The probability of being injured or killed in an accident is 19% higher in tunnels with bi-directional traffic than in tunnels with uni-directional traffic. While the casualty rate in tunnels with bi-directional traffic is 0.163 casualties per 1 million vehicle-kilometres, the corresponding rate in tunnels with uni-directional traffic is 0.137 casualties per 1 million vehicle-kilometres. In tunnels with bi-directional traffic, the accident cost rate and the fatality rate are respectively twice and 2.3 times as high as in tunnels with uni-directional traffic. While in tunnels with bi-directional traffic, 17.3 traffic fatalities occur per one billion vehicle-kilometres, the corresponding figure for tunnels with uni-directional traffic is 7.6 persons killed per one billion vehicle-kilometres. The accident cost rate in tunnels with bi-directional traffic is EUR 16.4 per 1,000 vehicle-kilometres and in tunnels with uni-directional traffic EUR 8.4 per 1,000 vehicle-kilometres.

4. SPECIAL ANALYSIS OF SAFETY IN TUNNELS

In this chapter accidents with personal injury in tunnels are analysed by the parameters point of origin, fault and cause.

As several aspects regarding the occurrence of accidents, e.g. causes and faults, are not considered in the accident statistics released by the authorities, evaluations performed by the police were included in the accident statistics 1999-2003. The tabulation below is meant as a supplement to the accident statistics of the authorities, which are analysed in the Chapter before. On the basis of the new results, measures aimed at raising safety in road tunnels are formulated in the following chapter.

4.1. Accident rate and point of origin of the accident

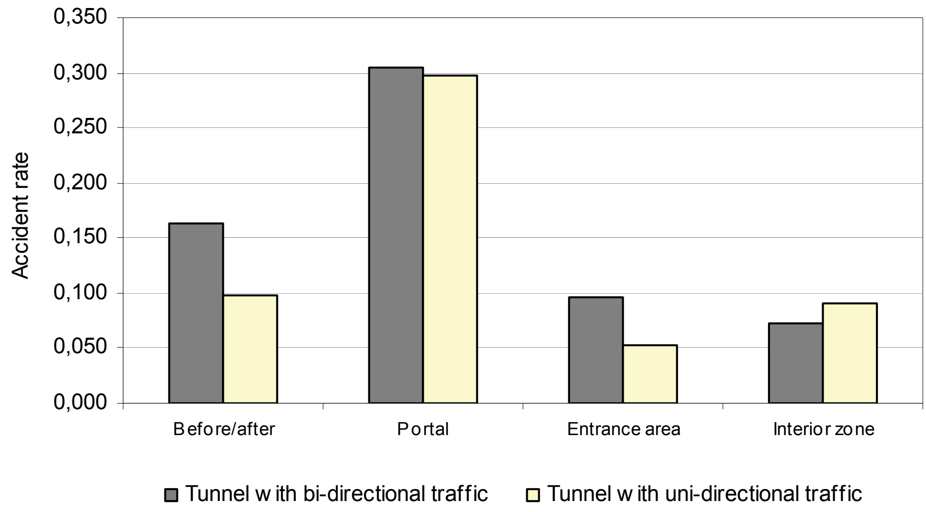

Figure 4: Personal injury accident rate [PIA/1 million vehicle-kilometres] in tunnels with bi-directional traffic and uni-directional traffic by point of origin of the accident (1999-2003)

In tunnels with bi-directional traffic and uni-directional traffic the highest accident rates are reported in the portal area. What is striking is that in both types of tunnels the accident rate is higher in the areas before the entrance and after the exit than in the interior zone of the tunnel. The by far highest accident rate in tunnels with uni-directional traffic is found in the portal area.

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 and after the exit is very high due to the transition from uni-directional traffic to bi-directional traffic. The by far highest rate of accidents occurring in the portal area is found in tunnels with uni-directional traffic.

4.2. Accident type and point of origin of the accident

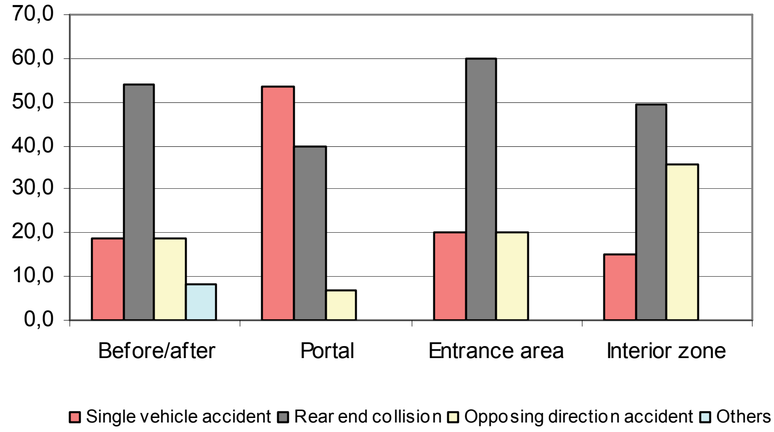

Figure 5: Types of accidents in tunnels with bi-directional traffic by point of origin of the accident, in percent (1999-2003)

In tunnels with bi-directional traffic the most frequent accident type in all areas, excepting the portal area, is rear-end collisions. The highest proportion of rear-end collisions is reported in the entrance area (60%), 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, whereas in the interior zone of the tunnel, besides rear-end collisions, mainly frontal collisions occur. 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 cause is speeding.

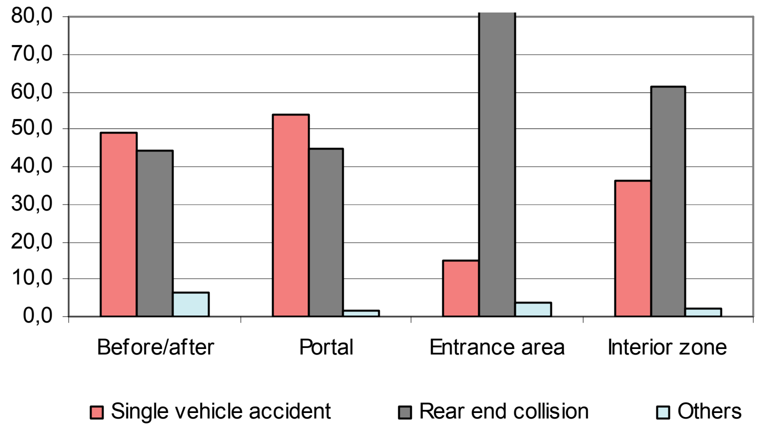

Figure 6: Types of accidents in tunnels with uni-directional traffic by point of origin of the accident, in percent (1999-2003)

In tunnels with uni-directional traffic two major trends are identifiable: In the areas before the entrance and after the exit as well as in the portal area, most part of the accidents occurring is single-vehicle accidents, whereas in the entrance area and in the interior zone of the tunnel mainly rear-end collisions occur. In total, rear-end collisions are the most frequent cause of accidents in uni-directional 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 speeding.

Summing up, in tunnels the proportion of rear-end collisions is significantly high. In the area of the portal 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.

4.3. Relationship between cause of accidents and traffic directionality of tunnels

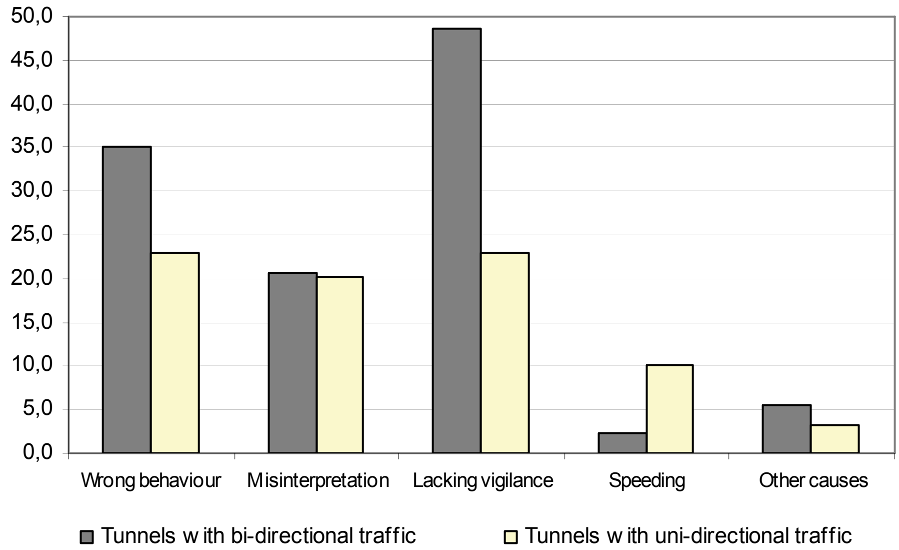

Figure 7: Causes of accidents in tunnels with bi-directional and tunnels with uni-directional traffic, in percent (1999-2003)

Generally, the most frequent cause of accidents in tunnels is lacking vigilance (over-fatigue, distraction, inattentiveness). On the second place are 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. The third most frequent cause is misinterpretation of road design and layout, meteorological conditions and other vehicles.

Lacking vigilance is by far the most important problem, particularly in tunnels with bi-directional traffic, whereas in tunnels with uni-directional traffic wrong driving behaviour plays an as important role as lacking vigilance. Moreover, the rate of accidents caused by speeding is particularly high in tunnels with uni-directional traffic. Other causes of accidents, such as unpredictable events and technical defects (motor, tyres and brakes) were negligible.

4.4. Relationship between cause and fault

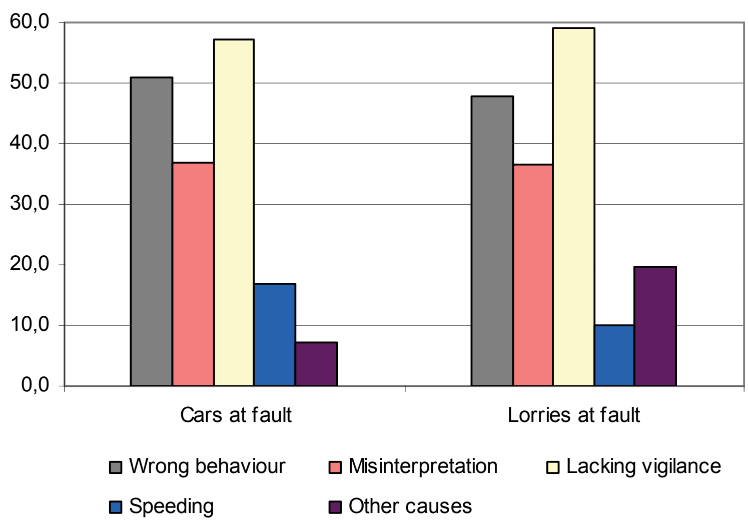

Figure 8: Cause of accidents in tunnels by fault (100%) and type of vehicle, multiple mentions are possible, absolute (1999-2003)

Lacking vigilance is the most frequent cause of both accidents with passenger cars at fault and accidents with Lorries at fault. On the following places are wrong driving behaviour and misinterpretation. What is striking is that the proportion of accidents caused by speeding is especially high in accidents involving passenger cars.

5. RECOMMENDATIONS

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 traffic morality regarding observation of speed limits and maintaining a safe distance to the vehicle in front. Every second accident is due to the failure to maintain a safe distance to the vehicle in front and many accidents are caused by 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 recommended for the area before the portal, beginning at least at 250 m before the portal, in order to raise tunnel safety in an optimal way.

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, measures aimed at making people aware of this problem should be taken and the placement of the traffic lights at the tunnel portal should be re-considered.

As 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.

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.

6. SUMMARY

The probability of an accident occurring in a tunnel or of being injured or killed in a tunnel is lower than on the open stretches of motorways, expressways and federal roads. However, if an accident does happen in a tunnel, the severity of injuries is significantly higher than on the open stretches of motorways. As a consequence, the accident cost rate is 52% higher than on the open stretches of motorways. In tunnels the risk of being killed in an accident is twice as high as on the open stretches of motorways

Looking at all accidents in the 130 motorway and expressway tunnels studied, it is not possible to draw any clear conclusions about the safety of tunnels with bi-directional traffic versus those with uni-directional traffic as one major factor influencing accidents is tunnel length. In order to prevent an excessive impact of tunnel length on relative accident rates, tunnels of a length of more than one kilometre with bi-directional traffic and uni-directional traffic were analysed separately. The accident rates of bi-directional and uni-directional tunnels with a length of over one kilometre are approximately at the same level. However, traffic safety is significantly higher in tunnels with uni-directional traffic than in tunnels with bi-directional traffic. The probability of being killed in an accident is 19% higher in tunnels with bi-directional traffic than in tunnels with uni-directional traffic. In tunnels with bi-directional traffic the accident cost rate and the fatality rate are respectively twice and 2.3 times as high as the corresponding rates in tunnels with uni-directional traffic.

Both in tunnels with bi-directional traffic and in tunnels with uni-directional traffic most accidents occur in the portal area. It is significant that in both types of tunnels the accident rate is higher in the area before the entrance and after the exit than in the interior zone of the tunnel.

In tunnels with bi-directional traffic rear-end collisions are the most frequent accident type in all areas excepting the portal area. In the area of the portals single-vehicle accidents are most frequent, whereas in the interior zone of the tunnel, besides rear-end collisions, mainly frontal collisions occur. In tunnels with uni-directional traffic most part of the accidents occurring in the area before the entrance and after the exit as well as in the area of the portal are single-vehicle accidents, whereas in the area of the entrance and in the interior zone of the tunnel, the main cause of accidents is rear-end collisions.

Generally, the most frequent cause of accidents in tunnels is lacking vigilance (over-fatigue, distraction and inattentiveness). On the second place is the failure to maintain a safe distance to the vehicle in front, wrong behaviour while overtaking and the failure to remain within the marked lane as well as misinterpretation of meteorological conditions and other vehicles. Particularly in tunnels with bi-directional traffic, lacking vigilance represents by far the most important problem, whereas in tunnels with uni-directional traffic wrong driving behaviour plays an as important role as lacking vigilance. Moreover, it must be said that in tunnels with uni-directional traffic the number of accidents caused by speeding is significantly high.

Lacking vigilance is a major problem, especially in the interior zone of the tunnel. This is particularly true in longer tunnels, where lacking vigilance resulting from over-fatigue and inattentiveness may have a high impact. Most part of the accidents occurring in the area of the portal is caused by speeding or by misinterpretation.

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THE RUNEHAMAR TEST TUNNEL R&D OF TUNNEL TECHNOLOGY AND THE NEED OF FULL SCALE TESTS

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ABSTRACT

Fires in road tunnels have happened more frequently over the last decade. To be able to prevent such fires, there is a need for understanding the specific elements related to fires and tunnels and how these matters influence each other. Laboratory testing has long been usual, full scale testing is rarer. The Norwegian contribution to tunnel research is an abandoned tunnel, upgraded with equipment to execute full scale fire tests.

As a part of the Norwegian R&D program on fire proof water and frost insulation for tunnels, The Runehamar test tunnel is of major importance. The aim of the program is to develop fire resistant solutions to replace the PE foam heavily used in low traffic tunnels.

The Runehamar test site is located 5 km from the town centre of Åndalsnes. Åndalsnes is a small town with beautiful surroundings in the western part of Norway. The Runehamar tunnel is about 1650 m long and the cross section is about 50 m^2. The tunnel has a small slope (1%-3%) downwards (going west) and a slight curve going north. The site of the tunnel, length and shaping make the Runehamar Tunnel ideal as a tunnel for research and development of tunnel safety technology.

Fires in European tunnels in recent years have clearly shown the risks and consequences of fires in large vehicles. The fire in the Mont Blanc tunnel in 1999 involved 20 semi trailers and more than 50 people have died in these recent fires in road tunnels. Nevertheless, knowledge of the growth and spread of fires in semi-trailers is very limited. The most recent fires in the Eurotunnel (1995), the Mont Blanc tunnel (1999), the Tauern tunnel (1999) and the St. Gotthard tunnel (2001) showed that such fires can develop very high energy release (150-600 MW), involving a dozen or so vehicles. Large scale fire tests were conducted in the Runehamar tunnel in 2003.

The benefit of such a test tunnel will be related to the fact that every research activity conducted in this tunnel will be in full scale. Previous laboratory tests can be evaluated in realistic conditions and environment compared to real expectations.

THE TUNNEL FIRE TEST SITE

The Runehamar test site is located 5 km from the town centre of Åndalsnes, which is a small town with beautiful surroundings in the western part of Norway. It is called the alpine town by the fjord.

Åndalsnes is located 500 km from Oslo and 40 km from Molde. It has a railway link to Oslo and buss link to Molde, which has an airport with flight connection to all major towns in Norway.

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The Runehamar test site has three road tunnels closed down for ordinary traffic, where two can be used for fire testing. The Old Runehamar tunnel has previous been used for fire testing of various tunnel insulation materials.

All tunnels at the site are easy to access by road. They are located about 1 km from road E136. The entrance has a key closed gate entering into a short tunnel, which leads to the site.

THE RUNEHAMAR TEST TUNNEL

In front of the Runehamar tunnel, there is an office building with all the necessary facilities. The entrance to the Runehamar tunnel is only 200m from the short tunnel which can be used for storage, etc.

The Runehamar tunnel is made in hard Gneiss type rock. It is about 1650 m long and the cross section is about 50 m^2. The tunnel has a small slope (1%-3%) downwards (going west) and a slight curve going north. A minimum fixed ventilation is installed. The tunnel is constructed in the early sixties.

The site of the tunnel, length and shaping make the Runehamar Tunnel ideal as a tunnel for research and development of tunnel safety technology.

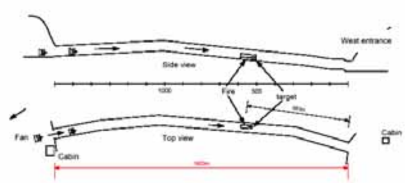
The benefit of such a test tunnel will be related to the fact that every research activity conducted in this tunnel will be in full scale. Previous laboratory tests can be evaluated in realistic conditions and environment compared to real life:

- Large scale fire tests
- Size of fires influencing accept criteria
- Size of fires and structural response
- Accept criteria for evacuation in tunnel smoke
- Tests of insulation materials
- Mitigation measures

LARGE SCALE FIRE TESTS IN THE RUNEHAMAR TUNNEL

In the frame of Swedish national and European research programs on tunnel safety, comprehensive large scale fire tests have been conducted in September 2003 in the abandoned Runehamar road tunnel. Especially semi-trailer fires similar to the size of the recent fires in Mont Blanc Tunnel (France/Italy) and St Gotthard Tunnel (Switzerland) were used. The Swedish National Testing and Research Institute (SP) has carried out the tests in collaboration with our UPTUN* partners from TNO Building and Construction Research in the Netherlands and the Norwegian Fire Research Laboratory (SINTEF/NBL).

Total four large scale tests with different semi-trailer fire loads where carried out. The worlds highest peak heat release rate ever measured in a tunnel fire test was registered. It was higher than 200 MW and the gas temperatures in the vicinity of the fire were registered above 1350^{o}C.



Fires in European tunnels in recent years have clearly shown the risks and consequences of fires in large vehicles. Over 20 semi-trailers, for example, were destroyed in a single fire in the Mont Blanc tunnel in 1999. Over 50 people have died in these recent fires in road tunnels. Nevertheless, knowledge of the growth and spread of fires in semi-trailers is very limited. The most recent fires in the Eurotunnel (1995), the Mont Blanc tunnel (1999), the Tauern tunnel (1999) and the St. Gotthard tunnel (2001) showed that such fires can develop very high energy release (150-600 MW), involving a dozen or so vehicles.

The purpose of the fire tests was to measure the rate of growth of various types of semi-trailer cargoes and to investigate the heat exposure to the tunnel linings. The purpose was also to obtain information to assist a new approach to fighting fires in tunnels. The information will be used to develop design scenarios for road tunnels and guidelines for protection of such tunnels. Variation of loads is infinite, but we shall attempt to restrict the number to those most commonly encountered.

Detailed information about the tests and the results of the testes can be found at the website: www.uptun.net or www.sp.se

During 2005 two more full scale tests were conducted in Runehamar:

- Test of tunnel membrane used for water protection. A total length of 30 m of membrane was installed and the test fire was approximately 25 – 30 MW with a time-temperature curve similar to HC. The test confirmed that the given demands for such a membrane were fulfilled.
- A full scale mitigation test was conducted at the end of the year. The results of this test are not yet available.

For 2006 the Norwegian Public Roads Administration is planning for 3 – 4 different full scale fire tests of materials related to water-frost insulation.

NEED FOR FULL SCALE TESTS

Full scale testing can focus on;

- Large scale fire tests
- Size of fires influencing accept criteria
- Size of fires and structural response
- Accept criteria for evacuation in tunnel smoke
- Tests of insulation materials
- Mitigation measures

Safety tunnel equipments of various kinds offered to tunnels are very often equipment and technology that has been used successfully in other connections and environments. However, transferring such technology uncritically into tunnels and base the efficiency and functionality exclusively upon laboratory tests can in the worst case be gambling with reliability.

Examples of such transferring technology can be:

- Fire detection systems
- Fire protection systems
- Water mist systems
- Air cleaning systems
- Insulation materials

This is equipment and technology aiming to take care of and improve the tunnel safety for the benefit to the users. And the technology itself is very often well proven. But the key questions will always be:

- Will the same technology function in a tunnel environment?
- And is the reliability sufficient in the same environment?

It is normal procedure to verify technically demands for such equipments in laboratory tests, both small and large scale. But it is still laboratory tests and the documentation can only verify the specific technical demands in a controllable stable environment.

That does not mean, however, that the same technology / equipment automatically will function in the same way in the real life tunnel environment which is very different from controllable laboratory environment. The tunnel geometry, environmental conditions, air velocity, ventilation conditions, etc. etc. are influencing the functionality, the stability and in the last hand the reliability of such technology/ equipment. And we need to know as much as possible about that influence.

We have to be 100 % sure that safety equipment that are installed in tunnels to take care of vital functions in case of an incident has to function in the purposed way that only time it is needed for use. That can only be verified through full scale tests in conditions similar to the real life. We can not and are not allowed to gamble with such reliability.

A full scale test verification is the first and most important step on the reliability line. It verifies that the technology/equipment is functioning in the right environmental conditions. The next will be the maintenance face. The equipment has to be build for maintenance in a long time run. The maintenance executed is also the final key to the technology/equipment reliability in the long term. That relation must never be underestimated.

CONCLUSIONS

Full scale fire testing is an expensive matter. Nevertheless, it is important to assure safety requirements. Research and development of tunnel technology in general has a basic need for arenas of full scale tests and full scale testing can be recommended in order to:

- Verify laboratory tests and the interaction between elements.
- View functionality and safety related to a real life environment.
- Evaluate maintenance and operation of safety systems in a holistic approach

An increase in safety equipment does not itself imply higher tunnel safety. The really important thing is to choose the right equipment and that it is full scale tested in a way that verifies its functionality in a certain incident.

The development of the tunnel technology goes very fast and new smart solutions pops up frequently. There are no technically limits. Those limits are up to us to define and we have to define them in a way they can be lived up to and re-examined in a practical way.

In addition to full scale testing of equipment and technology, maintenance and operation of the safety system as a total must not be forgotten. For emergency situations this equipment is to be used very rare, and the more high- tech, the more knowledge is required to maintain it in a proper way. For many tunnels this might be the future challenge that is more difficult than develop new solutions.

ADVANCED STUDIES OF FIRE PROPAGATION IN A MOTORWAY TUNNEL - CASE HISTORY BY THE TEST CENTRE

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ABSTRACT

Cofiroute is the largest private motorway operator in France, and responsible for a motorway network of approximately 900 km in the western part of the country. The centrepiece of the A86 motorway west of Paris is a tunnel which carries traffic on two levels, which prevents any risk of head-on collisions. Each level will be comprised of a two-lane carriageway and a hard shoulder for emergencies. In the event of a fire, this design gives rise to a variety of questions regarding the safety of tunnel users and intervention forces as well as the tunnel staff. Extensive tests on the basis of an experimental simulation of a serious accident resulting in a fire are to be used in order to study the propagation of fire between the vehicles in the tunnel, both above and below the seat of the fire [1].

Keywords: fire propagation, large scale fire tests, water mist, test centre

1. INTRODUCTION

The centrepiece of A86 motorway west is a single-tube road tunnel with a length of approx. 10 km and an inner diameter of 10.40 m which carries traffic on two levels. The resulting clearance height is 2.55 m for each traffic level, so only vehicles with a maximum height of 2.00 m are permitted in the tunnel. Each level has two traffic lanes, one shoulder, its own ventilation system and its own emergency exits, and may be used irrespective of the other level. Early in 2003, Cofiroute commissioned VSH-Hagerbach Test Gallery Ltd. to construct the most realistic possible test environment in order to carry out studies on fire propagation. The aim is to study the propagation conditions for a fire and - with respect to the possibilities for human escape routes - the environmental conditions in the area near the exiting fire fumes. [1]. Toxic smoke and gases resulting from a fire, reduced oxygen content, diminished visibility and high temperatures together with thermal radiation can impose sustained restrictions on the actions that tunnel users can take to save themselves.

BG Consulting Engineers, Lausanne, Switzerland, was commissioned by Cofiroute with the planning of the tests, and in April 2003 the VSH-Hagerbach Test Gallery Ltd. was awarded the project to organize the test area and to carry out realistic fire tests. The Centre Scientifique et Technique du Bâtiment (CSTB), Marne-Vallée Cedex, France - as an independent institute - supervised the entire test program.

In detail, the terms of reference for VSH-Hagerbach Test Gallery Ltd. was comprised of the following items:

- preparation of the test area
- design and operation of extensive instrumentation and video systems
- provide wrecked and operational motor-vehicles
- realization of the tests

2. THE TEST SECTION

2.1. General

Tests and experiments aimed at increasing safety in tunnels have been carried out continuously in the fire gallery at the VSH-Hagerbach Test Gallery since 2000. The fire gallery has a gradient of about 4 % with a length of approx. 230 m, a width of approx. 9.5 m and a height of approx. 6.5 m, thus giving it the same cross-section as a two-lane motorway tunnel. Prior to the Cofiroute tests, the surfaces were largely of a rocky nature and only a short section of the floor was concreted. Extensive construction was required in order to be able to carry out the tests under realistic operational conditions and with the required quality.

2.2. The intermediate ceiling

The greatest challenge in connection with the adaptation of the fire gallery was posed by the installation of an intermediate ceiling throughout the entire test area (145 m length), as there was a clash of conflicting interests. On the one hand, safety considerations necessitated a ceiling with the maximum possible stability while on the other hand; it had to be possible to dismantle the ceiling after the tests at a reasonable cost. It very quickly became apparent that a design based on lightweight construction would be out of question, mainly due to the high temperatures that were to be expected. After weighing the pros and cons, a “mobile ceiling” (concrete and steel) was constructed. The basic supporting structure was constructed of steel girders in the tunnel walls, on which transverse girders were placed at intervals of approx. 2 m. Reinforced concrete slabs, were placed between the transverse girders. The ceiling was protected with fireproof panels in the area of the seat of the fire.

Figure 1: Construction of the concrete ceiling and fire protection in the central fire zone.

A concrete floor was constructed throughout the entire length of the test section, following the gradient of the gallery. The tunnel walls were spray-coated with a special fire protection mortar to prevent the high temperatures from causing any damage.

2.3. Lighting

The test area was lit with fluorescent lights of the sort used in the A86 road tunnel. 55-watt fluorescent lights (l = 1.5 m) were positioned at intervals of 5 m on both sides [3]. In the area from -60 to -15 m, the lights were positioned below the tunnel ceiling. In the area from -10 m to +85 m, they were placed near the ground (30 cm from the ground) in order to protect the lamps against the high temperatures so that the lighting could be guaranteed for as long as possible even after smoke development.

2.4. Fire zone

The centre of the fire is located at ±0 m (vehicle "D"). Starting from the centre of the fire, the distances in meters are prefixed with a positive sign in the direction of flow and with a negative sign against the direction of flow. The descriptive terms "downstream" (positive) and "upstream" (negative) are used analogously.

The fire zone is the part of the test area where the fire takes place [3]. The fire zone starts at -25 m and ends at +30 m, giving it a total length of 55 m. In the area of the fire zone, the intermediate ceiling was protected against high temperatures by two layers of fireproof panels.

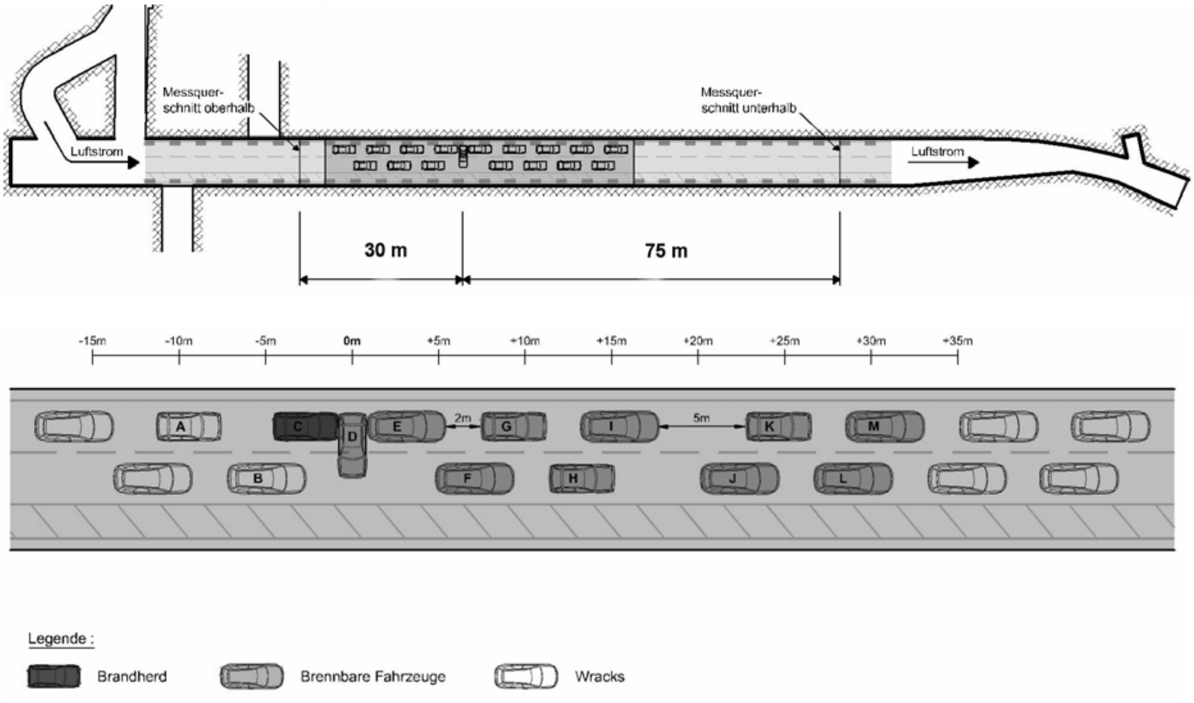

Figure 2: Entire test section on top and fire section below [3].

2.5. Air speed

Overpressure in the fire gallery was used to produce the required longitudinal flow in the test section. The air was accelerated and forced into the test section by two axial fans with a diameter of 1.8 m (80'000 m^3/h). The air speed in the test section was controlled by the sensor V1002 in the upstream measurement cross-section. In the access area of the test gallery, two gates were controlled on the basis of the effectively measured air speed, enabling the required air speed to be set.

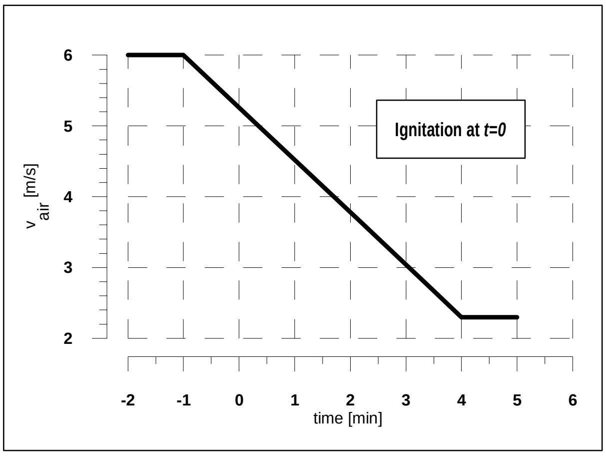

Figure 3: Fans of the ventilation system and development of the air velocity at the beginning of the test.

2.6. Safety

The safety of the test team and the visitors were ensured by a fire engine with 12 men of a local fire brigade with operational equipment. To enable people to exit safely from the test area in the event of a power failure, the marked escape route was additionally safeguarded by lighting which was independent of the power mains [2].

3. MEASUREMENT TECHNOLOGY

3.1. General

All the technical measuring equipment had to be reliable and robust in order to operate without faults under the extreme test conditions such as humidity, high temperatures, smoke and aggressive gases [1].

3.2. Central measurement technology unit

The central measurement technology unit was located at the entrance to the fire gallery. It consisted of two rooms, one used as the command room and for data acquisition, and the other used to produce the video recordings. The central measurement technology unit was linked to the data network of the gallery installation and was also connected directly to the seminar room in the VSH-Hagerbach Test Gallery. During the tests, all the visitors were able to follow events on three screens in the seminar room. Two of these were used for video transmission and one was used for real-time data transmission.

3.3. Data recording

Central recording of the measured data was handled by the MDA-600 multi-channel measurement and monitoring system. One or more limit values can be assigned to each channel. These values are stored in a non-erasable, protected memory. All the measurement cards were tested by the manufacturer according to the DIN standard. The CSTB accepted the entire system after further testing prior to the start of experiments.

The MDA-600 was accommodated in the central measurement control room and was protected against power failures by an uninterruptible power supply.

3.4. Sensors

Measurement cross-sections were located on both sides of the fire, but all the data cables ran together in the central measurement technology unit, necessitating that sections of the cable be routed past the seat of the fire. In order to circumvent this weak point, it was decided to place all the measurement cables and some of the measurement electronics on the intermediate ceiling. The advantage of this choice was that the cables and electronics were not only protected against the high temperatures, but also against the extinguishing water used by the fire brigade. The test area contained a total of 227 sensors and about 4800 m of measurement and data cable. Specifically, the sensors were for [1]:

- temperature
- air speed
- air pressure
- air humidity
- heat flow density
- visibility
- gas (CO, CO2, O2, NO_x, HCl, HCN, SO2).

3.5. Measurement cross-section

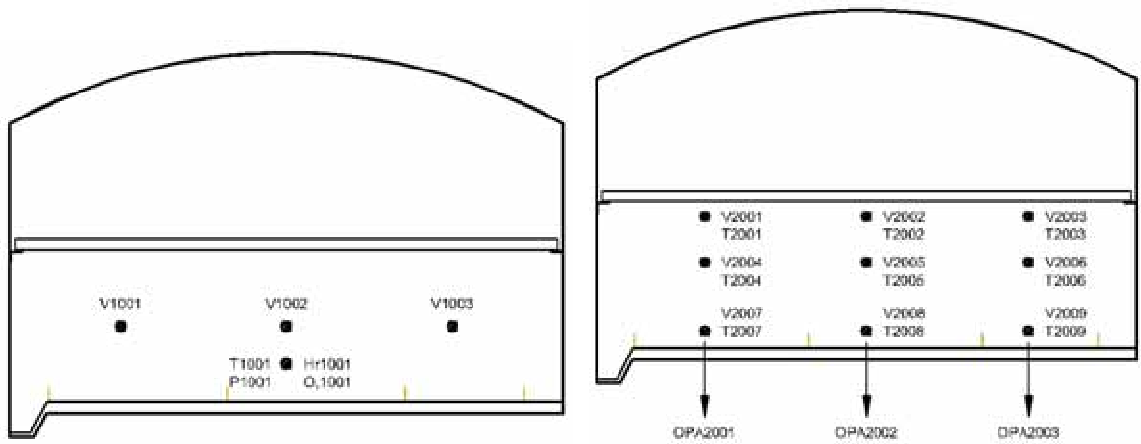

Figure 4: Measurement cross-section upstream (left) and downstream (right).

3.6. Cameras

The tests were monitored by ten cameras mounted in fixed positions and one mobile camera. Given that restricted visibility was to be expected, in particular below the seat of the fire, six normal image cameras and four thermal image cameras were used. All video signals were converted into PAL signals via a central production unit for recording on eleven analogue VHS recorders. The time code (min/sec) was added when the DVD was produced.

4. VEHICLES

To make the tests as meaningful as possible and in order to carry them out realistically, the choice of vehicles was to be based as closely as possible on the European average. The categories of vehicles were specified by the client [1] and the selection of the individual vehicles within these categories was made by VSH-Hagerbach Test Gallery Ltd, depending on their availability on the used vehicle market. About 70 vehicles were burned in the course of the entire series of tests (with and without a water mist system).

4.1. Ready-to-operate vehicles

These vehicles were designated for those positions to which the fire can spread during the test period.

The combustible vehicles serve the purpose of making the test procedure realistic, and they had to meet the following conditions [1]:

- engine in working order;
- undamaged bodywork;
- all window glass must be complete;
- it must be possible to drive the vehicles
- all tires must be mounted;
- the fuel system (tank, pipes) must be tight (no leaks);
- the interior finish of the vehicles must be complete;

4.2. Wrecked cars

The non-combustible wrecks were designated for those positions where the possibility of the fire "skipping" could be ruled out. Their primary purpose was to create an air flow as realistic as possible in the test area.

The wrecked vehicles had to meet the following conditions [1]:

- all the combustible materials (engine, tires, interior finish, fuel system, insulation material) had to be removed;
- the bodywork must not show any major damage;
- all window glass must be complete;

5. WATER MIST SYSTEM

A water mist system combines the extinguishing characteristics of water with the penetrative qualities of gases without any safety hazards for personnel or the environment.

A fixed-position water mist system from Aquasys Technik GmbH, was used for this series of tests. Erection, dismantling and operation of the system were undertaken by the staff of Aquasys. The system was comprised of five controllable pipe trains with a total length of 66 m (-33 to +33 m) per train. The system was operated at about 500 l/min and a pressure (sensor 2) of approx. 30 bar.

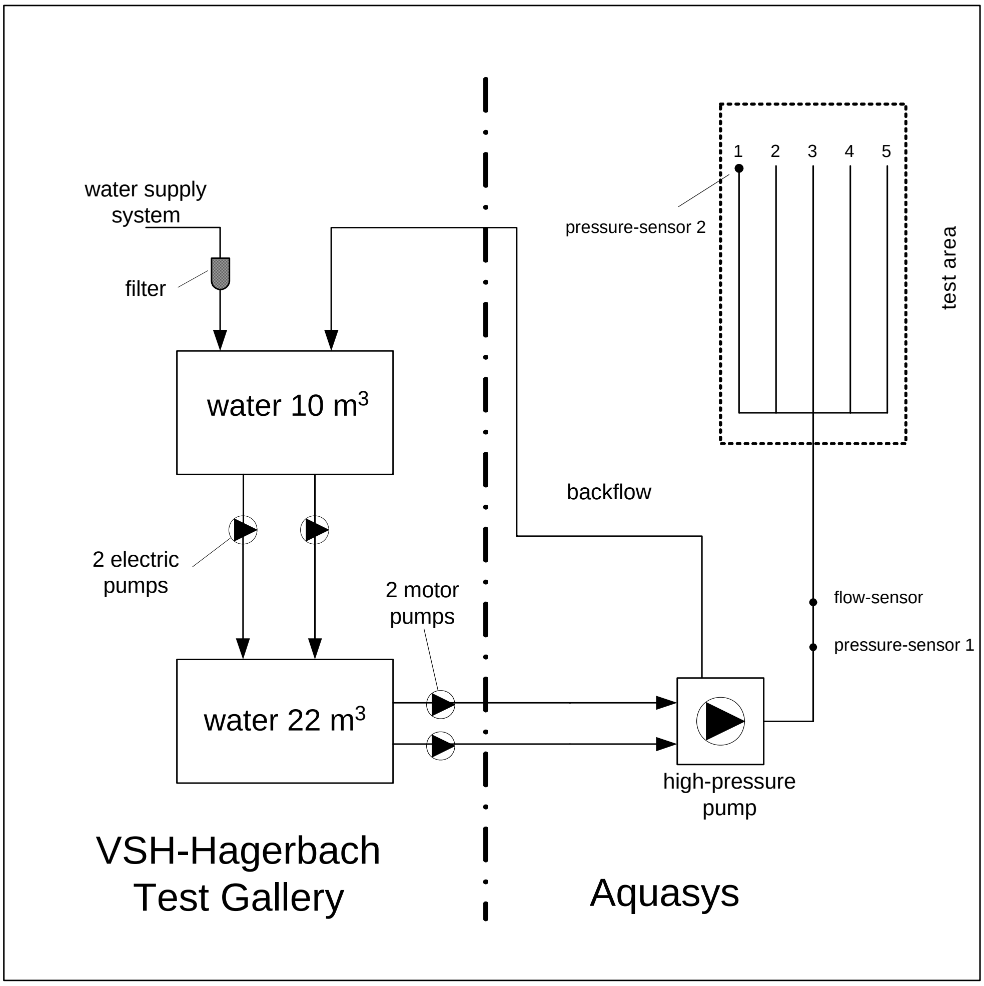

Figure 5: Scheme of the water mist system.

6. TESTS UNDER LIVE CONDITIONS

6.1. Tests without the water mist system

The tests were split into preliminary tests and major tests. The preliminary tests were carried out to check the entire instrumentation and camera system. Diesel was used as the combustible for the preliminary tests. The seat of the fire consisted of four cylindrical steel pools with a combustion surface of 1.07 m^2 each and a height of 300 mm. Each container was filled with 40 l of diesel and one litre of heptanes. In order to create the most realistic flow conditions possible, four wrecked cars were placed behind the fire troughs and four were placed in front of them. The distance to the fire centre was selected so as to make it impossible for the fire to skip over.

The vehicles were set up for the main tests as per Figure 2. The tanks of vehicles C, D and E were open and were each filled with 2 litres of petrol + 5 litres of diesel; the tanks of the remaining vehicles were empty. On vehicle D, a leak was simulated by a drop point on the tank. On vehicle C, the front windscreen was damaged and on vehicle D, the rear window glass on the passenger's side was missing.

Using heptanes (250 ml) as the fire accelerator, vehicle C was set on fire. A total of three main tests took place between September 25th and October 9th, 2003.

6.2. Test with a water mist system

The objective of the preliminary tests was to check the entire measurement system and the camera system, and to verify functionality of the water mist system. Vehicles were used as per 5.1. depending on the position of the vehicles, they were filled with fuel: 2 litres of petrol + 15 litres of diesel. In addition, a controllable drip point was installed in the tank system to simulate the escaping fuel.

Vehicles as per 5.1 and 5.2 were used for the main tests; these were filled with fuel in the same way as for the preliminary tests. A computer program written by BG made it possible to monitor the measured values in real time on the computer and to assess the progression of the fire power. The water mist system was activated manually on the basis of these assessments.

Between November 4th and 11th, 2003, a total of 6 preliminary tests and 4 major tests were carried out with a water mist system.

7. SUMMARY

Cofiroute’s concept for the tunnel on the A86 motorway only allows for vehicles with a maximum height of 2 m due to the clearance height – this systematically rules out hazards caused by larger quantities of goods transportation. The special geometric parameters and the specific features of the organizational measures have nevertheless brought up a large number of novel questions.

This series of tests, the nature and scope of which make them unique in the world, are intended to answer as many of the open questions as possible with the necessary care.

Tests such as these can play a major part in enabling the residual risk in tunnels to be reduced to a minimum, even though - inevitably - some risk will always be present. For this reason, it will also be indispensable to carry out tests on a 1:1 scale in the future.

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EXPERIENCE WITH THE SAFETY AND VENTILATION DESIGN IN OPERATION OF THE PLABUTSCH TUNNEL

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ABSTRACT:

For more than 17 years the Plabutsch tunnel was operated as single bore tunnel with bidirectional traffic. Two years ago the Plabutsch tunnel was opened as a twin tube tunnel with uni-directional traffic. Safety standards and the ventilation system were upgraded and new safety installations introduced. Since December 2004 both bores are in operation. This paper reports on the experience gained since that time with the operation of the safety systems and the ventilation of the tunnel.

Key words: *road tunnel, operation, safety installation, ventilation*

1. STATUS OF THE SAFETY AND VENTILATION DESIGN

The Plabutsch tunnel is still one of the longest tunnels in the world having two bores and unidirectional traffic. Since December 2004 the second bore is in operation. Hence it is possible to report on 2 years of continuous operation.

The safety standard and the ventilation design of the newly built 2nd tube as well as of the upgraded 1st tube of the Plabutsch tunnel was presented in detail at the 2nd international conference for safety and ventilation in Graz in 2004 (Waltl, 2004). The main items of these installations are:

- Reduction of the length of the single energy supply sections
- Cabling in E90 standard
- Traffic management with video image processing
- Emergency call system on bases of voice over IP
- Exhaust gas fans with 450kW and a temperature resistance of 400°C over 2 hours
- Improved lighting of the tunnel with lamp/body constructions fulfilling high temperature and tightness requirements

A main focus of the update of the ventilation system was put on the new ventilation concept in case of an incident. The ventilation control makes use of all 5 ventilation sections independently and allows a generation of air/smoke flows in longitudinal direction although the tunnel is equipped with a fully transversal ventilation system (Almbauer 2004, Waltl 2004)

1.1. Development in traffic volume

Traffic volume amounted already to over 30,000 vehicles per average working day. The development of the traffic volume is shown in **Figure 1**.

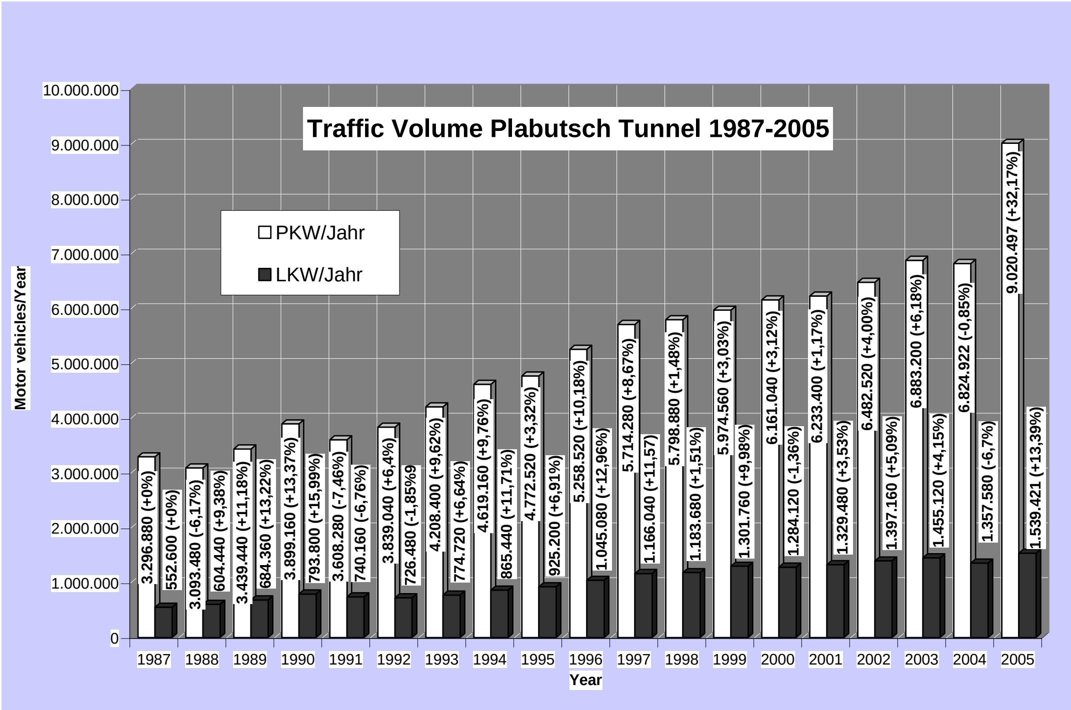

Figure 1: Development of the traffic volume

In spite of higher traffic volume and an increased average speed (around approx. 40 km/h more than before), the number of accidents was reduced noticeably.

1.2. Energy consumption

The change in energy consumption of the tunnel was surprisingly. Due to the opening of the second bore the connection power requirement was more than doubled, from 5 MW to 10.5 MW. However, the improvements in tunnel lighting, ventilation control and utilisation of the self ventilation effect due to the piston effect, the overall energy consumption of the tunnel in operation did not increase at all.

Due to reduced pollution inside the tunnel (remarkably reduced amount of lost goods like gravel) and reduced re-suspension of dirt (due to reduced turbulence because no passing trucks like in counterflow) the in-tunnel air quality and the visibility improved remarkably. **Figure 2** shows the changes in energy consumption since January 2004.

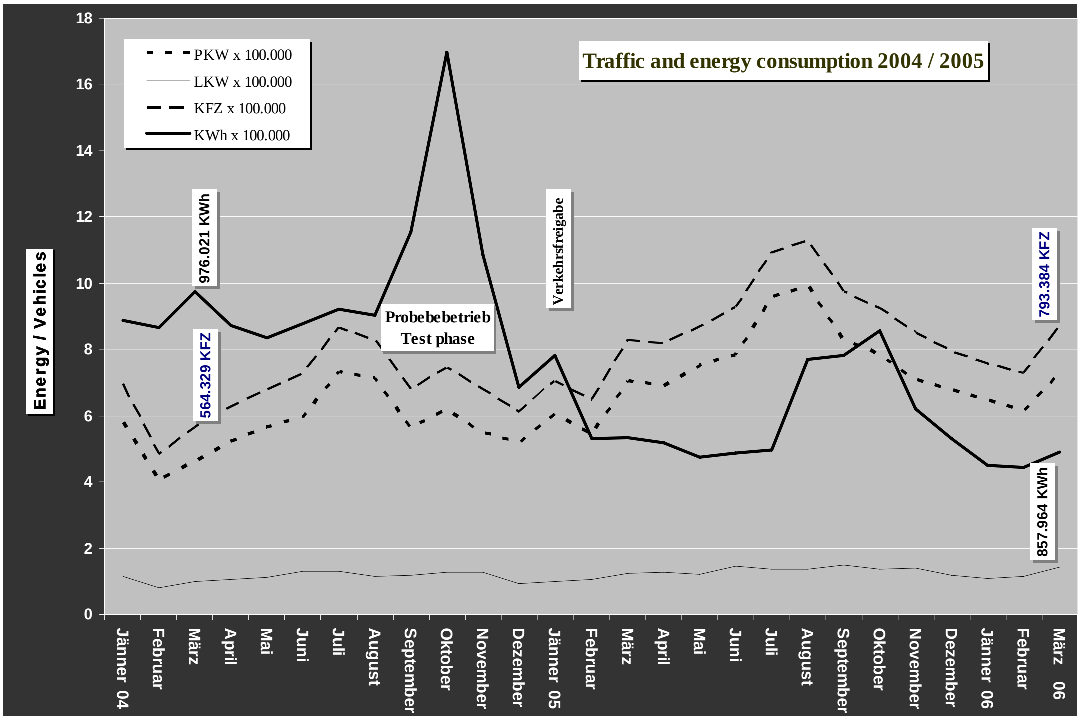

Figure 2: Energy consumption of the tunnel

1.3. Video image processing

High expectations were set into the video image processing, as this technology is ought to be the most up to date development in recognition of unexpected events in traffic monitoring. Unfortunately a high rate of false alarms occurred and a lot of updates of the process software were required to minimise the number of false alarms. At the moment different tests for event evaluation as well as a research project called VITUS are ongoing activities which take place in the Plabutsch tunnel.

It has to be noted, that in improvements in the operation surface are necessary. In addition, a pre-evaluation of recognised events in disturbances in traffic is required, before an alarm is triggered and sent to the dashboard in the operation centre and as a follow up action a measure like a tunnel closure is started.

Improvements in image processing are proposed for:

(a) congestions

(b) incident without fire

(c) smoke or incident with fire

(d) “ghost” driver (wrong way)

2. CONGESTIONS

To reduce the number of false alarms the information from the image processing has to be liked to information of traffic signals. I.e.: a red traffic signal shall not be interpreted automatically as "congestion". The same is valid shortly after setting the signal to green where an accumulation of vehicles leads automatically to a "congestion" alarm. A link with parameters like acceleration or deceleration could reduce the frequency of false alarms.

Figure 3: Detection of congestion

Is a congestion message evaluated and recognised as true, the following actions should be started automatically:

- Automatic visualisation of the video pictures of the considered section in the control centre.
- Closure of the entrance
- Activation of a "speed reduction cone" (i.e., activation of different speed limits) in the approaching zone of the entrance portal.
- Information to the tunnel users.
- Increase of the illumination level in the concerned tunnel zone
- Increase of ventilation in the concerned tunnel zone
- Reduction of the "congestion recognition sensitivity" of the image processing system in order to avoid further triggering of alarms

3. TRAFFIC ACCIDENTS

Figure 4 shows an image taken from a detection of an accident and some lost goods (left hand side).

Figure 4: Image from a traffic accident

The detection of non-moving vehicles works relatively well. Problems occur when the road surface is wet. In such cases the reflections disturb the processing. New evaluation algorithm should yield to reductions of the false alarms.

The recognition of lost goods in the tunnel is not satisfactory.

In case of an evaluated alarm the following actions should be started automatically:

- Automatic visualisation of the video camaras of the considered section in the control centre.
- Closure of the entrance
- Activation of a “speed reduction cone” (i.e., activation of different speed limits) in the approaching zone of the entrance portal.
- Information to the tunnel users.
- Increase of the illumination level in the concerned tunnel zone
- Increase of ventilation in the concerned tunnel zone
- Reduction of the “congestion recognition sensitivity” of the image processing system in order to avoid further triggering of alarms

4. FIRE AND/OR SMOKE IN THE TUNNEL

Figure 5: Detection of a smoking vehicle

The detection of smoke and smoking vehicles is sufficiently good. However, the location of the triggering of the alarm is in most cases not identical with the location of the incident (see **Figure 5**). Even for not moving smoking vehicles the “smoke” alarm is triggered in most cases by the camera in the second section next to the incident location. One reason could be in the “calibration” of the image processing software for the event of smoke.

If the detection is too sensitive a lot of false alarms will be the result, as e.g. re-suspended dust might have a similar appearance for the processing software. If once a fire alarm is triggered, cameras downstream the event shall not trigger new alarms, they might send an alert signal, but not more. Otherwise the fire location would virtually move downwards until it reaches the exit portal (in longitudinal ventilated tunnels).

The following actions should be started when a smoke/fire event is triggered:

- Increase of the illumination level up to the highest possible level.
- Pre activation of the exhaust fans in the concerned zone.
- Automatic visualisation of a moving smoke source by the cameras until the vehicle comes to a stand still.
- Closure of all tunnel entrances
- Setting of all traffic lights between entrance portal and incident location to red

The start of the automatic ventilation procedure for fire is coupled with the fixed fire detection system (cable) only and not with the CCTV. If the event is coupled with a stopped vehicle the CCTV brings the information to the operator and highlight automatically the correct ventilation procedure (response programme). The operator has than to confirm and start the programme manually (if not already started be the automatic system).

5. Wrong way driver

Ghost drivers are unfortunately not a very rare event in a tunnel (see **Figure 6**). They must be detected very quickly and with a high accuracy. All required system reactions have to be set automatically and without any time delay. Warnings for drivers in the correct way must be clear and unmistakably. The information can happen via tunnel radio or info boards. A stop of vehicles driving in the correct way might not be the best recommendation as a standing vehicle can not react anymore. The following actions are proposed:

- Warning via tunnel radio or/and info boards
- Switching illumination at highest level
- Automatic chasing of the wrong way driver by the cameras

Figure 6: Detection of a wrong way driver

6. OTHER REQUIREMENTS

All information systems must be able to switch automatically between uni- and bidirectional traffic. Useful would be the utilisation of statistical information to increase the detection limits. The consideration of sequences with increased traffic volume, daily change in traffic volume, special operation regimes like maintenance, etc. would be helpful. The following operation modes are an example:

- A shut off of the detection in certain sections is necessary e.g. at construction sites inside the tunnel (shall not yield to a full shut off of the system).
- Consideration of partial or short time counterflow is required.
- Short term reduction of the detection sensitivity after a traffic stop or at the region where a speed reduction is imposed.

6.1. Tunnel lighting

The strongly increased requirements enforced by the new RVS Standard have shown very positive effects.

The temperature requirement (250°C for one hour) and the proof of increased tightness are important features. The two fires recorded during the last two years showed that due to the E90 cabling and the increased temperature resistance of the lamps the effects of the accidents on the tunnel equipment could be kept low. In both cases it was possible to reopen the tunnel without any restriction already within a short time after removal of the damaged vehicles.

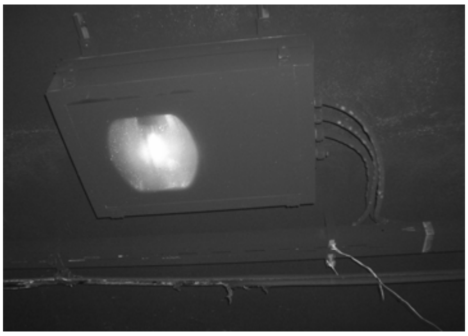

Figure 7: Lamp after the fire event

The usage of sodium vapour high pressure lamps showed positive effects although the illumination density was reduced.

Problems occurred with the illumination of the emergency niches. In these zones with higher illumination levels the metal vapour halogen lamps start to melt, due to too high temperatures (**Figure 8**). Currently a search for alternatives has been started.

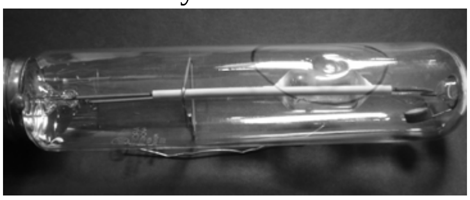

Figure 8: Melted lamp during normal operation

6.2. Roadside marking with LEDs

The marking of both roadside is performed with LEDs. They have been proven to be very effective as orientation lights during fire events combined with dense smoke, as they are visible for a very long time (see **Figure 9**) and almost not affected by temperature. It is foreseen to upgrade the LEDs with active emergency exit signalling.

Not sufficiently is the usage of LEDs in context of pollution and operational safety. There is a strong request for an improvement of the durability in operation and an improved behaviour in a dirt environment.

Figure 9: Visibility of the LEDs in a smoke filled tunnel

7. EXPERIENCE WITH THE VENTILATION SYSTEM

The ventilation system and the incident ventilation philosophy have been presented in Almbauer (2004) and Waltl (2004). The main feature of the incident ventilation is the utilisation of all of the five ventilation sections to achieve the required ventilation result. A PID controller is employed to steer the system. The system has been developed and installed first time in the Plabutsch tunnel. It allows a built up of a controlled longitudinal air/smoke flow in this transversal ventilated tunnel. In 2005 this system had to prove its capability during a considerable fire accident.

7.1. Ventilation system

The Plabutsch tunnel is equipped with 5 ventilation sections in each tube. All of these sections are fully transversal. At the south portal a 400 m long section with longitudinal ventilation exists as due to environmental reasons no exhaust air shall be exchanged via this portal.

The 10 exhaust fans have a power of 450 kW each and are temperature resistant up to 400°C. They are speed controlled. The fresh air fans are speed controlled and have a variable pitch to support the starting procedure. Inside the tunnel two caverns exists. One has a vertical shaft of 100 m (south shaft), the other one 240 m (north shaft). Each cavern and vertical shaft supports 4 ventilation sections (2 per bore). The remaining 2 sections are supplied from the north portal station (seen **Figure 10**).

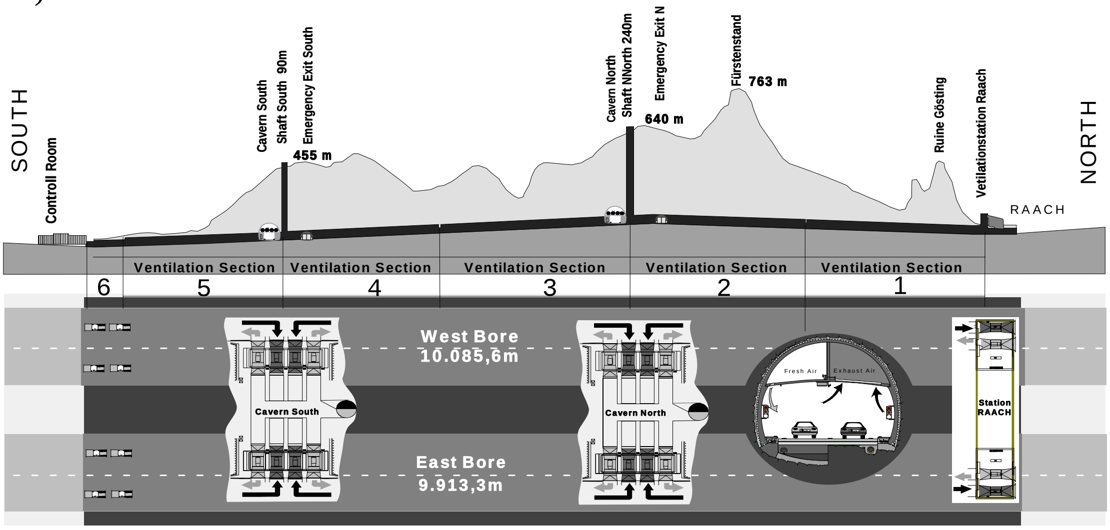

Figure 10: Sectional view of the tunnel

Hot smoke tests were performed to test and adjust the incident ventilation procedure. Some of the intensive tests were reported in Waltl (2004). The incident ventilation philosophy is based on the concept of generating over and underpressure in the various ventilation sections in order to steer the smoke to the proper exhaust gas damper (Almbauer 2004).

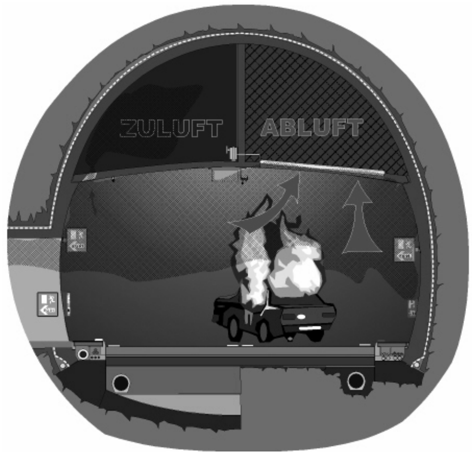

Figure 11: Cross section and damper

The hot smoke tests proved the functionality of the system already in 2004. One of the main features in the incident operation strategy is the exact detection of the fire location, as the exhaust dampers (12m²) are installed only every 106m. The opening of a wrong damper can have negative effects on the efficiency of the smoke extraction. In very unluckily cases it could even happen, that only fresh air would be extracted and the smoke would be kept inside the tunnel.

7.2. Vehicle on fire

In November 2005 the following incident happened. A vehicle started to burn and the ventilation had to react. The boundary conditions were very unpleasant as due to the uni-directional traffic a very high longitudinal air velocity occurred. **Figure 12** shows the location of the event.

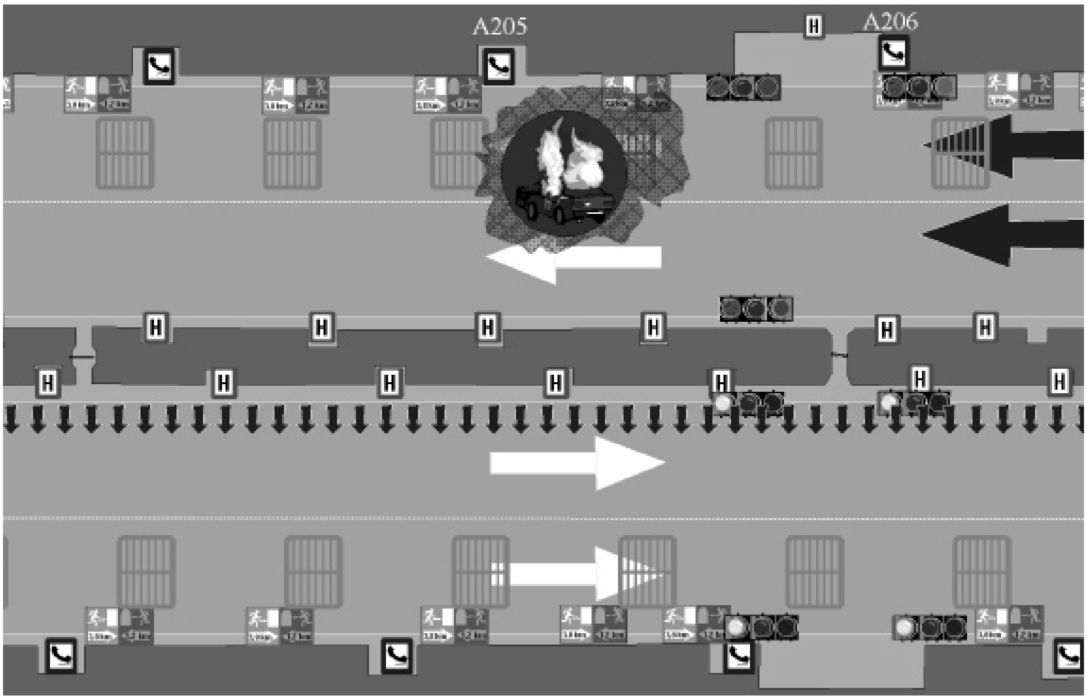

Figure 12: Sketch of the incident location

The vehicle – a van with a caravan with a mass of more than 2 tons– was forced to stop shortly before the emergency niche A205. Most likely due to overheating the engine of the van caught fire. The driver tried to reach the tunnel exit with his burning vehicle. In the meantime other tunnel users had already called the fire department using their cellular phones. As they could not give the exact location of the burning vehicle it was not possible to find this vehicle immediately. The video system detected congestion and came up with the proper images and location information a few minutes later (17:44). From that time on the video system chased the smoking vehicle automatically. At that time the fire was still small. As soon as the vehicle stopped, the fire alarm was triggered and the incident ventilation procedure started.

The detection of the fire resulted in the opening of the damper next to the incident location (downstream the fire). The exhaust fan went up to full ventilation power in that section. Smoke extraction happened fully over this open damper.

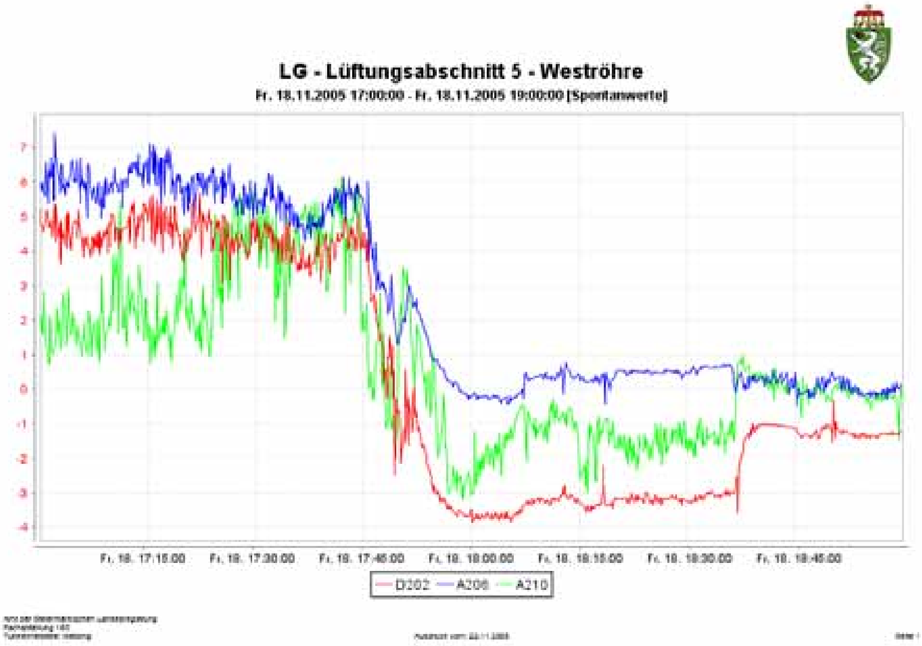

Figure 13: Course of the air/smoke velocity over the time.

Figure 13 shows the development of the air velocity at the sensor responsible for ventilation control. At the beginning a very high longitudinal velocity of 7 m/s occurred. Although the system has never been tested at those high air velocities it was able to slow down the velocity within a very short time.

During the fire event the big connection doors between the two tubes were opened and closed. Such interferences as well as the manual opening of other dampers were compensated by the automatic PID controller without any problem.

Figure 14: Burned out vehicle

Although the vehicle burned out totally (see **Figure 14**) and caused severe damage to the concrete surface (up to 7 cm in dept over an area of some square meters, see **Figure 15**), it was no problem to keep the tunnel from both sides of the fire fully free of smoke (except the zone between fire and open damper).

Figure 15: Damage in the road surface

Due to the temperature requirements enforced for the cables, the equipment and the lights, there was no breakdown in any of the safety installations to be reported. The radio transmission cable had some damage, but transmission was possible without any restriction throughout the whole event.

8. CONCLUSION

After two years of operation of the new respectively upgraded Plabutsch tunnel a lot of experience was gained concerning operation of the tunnel. Although the second bore required an increase in electrical power by a factor of two, the energy consumption of the tunnel did not raise. This is due to improved efficiency of tunnel lighting as well as reduced ventilation power due to the utilisation of the self ventilation effect in uni-directional tunnels.

Many of the performed improvements in safety technology proved their usefulness and some showed that further improvements are required (e.g. video image processing, etc.). In any way, the concept of improving self rescue possibilities due to keeping the smoke away from possible escape routes showed to be very effective. Although the two fire events occurred during the last two years were not major fires, especially the event with the burning van showed the capabilities. The ventilation system was able to cope with unfavourable boundary conditions like high air speeds at event triggering, open cross passages, manual interference by tunnel operator, etc.

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CFD SIMULATIONS OF ROAD TUNNEL FIRES TO ESTIMATE THE INFLUENCE OF VENTILATION SYSTEMS ON SAFETY

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ABSTRACT

A computational fluid-dynamics (CFD) code, *JASMINE* (BRE), was employed for the simulation of a gasoline pool fire in a tunnel subsequent to a spill from a road tanker involved in an accident. The simulation was performed on a real three-lane one-way tunnel, about 800 m long, situated on a road highway in the Southern Italy with intensive traffic of vehicles and trucks. This hypothetical tunnel fire scenario was studied to investigate the effect of natural (in case of stable or unstable atmospheric conditions), longitudinal (by axial fans) and semi-transverse ventilations (through either supplying or extracting ducts). Simulations provided an useful mean for gaining an insight of the region of the studied fire and for predicting the escape probabilities for the passengers, under different tunnel ventilation conditions. Results in terms of gas temperature, O_2 and CO_2 concentration and visibility for illuminated signs were compared to safety conditions values, and to the presumed location of escaping pedestrians, in order to evaluate if people can safely run away the tunnel.

Results showed that for the studied tunnel fire scenario, the use of a mechanical ventilation system may allow safer people evacuation and rescue. In particular, the longitudinal ventilation proved to be more effective than the semi-transverse ventilation, in both exhaust and supply mode. In contrast, in the absence of any forced ventilation system consequences on safety can be serious because of the rapid increase of temperature and smoke concentration that strongly compromise the possibility for people to safely evacuate the tunnel.

In Italy, according to the ANAS directives for tunnel safety, only in particular cases tunnels shorter than 1000 m have to be equipped with ventilation systems. Simulation results, on the contrary, well agree with European guidelines, that recommend mechanical ventilation systems for one-way road tunnels longer than 500 m.

Keywords: tunnel fires, ventilation configuration, visibility

1. INTRODUCTION

The European economy is heavily based upon an efficient and reliable transportation system, (road as well as rail) in which tunnels are a key element. The safety and efficiency of road transportation is a strategic goal especially in countries, like Italy, in which about 80% of goods is nowadays transported by road, with a 30% increase with reference to the 2010 forecast (Fabiano et al., 2005).

In the last decades traffic has grown significantly and also changed in composition (more combustible and flammable goods), and consequently, the safety level in existing tunnels decreased and the number of accidents evolving in fires increased. Recent major accidents in tunnels, like the Monte Bianco, the San Gottardo and the Fréjus ones, resulting in loss of lives and severe damages to tunnel structures, have caught world attention on safety in tunnels.

To prevent the occurrence or at least to mitigate the consequences of accidental fires, existing tunnels should be upgraded and new tunnels should be equipped with efficient fire protection systems. The knowledge of detailed gas flow and smoke movement patterns inside tunnels is essential for the design of ventilation systems. An efficient way to estimate the flow patterns

of the fire-induced air velocity, temperature, pollutants and smoke concentration in tunnels can be done by mathematical models using computational fluid dynamics (CFD) techniques. Simulations can provide an excellent mean for gaining a better insight in the region of the fire and prediction of the escape conditions for the passengers.
In this work a CFD code, *JASMINE* (BRE), was employed for the simulation of a gasoline pool fire in a tunnel consequent to a spill from a road tanker involved in an accident. The work aimed at studying the effect of ventilation systems (natural, longitudinal and semi-transverse) on the conditions (safe or unsafe) occurring during the fire development inside a real highway one-way road. Results allowed the assessment of the effectiveness of different ventilation systems on the evolution of the hypothesised fire scenario, so resulting useful for suggesting improvements to the tunnel safety system.

2. TUNNEL FIRE SAFETY

In principle, all road tunnels require ventilation to dilute and remove pollutants during normal traffic operation: the fresh-air requirement depends on tunnel geometric characteristics, on traffic volume, composition and characteristics and on the specific motor-vehicle emissions. Moreover, ventilation is used for controlling smoke and hot gases during a fire emergency, in order to allow safe evacuation and rescue. From the beginning of a fire, the airflow in the tunnel becomes highly transient. The modifications are not only due to the fire itself, but also to the emergency ventilation mode, either natural or mechanical. The choice of the type of ventilation to use depends on several parameters (tunnel length, cross-section and grade; surrounding environment; traffic volume, installation and operating costs). In each country, safety standards are regulated by National Road Societies and Ministries. In Italy, according to the ANAS directives (1999) for tunnel safety, only in particular cases tunnels shorter than 1000 m have to be equipped with ventilation systems. However, according to European guidelines (Decision N° 1692/96/CE, for the harmonization of safety facilities and procedures for the development of the trans-European transport network), for one-way road tunnels longer than 500 m mechanical ventilation systems are recommended.

3. CFD

The computer model *JASMINE* (Analysis of Smoke Movement In Enclosures), developed by FRS/BRE, uses a CFD to describe the heat and mass transfer processes associated with the dispersion of combustion products from a fire. The processes of convection, diffusion and entrainment are simulated by solution of the Navier-Strokes equations. The code includes the key processes of buoyancy, convection, entrainment, turbulence, combustion, thermal radiation and boundary heat transfer relevant to the movement of smoke. It is a finite-volume code using a Cartesian grid and is based on the SIMPLEST pressure-correction procedure. The upwind discretisation scheme is employed. Transient solutions are advanced by a first-order, fully implicit scheme. Turbulent closure is provided by a standard, high Reynolds number, two-equation (k-ε) model. Various physical sub-models are included for combustion and radiation processes, gas phase properties (density and specific heat) and solid boundary heat transfer (BRE report, 2003).

4. SIMULATIONS

The major contribution to the risk deriving from goods transportation–on the road is due to liquid fuels and LPG (Milazzo et al., 2002), which can cause flash fires, pool fires or even vapour cloud explosions. These scenarios usually have a rather small impact area so they mainly affect vehicle drivers. Among various scenarios the one more likely to occur for liquid fuels (like gasoline) road transportation is a pool fire subsequent to a small, a medium or a

catastrophic release (tanker collapse). For this reason in this work, a gasoline pool fire in a tunnel, consequent to a spill from a road tanker involved in an accident, was assumed to occur.
The tunnel investigated is a two-tubes (each tube one-way) road tunnel along the Southern Italy highway A3, between Pontecagnano and Salerno, 60 km from Naples. The A3 highway is the main highway for the transportation of goods in Southern Italy.
CFD code form BRE (*JASMINE)* was employed for the simulation. The mentioned tunnel is about 800 m long, with an arched cross section of 12 m x 7 m. The pool fire was assumed to be subsequent to a medium release, lasting 10 min, from a hole in a road tanker. The tanker (20 m^3, 6 m long, 2 m in diameter) was assumed to be stopped at a distance of about 400 m from the tunnel entrance. A 25 mm hole was supposed to form at the rear side of the tank, from which about 720 kg of gasoline spilled out in 10 min, generating an enlarging pool (10 mm in thickness) up to 10 x 10 m^2.
After the ignition, the heat release rate from the pool fire rose rapidly (in 90 s) up to 170 MW, and remained constant for about 10 min. For very large pools (>5-10 m in diameter) a 20% decrease in the burning rate, and consequently in the HRR, is usually noted, attributed to poorer mixing, poorer combustion and formation of a cold smoke layer above the pool surface (Babrauskas, 1995). Therefore, a burning rate of 0.04 kg m^{-2} s^{-1} was assumed.
Different runs were launched to study the influence of ventilation systems. In particular, the pool fire was simulated under the following conditions:

1. natural ventilation, in case of stable or unstable atmospheric conditions;
2. forced longitudinal ventilation with 80 m^3 air flow rate, provided using two axial fans mounted on the tunnel ceiling close to the entrance portal;
3. forced supplying semi-transverse ventilation performed with 80 m^3 s^{-1} air supply from 80 (10 m spaced, 0.42 m x 0.42 m) square inlet ports. The position of the air feed system was supposed between the two tunnel tubes, so the supply vents were located on the tunnel inner side wall at 0.5 m above the tunnel floor;
4. forced extracting semi-transverse ventilation, performed with 80 m^3 s^{-1} smoke and hot gases withdrawal through 80 (10 m spaced, 0.2 m wide and 0.9 m long) extraction ports located at the centreline of the tunnel ceiling.

5. RESULTS

Simulations results yielded fire-induced temperatures, and oxygen, carbon dioxide and smoke concentrations in the presence or not of ventilation systems. Safety aims are: i) to keep pollutants and toxic species concentrations below dangerous values (IDLH is 5.0 10^4 ppm for CO_2); ii) to guarantee a minimum O_2 concentration (17vol %) to allow breathing; iii) to control smoke and, then, visibility (illuminated signs should be discernible at 9.1 m); iv) to provide survivable gas temperatures (i.e. not exceeding 60°C). Therefore, the calculated space profiles of these parameters (temperature, CO_2 and O_2 concentrations, visibility) during fire evolution were compared to safety values of such variables. In order to know if people can safely escape the fire, the presumed location of pedestrians in the tunnel was evaluated by considering that the evacuation walking speed in a road tunnel under critical conditions can be assumed to be about 1.2 m s^{-1} (Sabato, 1999), and taking also into account the time to perceive the risk and the time to react and leave the vehicle. If the walking speed is 72 m min^{-1}, the time for walking the maximum distance of 400 m in the tunnel is about 5.5 min; the escape is assumed to start 90 s after ignition so the total time to run away can be assumed to be 7 min. Finally, since the normal breathing height inside the tunnel is between 1 and 3 m, the reported values of the calculated variables are those at 2 m above the tunnel floor.
Results are shown in Figures 1-4 as space profiles of the variables and in Tables 1-4 as values of the variables. Specifically, Figure 1 reports the comparison between temperature space

profiles, calculated 4 minutes after the fire start for the various simulated ventilation systems. Figures 2-4 report similar comparisons between space profiles of oxygen concentration, carbon dioxide concentration and maximum visibility length, respectively. In the tables, instead, the values of the mentioned variables at 3 different distances from the fire location (i.e. 36, 180 and 324 m on both sides), corresponding to the distances travelled by people who started escaping from the fire location at t = 1.5 min, are summarized. That people reached such distances after 2, 4 and 6 min from the fire start, respectively. When the value of the variable gives rise to unsafe conditions for people the character is bold while it is italic when it results in safe conditions.

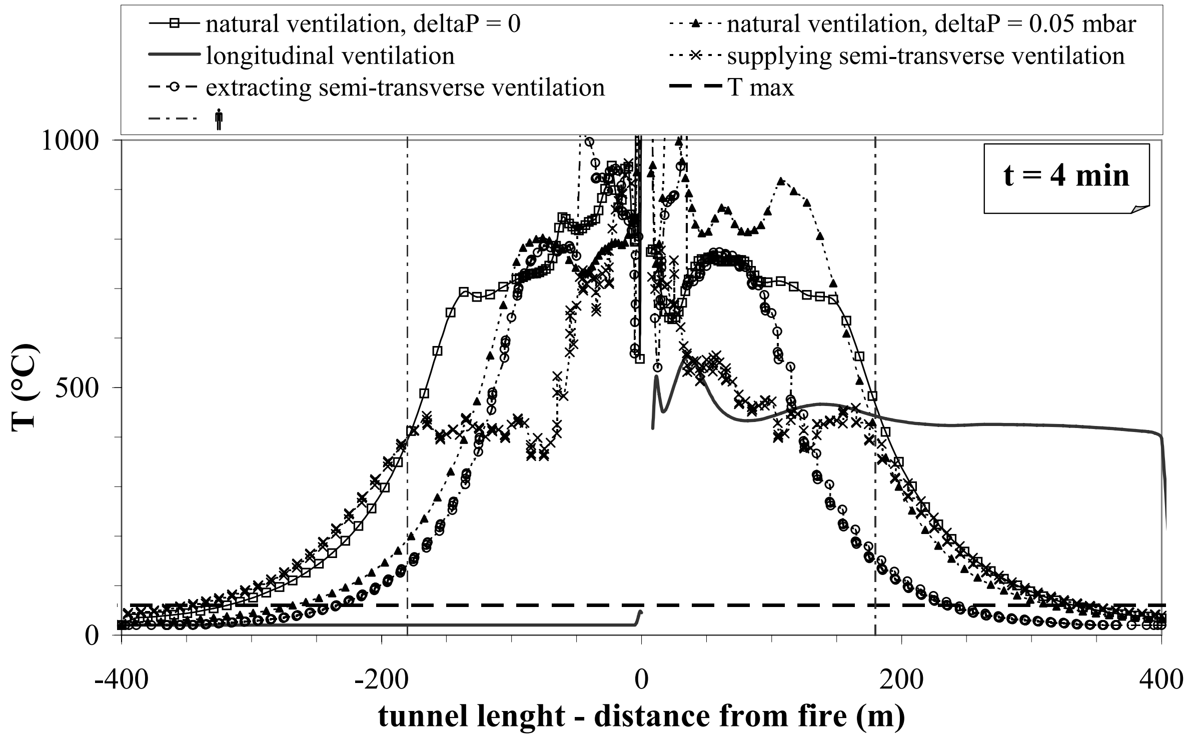

Figure 1: Temperature profiles along the tunnel centreline at 2 m from the floor

5.1. Temperature

All the calculated temperature space profiles along the tunnel, but that obtained with longitudinal ventilation and at a lesser extent that achieved with natural pressure gradient between the portals, are almost symmetric with respect to the fire location. This clearly appears from Figure 1 in the case of profiles calculated 4 min after the fire start up and has been verified also at different times. Temperature maximum for each profile are achieved in correspondence of the fire, then the profiles decline on both sides more or less quickly in dependence of the ventilation system employed.

With natural ventilation and $\Delta P = 0$ between the portals, the temperature profiles are almost symmetric and the gas temperatures on both fire sides at 180 m from the fire (the distance travelled by a escaping people after 4 min) are the highest (Figure 1). With natural ventilation and $\Delta P = 0.05$ mbar the temperature profile appears lower on the fire side where of the air stream induced by the pressure difference between the portals goes in. Correspondingly, at 180 m from the fire the temperature on the colder side is significantly lower (about 200 °C) than that on the hotter side (Figure 1). Longitudinal ventilation keeps the temperature upstream the fire to very low values but makes the gas temperature almost uniform and relatively high along the whole tunnel portion downstream the fire (Figure 1).

The effect of air delivering along the whole tunnel length is to lower the gas maximum temperature but also to increase on both fire sides the average temperature at distances from the fire crucial for escaping people (Figure 1). On the contrary, the effect of exhaust gas extraction from the tunnel ceiling is to lower significantly the gas temperatures at such distances but also to increase them closer to the fire (Figure 1). In any case, for what concerns the temperature for a given gas flow rate, the semi-transverse extracting ventilation system appears more effective than the semi-transverse supplying ventilation.
For what concerns the temperature Table 1 shows that safe escaping conditions for people who initially stands close to the fire location are achieved only with longitudinal ventilation and only in the upwind direction. It is worth noting, however, that people not standing initially very close to the fire could leave safely the tunnel.

Table 1: Temperature (°C) at the escape distance

Ventilation type	t = 2 min		t = 4 min		t = 6 min	
	upwind	downwind	upwind	downwind	upwind	downwind
Natural $\Delta P = 0$	**315**	**229**	**412**	**483**	**73**	**78**
Natural $\Delta P = 0.05$ mbar	**340**	**331**	**200**	**430**	*46*	**135**
Longitudinal	*20*	**526**	*20*	**444**	*20*	**429**
Semi-transverse supply	**530**	**805**	**400**	**390**	**168**	**156**
Semi-transverse extraction	**655**	**569**	**140**	**153**	*46*	*41*

5.2. Oxygen and carbon dioxide concentrations

As observed for temperature in Figure 1, the oxygen concentration profiles, reported in Figure 2 at 4 min after the fire start up, appear almost symmetrical with respect to the fire location for all the ventilation systems, except for longitudinal ventilation and less significantly for natural ventilation in unstable atmospheric conditions ($\Delta P = 0.05$ mbar).
It is worth noting that the longitudinal ventilation assures along the whole tunnel an oxygen concentration higher than the minimum concentration to allow breathing, during the entire evolution of fire, being equal to 21 vol % upwind the fire and approaching 17 vol % downwind. In all the other cases, the ventilation system is not able to guarantee safety conditions in the whole tunnel. In particular, the safe conditions at the escape distance (corresponding to the distance travelled by escaping people in a given time) are verified with both natural ventilations and with longitudinal ventilation after 2 min from the fire start up, with longitudinal and semi-transverse extracting ventilation after 4 min and with all ventilation systems after 6 min (Table 2).
With reference to CO_2 concentration (Figure 3) considerations similar to those relevant to O_2 concentration and temperature about the symmetry of profiles varying the ventilation system can be done. But, in this case, carbon dioxide concentrations lower than 5 vol %, which corresponds to safe conditions, are assured by all the ventilation systems at the escape distance, as evident from Table 3.

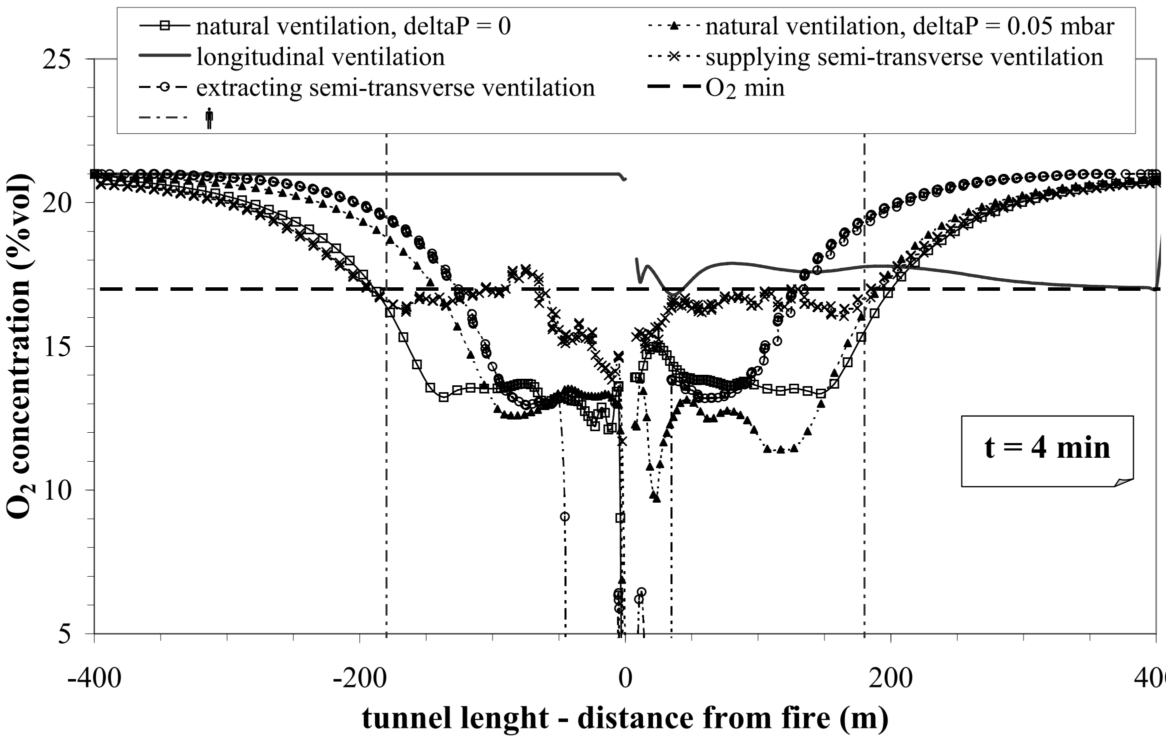

Figure 2: Oxygen concentration profiles along the tunnel centreline at 2 m from the floor

Table 2: Oxygen concentration (vol %) at the escape distance

Ventilation type	t = 2 min		t = 4 min		t = 6 min	
	upwind	downwind	upwind	downwind	upwind	downwind
Natural ΔP = 0	*18.9*	*19.4*	**16.2**	**15.5**	*20.0*	*19.9*
Natural ΔP = 0.05 mbar	*18.4*	*18.6*	**18.7**	**16.2**	*20.5*	*18.9*
Longitudinal	*21.0*	*17.4*	*21.0*	**17.8**	*21.0*	*17.2*
Semi-transverse supply	*17.1*	**15.1**	**16.6**	**16.7**	*18.5*	*18.6*
Semi-transverse extraction	**15.9**	**16.6**	**19.5**	**19.3**	*20.5*	*20.5*

Table 3: Carbon dioxide concentration (vol %) at the escape distance

Ventilation type	t = 2 min		t = 4 min		t = 6 min	
	upwind	downwind	upwind	downwind	upwind	downwind
Natural, ΔP = 0	*1.39*	*0.99*	*2.75*	*3.25*	*0.61*	*0.67*
Natural ΔP = 0.05 mbar	*1.54*	*1.46*	*1.30*	*2.83*	*0.31*	*1.25*
Longitudinal	*0*	*2.41*	*0*	*1.93*	*0*	*2.30*
Semi-transverse supply	*2.33*	*3.51*	*2.66*	*2.60*	*1.50*	*1.42*
Semi-transverse extraction	*3.07*	*2.64*	*0.91*	*1.00*	*0.29*	*0.27*

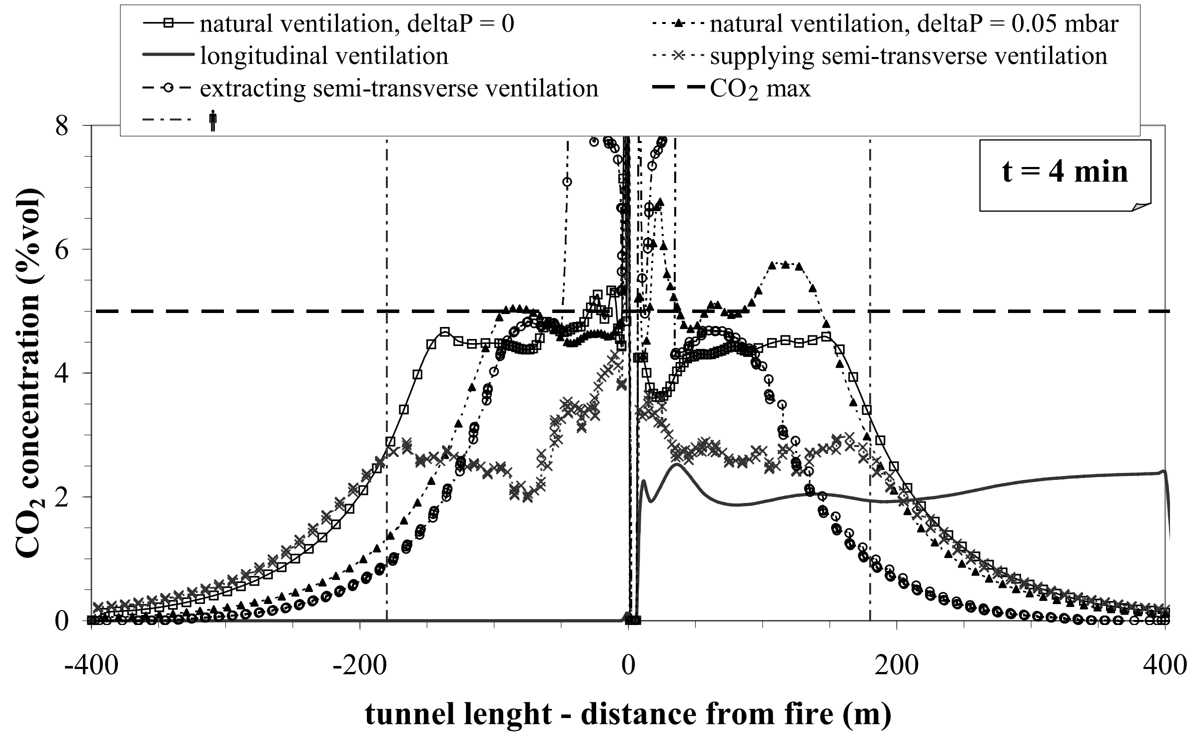

Figure 3: Carbon dioxide profiles along the tunnel centreline at 2 m from the floor

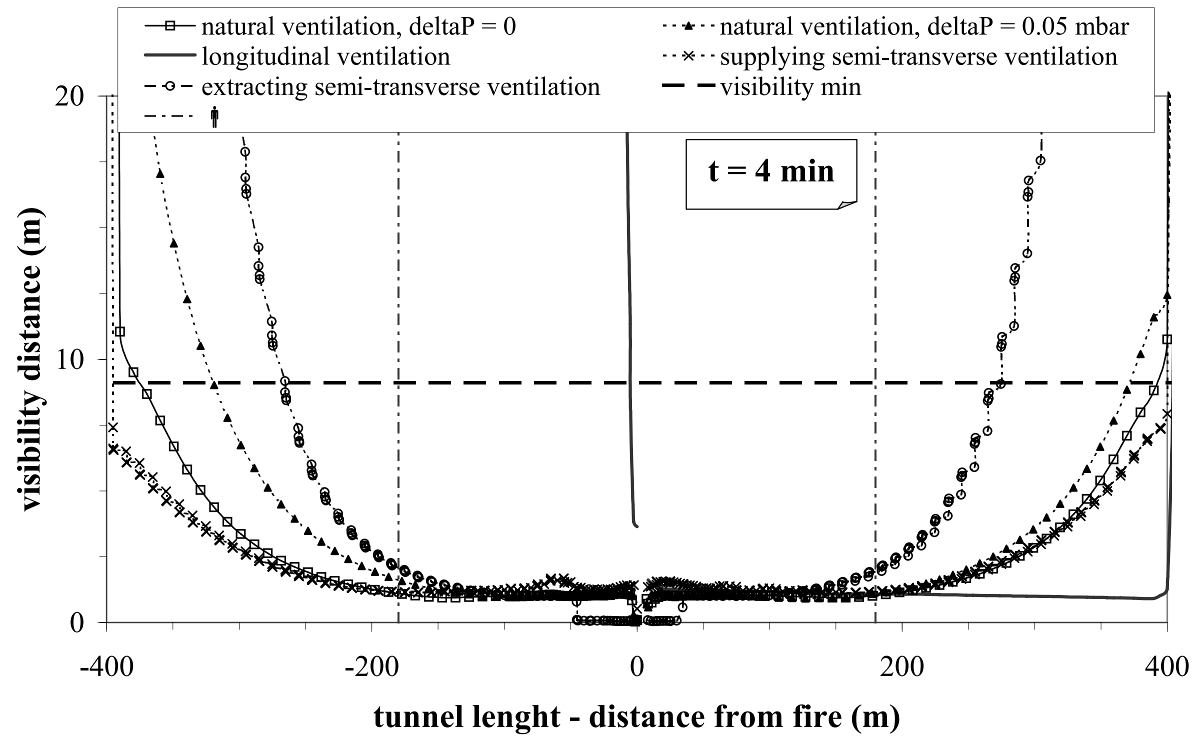

Figure 4: Visibility distance profiles along the tunnel centreline at 2 m from the floor

5.3. Visibility distance

As for the profiles of the other variables, most of the calculated visibility distance space profiles along the tunnel are almost symmetric with respect to the fire location, as shown in Figure 4 in the case of profiles calculated 4 min after the fire start up. Similar results were

obtained at different times. In the case of longitudinal ventilation and, to a lesser extent, in the case of ventilation induced by the natural pressure gradient between the portals, the profiles are asymmetric. Longitudinal ventilation keeps the portion of the tunnel upstream the fire very clear but makes quickly the visibility distance uniformly low along the whole tunnel portion downstream the fire (Figure 4).
The effectiveness of natural ventilation on the visibility distance, both with $\Delta P = 0$ and $\Delta P = 0.05$ mbar between the portals, appears quite modest. The profiles pertaining to $\Delta P = 0.05$ mbar are lightly better on the fire side where there is the ingress of the air stream induced by the pressure difference but in any case at 180 m from the fire (the distance travelled by a escaping people after 4 min) are below the safe value (Figure 4).
The worst result in terms of visibility distance is obtained when the ventilation is carried out by delivering air along the whole tunnel length since 4 minutes after the fire start up the visibility distance is below the safe value in the entire tunnel (Figure 4). On the contrary, exhaust gas extraction from the tunnel ceiling results to be the most effective ventilation system on the visibility distance, with the exception of the longitudinal ventilation on the fire upstream side. This assertion is confirmed also by the data shown in Table 4 from which it appears that safe escaping conditions for people who initially stands close to the fire location are achieved only with longitudinal ventilation and only in the upwind direction. However, people not standing initially very close to the fire could leave safely the tunnel on both fire sides especially in the case of the extracting semi-transverse ventilation system.

Table 4: Visibility distance (m) at the escape distance

Ventilation type	t = 2 min		t = 4 min		t = 6 min	
	upwind	downwind	upwind	downwind	upwind	downwind
Natural $\Delta P = 0$	**2.3**	**2.4**	**1.1**	**1.0**	**2.8**	**2.6**
Natural $\Delta P = 0.05$ mbar	**1.8**	**1.7**	**1.6**	**1.1**	**5.2**	**1.6**
Longitudinal	*100*	**1.5**	*100*	**1.7**	*100*	**1.4**
Semi-transverse supply	**1.3**	**1.4**	**1.1**	**1.1**	**1.4**	**1.5**
Semi-transverse extraction	**1.4**	**1.3**	**2.0**	**1.9**	**5.4**	**6.5**

6. DISCUSSION

The ensemble of the results obtained by the simulation of the pool fire inside the tunnel in the object consent to draw some considerations on the usefulness of the natural ventilation system (the only with which the real tunnel is equipped), on the need for a forced one and on its effectiveness.
Natural ventilation. The presence of natural ventilation, even excluding the worst case (i.e. $\Delta P = 0$ between the tunnel portals), is not sufficient to assure safety conditions for escape and rescue operations. In fact, in the case of non zero ΔP between portals, the induced airflow within the tunnel slightly blows smoke and hot gases downstream the fire, but isn't able to dilute and cold them significantly. This means that 30 s after the escape beginning, i.e. 2 min after ignition, gas temperature and visibility are already beyond the safety limits on both fire sides. In addition, as the time increases, environmental conditions in the tunnel further worsen. Only oxygen and carbon dioxide concentrations remain within safety ranges.
Semi-transverse ventilation. Both supplying and extracting semi-transverse ventilation systems appear to be suitable to maintain acceptable levels of contaminants in the tunnel at breathing height during the fire duration; nevertheless, temperature and visibility predicted

patterns are compromised. As a result, either for the relatively high temperature either for the scarce visibility escaping people, who initially stands close to the fire location, could not be able to reach the tunnel exit. Therefore, semi-transverse dilution was found to be ineffective as a mean for gas temperature and smoke control. However, comparing simulations results obtained with the semi-transverse ventilations, the extraction mode demonstrates to be much more efficient than the supplying mode to control the fire induced smoke and hot gases. In addition, the whole results show that the extracting semi-transverse ventilation system gives the best environmental conditions when both fire sides are considered. This could be important in particular situations, as mentioned below.

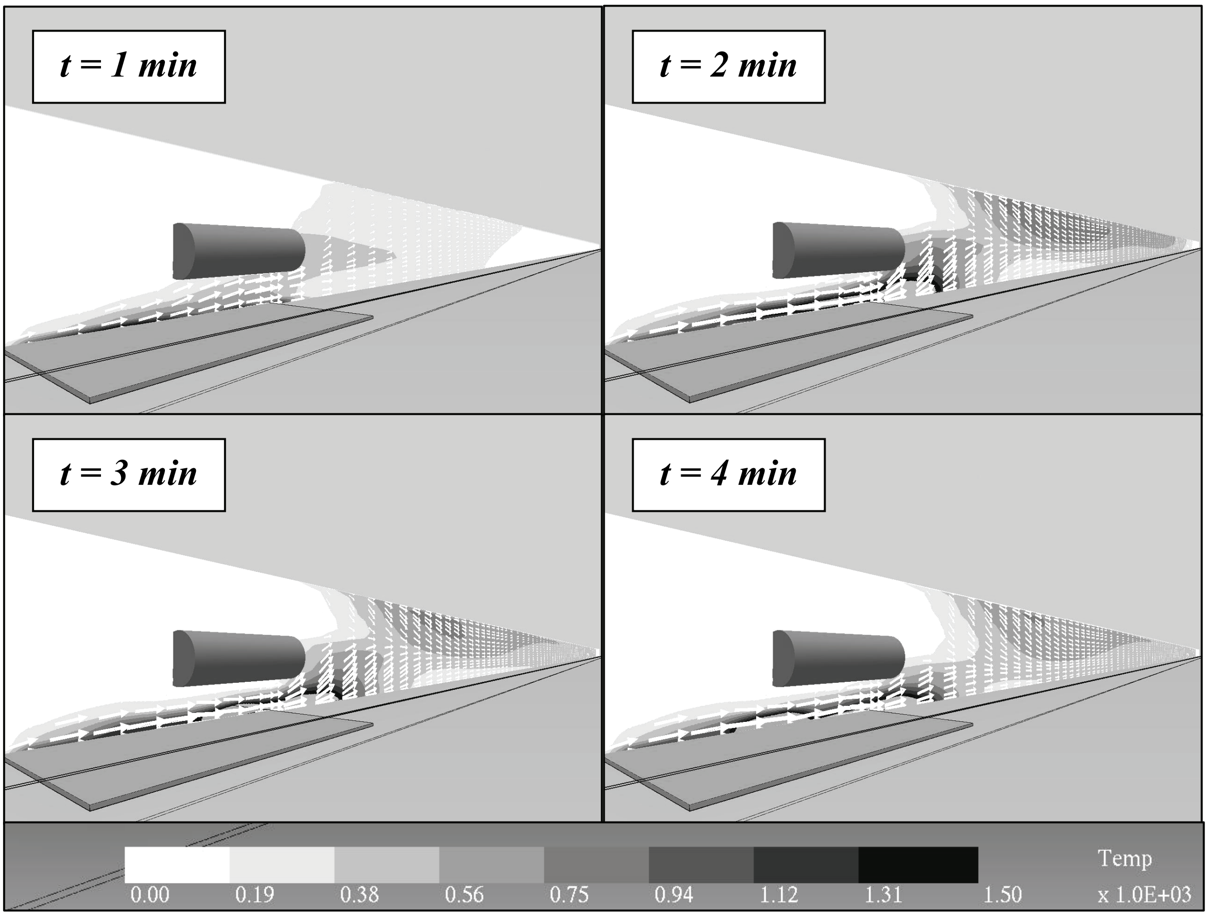

Figure 5: Time evolution (0-4 min) of temperature and velocity patterns on the tunnel middle plane with longitudinal ventilation (80 $m^3 s^{-1}$).

Longitudinal ventilation. Simulation results suggested that the longitudinal ventilation system is very effective for blowing all smoke and hot gases in the downstream direction, so immediately creating upstream the fire a safe route for evacuation and rescue. This is evident from Figure 5 where the time evolution of temperature and velocity patterns on the tunnel middle plane, are shown, relatively to the pool fire and the tanker. However, as Figure 5 indicates, this means that the portion of tunnel downstream the fire is rapidly filled with smoke and high temperature gases, nullifying any possibility of escape and/or rescue on that side. It is worth to note that, generally, in one-way tunnels there should not be vehicles downstream the accident and, then, the fire. However, a limit case could verify in which the traffic, before the accident involving the tanker occurred, was not fluid but slow or even at rest. This could happen, for instance, when an accident occurred, let us say, just outside the tunnel generates a queue that is the cause of the accident involving the tanker. In this case the longitudinal ventilation would be catastrophic for the people entrapped in the vehicles downstream the fire. On the contrary, the use of a semi-transverse ventilation system could result more effective and help to save more lives.

7. CONCLUSIONS

A gasoline pool fire generated by an hypothetical accident, involving a gasoline tanker, that could occur inside a real one way tunnel along the Southern Italy highway A3, between Pontecagnano and Salerno, was simulated by using *JASMINE* CFD code.
Various configurations of the tunnel ventilation system, including natural, semi-transverse and longitudinal, were simulated and their effectiveness for safe people evacuation and rescue was assessed.
Results indicated that, for the hypothesised accident, natural ventilation is not sufficient to assure safety conditions for escape and rescue operations. In addition, the longitudinal ventilation system results to be the most effective since it blows all smoke and hot gases in the portion of the tunnel downstream the fire, which is generally empty, so immediately creating upstream the fire a safe route for evacuation and rescue.
However, results also suggest that under conditions of traffic at rest, because of a previous accident occurred, extracting semi-transverse ventilation mode could be preferable to the longitudinal ventilation.

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CONTACT SYSTEMS AND MATERIALS IN ELECTRICAL CONNECTION TECHNOLOGY FOR ROAD TUNNELS

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ABSTRACT

Terminal rail components are component models and systems which guarantee as a main function the electrically and mechanically safe connection of lines . The most important group of line connectors are the terminals. The IEC 60947-1 lays down the specific requirements for terminals with screwed or screwless terminal strips which are primarily intended for industrial or similar application. In order to meet the electric and mechanic requirements the terminals are embedded in an insulation material which ensure maximum reliability under all climatic conditions. The insulation material WEMID applied by Weidmüller is a modified thermoplastic which compared with conventional thermoplastics possesses improved characteristics in behaviour in fire - according to UL-94 (V-0) – and regarding the continuous running temperature. Especially accidents in connection with tunnels and airports which happened in the past, but also traffic engineering require improvement and stabilisation of safety in favour of the public. WEMID insulation material is specifically adapted to the high demands regarding safety in extremely crowded places. Besides the use of WEMID insulation material, the metals for the electric and mechanic characteristics are selected under consideration of a very high quality level. They are subject to permanent tests in our own accredited laboratory and by the quality management. By consequently separating the tasks Weidmüller offers the best material for the respective functions. Steel for strength and copper for conductivity ensure a highest degree of contact reliability and are maintenance-free from the classic screw connection to the “innovative” industrially applicable insulation displacement connection with guaranteed multiple conductor connection!

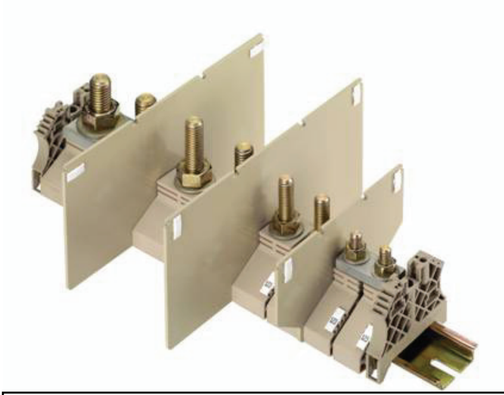
1. INTRODUCTION:

It took 13000 years until people could again travel by feet from the European continent to Great Britain. In 1802 a mine engineer presented a first serious proposal for the construction of a tunnel. In 1994 the Euro tunnel was put into operation. In 1911 the first European river tunnel was put into operation in Hamburg – the so-called “Elbtunnel”. Even today the construction of a tunnel is very cost intensive and in most cases a technical and geologic challenge for the engineers. A functioning safety system in the case of an accident or a fire becomes more and more important to save life. Thus, tunnel safety likewise means interface safety! This interface safety offers a variety of application possibilities where electric components are connected with power or data supply . In a modern industrial society where mobility increases more and more, safety and robustness are more important than ever. The used components und finally the necessary interfaces – like, for instance, the electrical connection technology – have to meet highest demands in order to cope with an increased traffic volume, difficult conditions, and to guarantee traffic control.

Weidmüller is **the** leading manufacturer and technology leader in the electrical connection technology and offers a variety of solutions and a broad product portfolio which meets the high demands of modern tunnel concepts. Today, the company is worldwide represented in more than 80 sales agencies and representations. For more than 50 years – some tunnels were already existing – when the SAK-terminal replaced the ceramic terminal by its new plastic housing and thus revolutionizing the electric cabinet, Weidmüller has been the technology leader in the field of electrical connection technology. This is especially reflected in the application of our products under extreme and changing connections. Since then the electrical connection technology is the core competence of our company and therefore it is also suited for your requirements in the field of tunnel safety and tunnel ventilation. Your demand represents the basis of our work.

2. FIELD OF APPLICATION: TUNNEL

Where in road tunnels do we find the necessity of electrical connection. – and which products does Weidmüller offer for this application? Subject energy: for power supply of control cabinets, for voltage distribution or for supplying ventilation systems stud terminals (pict. 1) are used which ensure a safe electrical connection up to 4000 V and 415A.

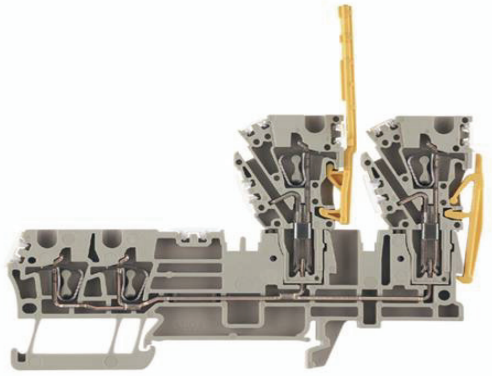


Pict. 1: Stud Terminals up to 300 mm^2 for Power Supply and Power Distribution

In the field of ventilation and lighting, where the electrical connections have to be protected against dust, dripping water and splash water, robust steel or stainless steel housings (which e.g. are equipped with terminals) are used for the distribution of data and feeders - if desired also with ATEX approvals and class of protection IP68 (pict. 2).

Pict. 2: IP68 Enclosures with ATEX-Approvals, acc. to customer requirements (drilled, milled and assembled)

For instance, pluggable terminals of the „WeiCoS"-type (Weidmüller Connection System) are used under cramped conditions where a great number of connections is necessary with only little room available. Here, installing and exchanging of prefabricated functional units is possible – extremely rapidly and precisely!! The plug connector is simply plugged onto the terminal (pict. 3).



It goes without saying that Weidmüller offers the corresponding tools and markers for all applications concerning connection technology – but also housings with ATEX approvals which are manufactured according to your requirements (milling, drilling, painting and mounting).

Pict. 3: WeiCoS-Plug Connector – The External Spring at the Plug Connector guarantees a reliable and permanent balance of the vibration stress as well as the extreme temperature fluctuations

3. REQUIREMENTS FOR TUNNELS

All components used for tunnel applications are subject to very high requirements with respect to climatic resistance, behaviour in fire and, of course, with regard to shock-proof features, e.g. in locations with explosion risk of different categories! For this purpose, our laboratory carries out special shock and vibration tests (acc. to BV 0440 0430) as well as tests for vibration-proof in the x, y and z-axes (pict. 4). Special requirements concerning controlling and monitoring are met by the following products: signal processing, overvoltage protection, relay and optocoupler insulation, terminals and multiple accessories which have been certified according to international standards . In the following I will explain how we, at Weidmüller, meet these high requirements concerning the electrical connection technology and how we even exceed them.

Pict. 4: Vibration Test with Stud Terminals!!

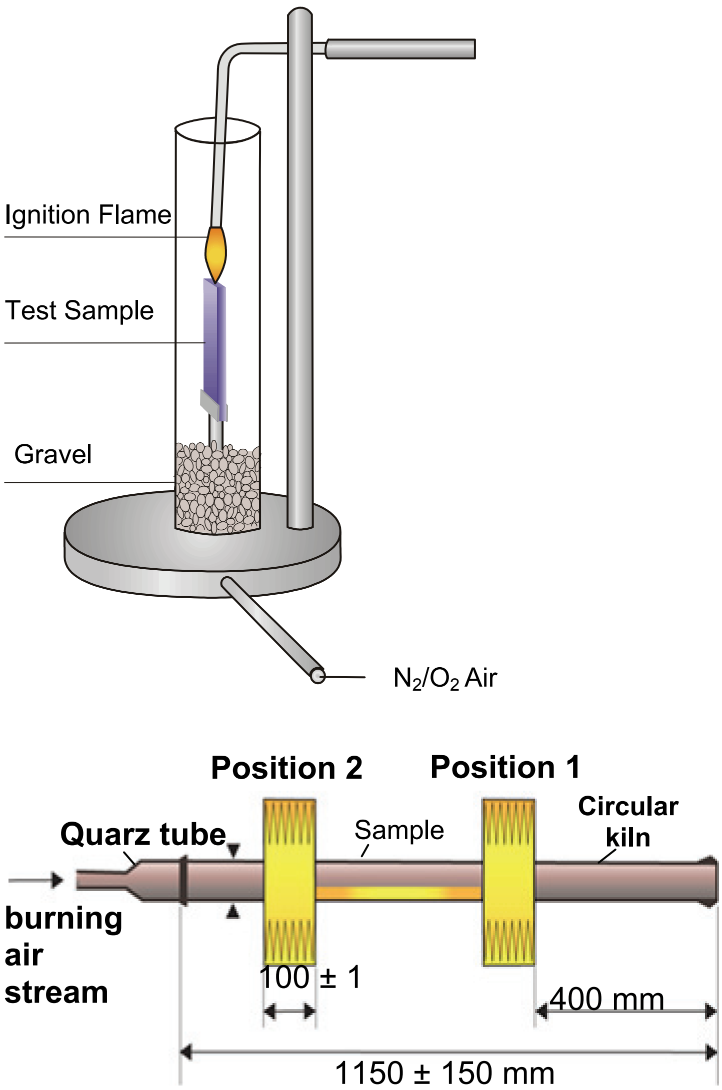
3.1 Separation of functions

One of the most important features of all Weidmüller contact systems is the separation of the mechanical and electrical function. Electrolytic copper is used to guarantee an optimum conductivity of the contact point – steel is used for the contact strength which holds the conductor in the contact point. So, the steel is used for mechanical stability. The result: a vibration-free and permanently maintenance-free fest connection.

This is the only way to achieve for both aspects the best results – and especially as far as contact strength is concerned one should not make compromises regarding durability and extreme conditions.

3.2. WEMID Insulation material

For insulating the housings of line conductors we use WEMID as a standard product. Apart from tolerating a higher continuous running temperature of -50°C to + 125 °C, being pollutant-free and being characterized by a high creepage current resistance (Comparative Tracking Index) CTI 600, this plastic has significantly better features regarding behaviour in fire (acc. to UL-94 (V-0), NFF 16-101/102 (I2/F2) as compared with conventional thermoplasts. Under consideration of recent fires in tunnels and airports, the emission of pollutants is in the focus of attention. During a "Low-Smoke-Emission" test (acc. To NFF16-101) the relevant components in the released smoke are measured in a precisely defined process, in order to determine the toxic potential. (Pict. 5). Here, WEMID has proved to be as far as possible pollutant-free and has been classified as "Low Smoke Emission" acc. to BS 6583.

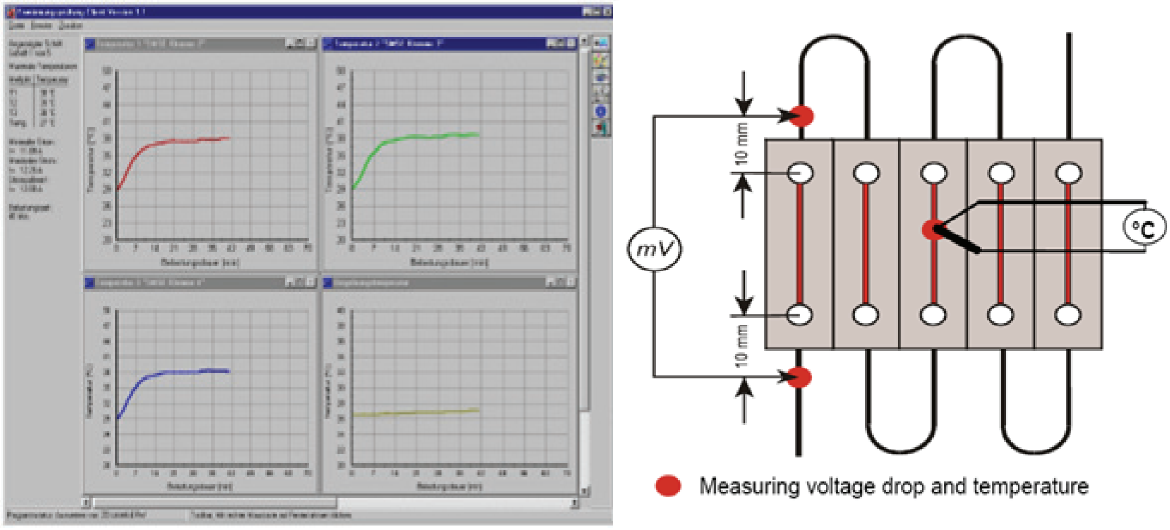


I2-test setup F2-test setup

Pict. 5: The insulation material WEMID – especially harmonized to the enquiries of tunnels – WEMID is toxic free and classified with "Low Smoke Emission" acc. to the BS6583 and NF16/101

3.3. Climatic, environmental and heating tests

Tunnels are always open! Therefore it is another important factor to expose the behaviour of the applied products to real, changing climatic and environmental influences in special climate chambers (pict. 6).



Pict. 6: Temperature Rise Test – for the determination of the behaviour under the exposure of heat

To ensure that electrical appliances and installations work faultlessly despite difficult climatic influences, standardized climatic tests (acc. To IEC 60068-2 and IEC 60512-6) are run in the certified Weidmüller laboratory (pict. 7) with all our components (pict. 8).

Pict. 7: Accreditation Certificate acc. to DIN EN ISO/IEC 17025 200-04 – the laboratory activities are within the ISO 9001 certified QM-System!

Pict. 8: Climatic Test – To make sure that the electrical equipment and installations operate properly despite climatic influences, standardized environmental tests have been devised in our accredited laboratory.

Specifically, we test the behaviour of the appliances under cyclic wet heat with a humidity of up to 97% over a period of ten days; a cold test at -65°C over a period of two days; dry heat at 130°C over a period of seven days and a salt mist test over a period of two days. During the salt fog test, the stability of metal parts, respectively surfaces, is tested; moreover they undergo an optical assessment as well as an electrical check. Corrosive gas tests with SO_2H_2S and other mixed gas complete the climatic tests. If an electrical contact finally has been installed and the connected applications are in use, a permanent operability is assumed.

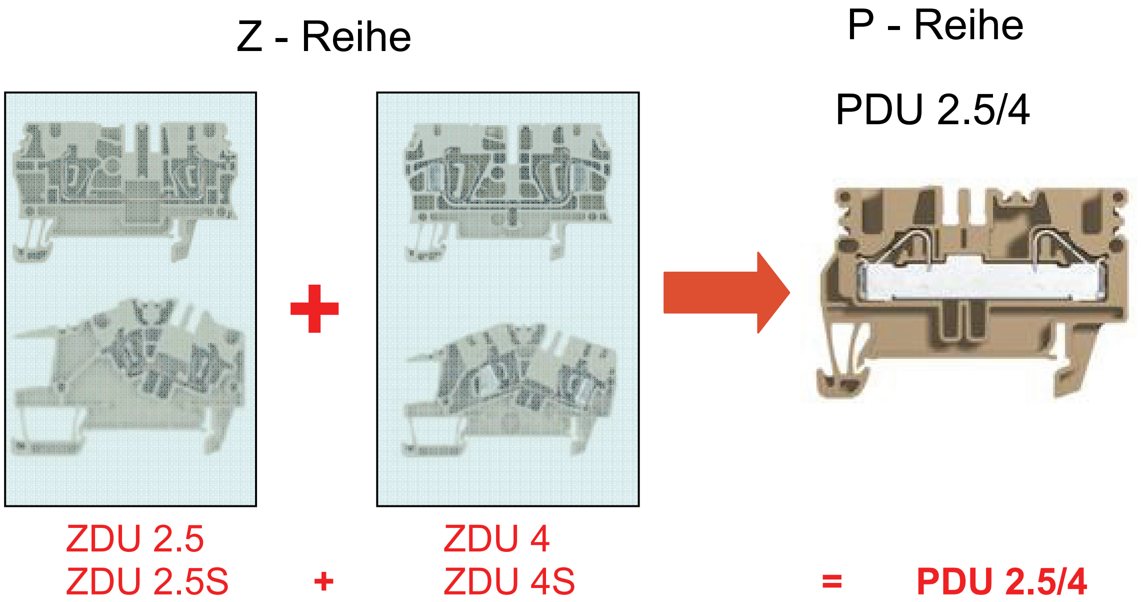
It is especially important for the application in road tunnels that the contact point does not loosen due to vibration, jerky movements or heating (flow behaviour) which would affect the power transmission (malfunctions) and cause unnecessary maintenance work. All connection technologies applied by Weidmüller (from the screw to the insulation displacement connection technology) are guaranteed maintenance-free. In order to achieve these metered values not only for products which have just left production, the conventional terminal with screw connection, for instance, has been subject to a thermal ageing at 130° over a period of 168 hours. Subsequently, a vibration test with the 20fold acceleration of gravity has been carried out for another 168 hours. After the test had been finished the pull-out force of the conductor was still about the 6fold of the required minimum value. Due to this definite proof of Weidmüller products being maintenance-free and to possess high contact reliability even after years, they by far exceed the international requirements.

4. TUNNEL SAFETY

It goes without saying that merely first-class material and extensive tests are no guarantors for an optimal product. – In order to meet the high demands with respect to rapid, simple and space-saving installation – despite highest safety requirements – conceptions which have been elaborated in detail are indispensable. In the following I would like to point out the effects of the long years of Weidmüller experience on electrical connection technology on the basis of 2 connection systems which are especially interesting for tunnels.

4.1. With safety – directly plugged - direct cost reduction

Weidmüller presents with its P-series a new generation of terminals which is characterized by a profitable overall conception. Cornerstones of this conception are the “Push-In” connection technology and the consistent reduction of types by means of a “3-pitch product conception (pict. 9), i.e.: wiring up to 16 mm2 can be realised efficiently with only three terminals (PDU 2.5/4, PDU 6/10 and PDU 16). Until now, the users had to apply 5 terminals – i.e. more types and article numbers –. The reduction of types ensures an efficient and profitable management of logistics and purchasing with the effect of cost reduction.

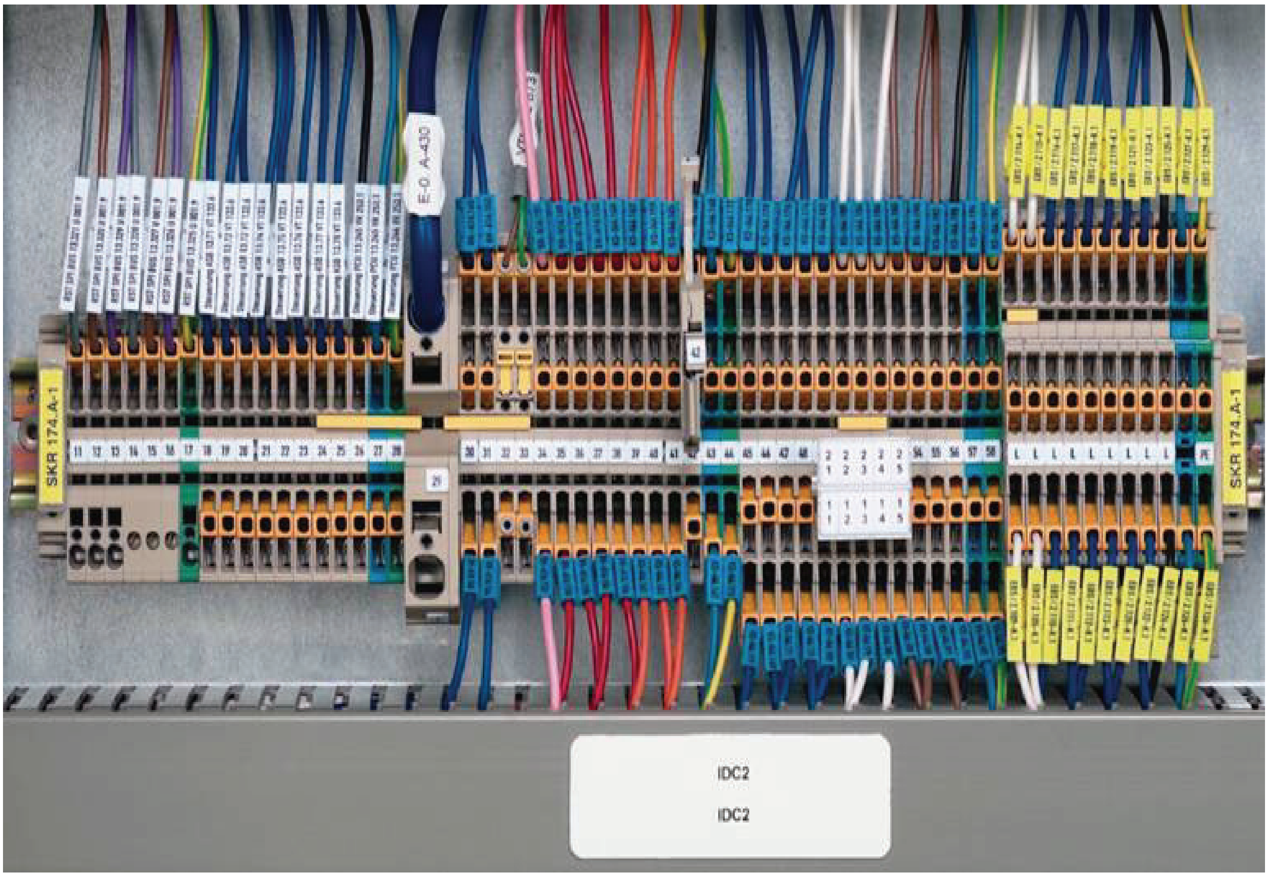


Pict. 9: Push In Connection Technology – Reducing types without restrictions for an economic Purchase and Logistic Management!

Cost pressure increases permanently. However, higher costs are hardly accepted by the customer and even reduce the competitiveness of the company. Therefore, product generations with additional value are of decisive importance. The Weidmüller P-series is such a product generation. Its advantage: Minimizing the overall size by simultaneously maximizing the rated current . Thus, conductor cross sections can be bundled and different types can be reduced. Less articles mean: less planning and administrative complexity as well as shorter article lists for a faster article selection. The simplification of order procedures, of logistic complexity with less storage space required and reduced receiving inspection tests as well as spare parts management, are essential elements of an optimisation of company processes with corresponding cost reduction. Article reduction also means: less capital commitment and better demand planning with increased purchase quantities; thus, frame contracts can enable further cost advantages. Weidmüller P-series with its “3-pitch product strategy” is the consequent step towards “total cost of ownership” (TCO). It enables a continuous cost reduction in the entire process chain of the company. The electro-mechanical conception – user friendly -. The motto of the P-series is: more efficiency features with a small size of the terminal. All terminals are characterized by the “Push-In” contact system. Here, the stripped, massive or finely-stranded conductor with its crimped wire end ferrule is simply plugged to the conductor stop in the clamping point – ready! A tool is not necessary for connection.

4.2. The new generation for control and signalling lines

Our second example is the insulation displacement connection in the IDC terminals (pict. 10). The abbreviation IDC can directly be derived from the conductor connection: Insulation Displacement Connection. The challenge is to achieve a safe electrical connection by opening the insulation without damaging the conductor (solid and finely stranded).

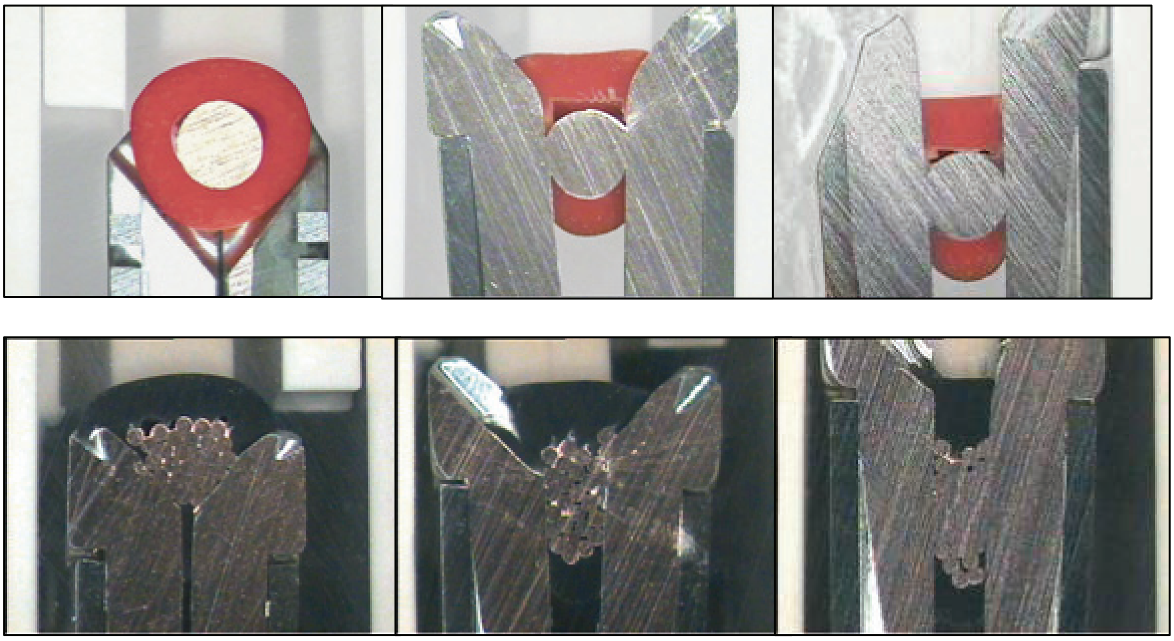


Pict. 10: The yellow slider guarantees a visible safe connection – So the position clearly indicates whether a right connection has been made or not.

The Weidmüller IDC terminal is at present the only terminal in the world which is based on the separation of steel for an optimum contact strength and copper for conductivity. Due to this fact it fulfils as the only terminal the requirements for multiple conductor connections according to IEC 60352-4. Here also a external spring contact ensures highest contact reliability comparable with the tension clamp technology.

Above all connection and disconnection of a terminal with copper conductors which are armoured with different insulations is a great challenge for the contact points between conductor and contact element (Pict. 11). Further proof for the contact reliability of the Weidmüller IDC technology is the fact that there is no inadmissible heating at the contact points. Due to the described contact reliability which is unique at Weidmueller the great advantage regarding conductor technology – 50% time saving with reduction of assembly costs – becomes obvious. To be only fast is not sufficient! We will also give you any support for the handling of the IDC terminal. For instance, the position of the yellow slider clearly indicates whether a right connection has been made. Here, the probability that a fault occurs is much lower as compared with the tension clamp or the screw.

If demanded, Weidmueller moreover offers a comprehensive comparison chart which contains all tested cable types.



Pict. 11: IDC-Connection Technology – Minimized Assembling Work without Stripping, Screwing or Special Tools!

5. CONCLUSION

Cooperating with Weidmueller means you have a partner who supports you with a profitable overall conception. Optimise your investments in the entire process chain with a partner for the electrical connection technology. With a portfolio of more than 30 000 products we offer systematic solutions to meet your requirements. Attain more tunnel safety due to the integration of Weidmueller products – no matter what kind of tunnel project you are just working on!

Reports of the
Institute for Internal Combustion Engines and Thermodynamics

HEFT NR.	VERFASSER	TITEL	ERSCHIENEN	PREIS in ATS
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67		Der Arbeitsprozeß des Verbrennungsmotors The Working Process of the Internal Combustion Engine Tagung / Symposium 18. und 19. September 1995	1995	950,--
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