TUNNEL ACCIDENTS AND THEIR IMPACT ON RELEVANT GUIDELINES IN AUSTRIA

Rudolf Hörhan
Federal Ministry of Transport, Innovation and Technology

ABSTRACT
The catastrophic tunnel fires of the year 1999 and a series of accidents in single-bore tunnels in the summer of 2001 triggered extensive discussions and proposals relating to tunnel safety.

The introduction provides brief descriptions of 3 catastrophic tunnel fires along with key data on the tunnels, the fires, and the consequences. Based on key insights derived from these fires, the changes are highlighted that have been implemented in the guidelines for safety equipment in road tunnels.

1. INTRODUCTION

In Austria, the two catastrophic fires of 1999 as well as a number of head-on collisions in single-bore tunnels in August 2001 had a major influence on national guidelines and regulations for the design of new and the rehabilitation of existing tunnels. New developments and improvements aimed at preventing disasters and defining emergency response measures are driven mainly by reports on and analyses of past incidents. Therefore, I wish to provide, by way of introduction, a brief overview of the key data of three major tunnel fires which have had a significant impact on the development of relevant guidelines.

2. FIRE REPORTS

2.1 Mont Blanc tunnel, 24 March 1999:

Specification:	Length	11,600 m
	AADT:	5,473
	Thereof lorries:	40 %

The tunnel has a transverse ventilation system comprising 4 fresh-air ducts and one ventilation duct for fresh air or exhaust air below the roadway (see Fig. 1). Each fresh-air duct has a capacity of 75 $m^3/_s$ and supplies one quarter (1,450 m) of one half of the tunnel length. Exhaust air is extracted at a rate of 300 $m^3/_s$, which corresponds to a flow rate of 25.8 $m^3/_{s,\ km}$. Exhaust openings sized about 1 m² are provided every 300 m. Fresh-air openings are located at the bottom of the side walls, about 1 every 10 metres. Fresh air is also supplied to separate shelter rooms which are separated from the road tunnel, designed for 2-hour fire resistance and situated every 600 m.

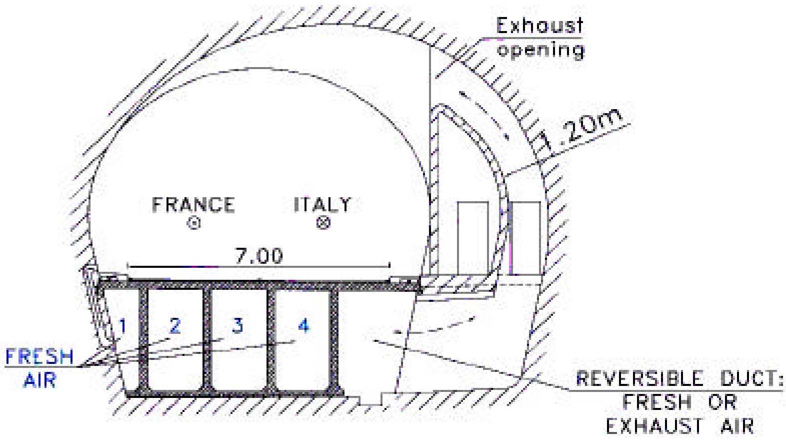


Figure 1 : Tunnel cross-sections

THE BLAZE

A tractor-trailer on its way from Chamonix to Italy caught fire about half-way through the tunnel (6,550 m from the French end and 5,050 from the Italian end). The vehicle was carrying 9 tons of margarine and 12 tons of flour. The tank contained approx. 550 l of diesel fuel and the refrigerated trailer was fitted with a highly flammable thermal insulation foam. The fire broke out below the driver's cabin and quickly spread from the tractor, which had stopped at Lay-by 21, to the entire vehicle. The driver's attempts to extinguish the fire failed. The truck driver fled towards Italy as the longitudinal air flow in the tunnel caused the smoke to drift towards France.

The ventilation system of the tunnel was set to maximum air supply to provide fresh air to persons at the site of the fire. However, this move fanned the flames even more and pressed hot fumes through the tunnel, with flames leaping across distances of up to 300 m. Thus, the air supplied did nothing to relieve the situation but, instead, even created additional dangers to tunnel users. The fire-fighters, who entered the tunnel first from the French side, were stopped by heavy smoke after approx. 3,700 m. After a number of attempts to turn their vehicles round, the fire-fighters finally sought refuge in the shelter rooms. Once there, they had to wait more than 5 hours for their rescue, which one of the fire-men did not survive. A total of 17 fire-fighters were trapped in the tunnel or in the shelters. They were finally rescued through the ventilation shaft. From the Italian side it was possible to get 10 m close to the burning lorry. Toll company vehicles rescued lorry drivers who had stopped their vehicles in the tunnel, taking them to the Italian side.

34 vehicles, including 20 lorries, were burned in the Mont Blanc tunnel. It took about 53 hours to get the fire under control. 39 people died, of which 27 had stayed in their vehicles, 2 had fled to another vehicle, 9 died outside their vehicles. 2 persons were found dead in a shelter room. They are thought to have been killed by the high temperatures. The tunnel was heavily damaged along a length of 900 m.

2.2 Tauern tunnel, 29 May 1999:

Specification:	Length	6,400 m
	AADT	14,100
	Thereof lorries:	26 %

The tunnel is equipped with a full transverse ventilation system comprising 4 ventilation segments, with the fresh and exhaust air of the outer segments being routed through the tunnel portals and the internal sections being supplied by a ventilation shaft located in the middle of the tunnel.
Fresh air can be supplied at a maximum rate of approx. 190 $m^3/_{s,\ km}$ and exhaust air extracted at a maximum rate of about 115 $m^3/_{s,\ km}$. The exhaust air openings are about 0.2 m^2 in size and located every 6m in the tunnelceiling roof. The tunnel is equipped with an automatic fire detection system.

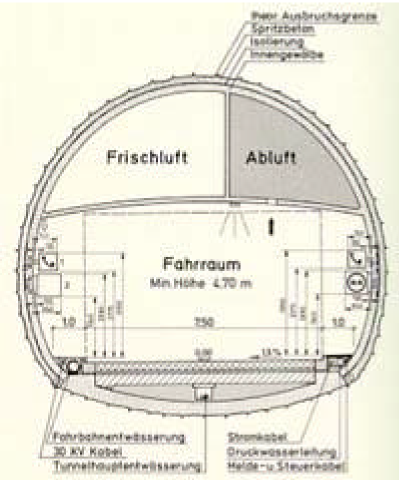


Figure 2 : Tunnel cross sections

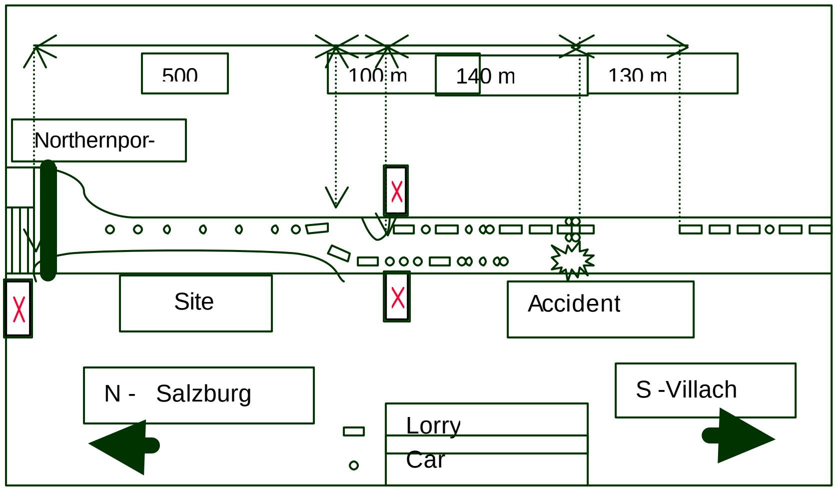


Figure 3: Situation of the incident

THE BLAZE

In the Tauern tunnel, roadwork was being carried out over a length of about 500 m close to the northern portal. One lane had been closed to traffic. Traffic flow past the roadwork site was controlled by traffic lights. The accident on 29 May 1999 was triggered by a rear-end collision. A lorry carrying hazard class 9 spray tins and paints stopped behind a column of vehicles waiting at the traffic lights ahead of the roadwork site. This lorry was followed by 4 cars, all of which stopped duly. The tractor-trailer unit behind them was unable to stop in time, shoved two of the cars under the lorry loaded with the paint and smashed 2 cars against the tunnel wall. The vehicles caught fire immediately. The flames spread to the vehicles that had meanwhile been queuing up. A total of 16 lorries and 24 passenger cars were burned.

Only 15 minutes after the fire alarm fire-fighters entered the tunnel from the south entrance but came up against heavy smoke 4,500 m from the south end, which prevented their further progress. It was only after the ventilation system had pushed the smoke towards the north end of the tunnel that the fire-fighters were able to penetrate farther into the tunnel and rescue 3 persons who had fled to an emergency niche. Heat and smoke prevented the fire-fighters from approaching the site of the accident from the south. Therefore, the ventilation system was reversed to blow the smoke south-wards again and thus enable fire-fighting from the north end.

North of the scene of the fire, smoke levels and visibility permitted an escape during the first 20 minutes. This chance was used by most of the persons inside the tunnel.

Overall, 12 people died in the fires, including 8 who were killed when the lorry crashed into 4 cars. 2 victims, who had obviously not even tried to escape, were found in their vehicles. One person tried to escape but finally returned to the car. A German long-distance lorry driver was suffocated some 800 m south of the accident site as he attempted to escape. 80 persons managed to flee from the tunnel, either on foot or by car. A total of 16 lorries and 24 cars were burned.

The tunnel was damaged along a length of 500 m. The inner ceiling, the roadway and the side walls were destroyed over a length of about 300 m. The Tauern tunnel was cleaned and repaired within a period of 3 months. At the same time, significant improvements were carried out.

2.3 Gleinalm tunnel, 6 August 2001:

Specification:	Length	8,320 m
	AADT	14,570
	thereof lorries:	10.5 %

The tunnel ventilation system is a full transverse ventilation system with 6 ventilation segments, with fresh air and exhaust air being routed through the portals as well as 2 ventilation shafts, located at one third and two thirds of the tunnel's length. Fresh air is supplied at a maximum rate of 135 $m^3/_{s,\ km}$ and exhaust air extracted at a maximum rate of 108 $m^3/_{s,\ km}$. The exhaust openings are located every 12 m in the tunnelceiling. The tunnel is equipped with an automatic fire detection system.

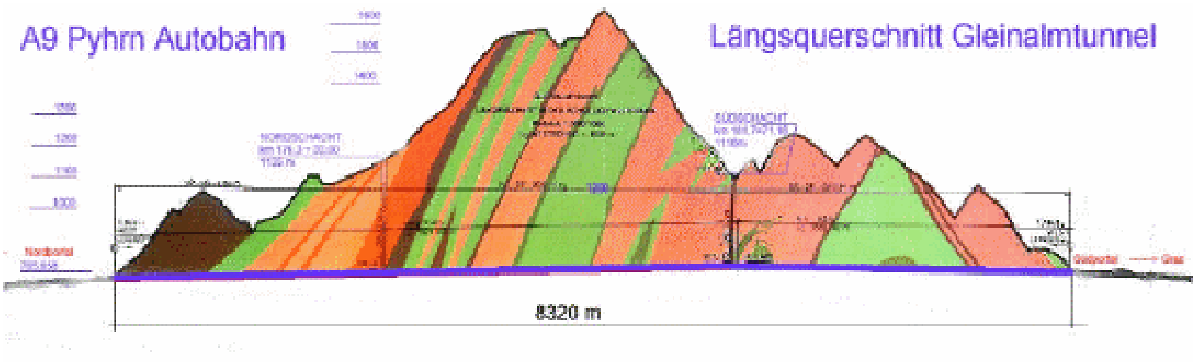


Figure 3: Longitudinal section

THE BLAZE

On 6 August 2001, a station wagon carrying 3 passengers crashed into a minivan with 6 passengers on board and a camping trailer in tow. The two vehicles involved in the accident caught fire immediately and burned out completely. The car driver who had caused the accident and his two passengers were seriously injured but able to escape. They were taken to the north entrance by other motorists. 5 of the 6 persons on board the minivan burned to death in their vehicle. One girl managed to escape with her clothes on fire. A motorist extinguished the flames and took her out of the danger zone but had to leave her lying on the floor due to a lack of oxygen. Unfortunately, a number of drivers passed the girl without offering help. She was finally rescued by fire-fighters arriving on the scene.

Only one minute after the collision the fire emergency response programme was activated. Over the tunnel radio system, motorists who were already in the tunnel were asked to leave the tunnel immediately. When the fire-fighters arrived at the scene of the fire, all other vehicles had left the tunnel with the exception of the two that were ablaze. Entrance to the tunnel had been blocked automatically. The fire lasted 37 minutes.

Damage caused by the fire comprised mainly concrete spalling along the eastern tunnel wall, along the kerb, and along not more than 10 m of the roadway. The tunnelceiling and the fresh air and exhaust ducts were left undamaged. About 170 m of the tunnel were polluted by soot particles.

2.4 Summary

In all three events, the first fire-fighter vehicles arrived on the scene within a relatively short time (about 15 minutes). However, in both the Mont Blanc and the Tauern tunnels, fire-fighting activities were started on the side where the smoke was heaviest. In both fires, the fire-fighters' effectiveness in saving human lives was limited. In the Mont Blanc Tunnel, people were rescued who had fled to the shelter rooms; in the Tauern tunnel, 3 persons were rescued from emergency niches, which was made possible by reversing the direction of smoke propagation. The tunnel users' safety thus depended primarily on the appropriate response immediately after the fire had broken out. This highlights the importance of educating and training tunnel users in correct behaviour. Also, the need for effective communication between the tunnel control room and tunnel users and emergency personnel was clearly recognised. Changes in the guidelines were based on the insights outlined above and measures designed to prevent accidents or minimise their consequences. One of the key measures taken aims at improvements in the self-rescue phase.

3. CHANGES IN AND AMENDMENTS TO THE GUIDELINES:

3.1 Ventilation

The design fire for a two-lane tunnel was specified as a blaze involving one lorry and two passenger cars, with smoke being generated at a rate of 120 $m^3/_s$. In the future, smoke is to be extracted through large openings with proven effectiveness at any point within a 150-metre segment of an air duct. The possible existence of leaks in the air ducts and thus in the extraction louvres has to be taken into account by introducing leakage coefficients. Specifications for extraction louvres are determined relative to the calculated air pressure. The leakage coefficient for the air duct has been specified as 5 $m^3/_{s,\,km}$. The capacity of the ventilator has to be increased by the leakage coefficient applying to the respective ventilation segment. The extraction louvres should be designed for maximum width, with the desired target being 3 metres. When retrofitting a system, care must be taken to match the aperture in the concrete provided for the louvres to the cross-section of the air duct.

Individually controlled extraction louvres are also required with semi-transverse ventilation systems. Since fresh-air supply through a semi-transverse ventilation system may require stopping and reversing the air flow in a time-consuming procedure, semi-transverse ventilation systems are permitted only for extraction. In addition, extraction fans have to be design to resist and remain operational at temperatures of 400° C for 60 minutes.

Ventilation control is of great importance in a fire emergency. Apart from ensuring well-coordinated extraction, fresh air supply must be operated at minimum positive pressure in the section affected by the fire.

3.2 Fire detection

Keeping smoke away from the roadway also requires efficient fire detection. The guideline regulating tunnel equipment (RVS 9.282) provides that every tunnel must be fitted with a ventilation system designed for fire emergencies as well as with an automatic fire detection system. Maximum permissible fire detection time is defined in seconds relative to the velocity of the longitudinal air flow. Compliance with this requirement has to be demonstrated for a given fire load.

Tab.: Maximum fire detection time in seconds

LONGITUD-INAL AIR SPEED	FIRE DETECTION		FIRE LOAD
	PRE-ALARM	ALARM	
up to 3 m/s	60	90	2 x 1 m² fire fuelled by 10 litre spirit pool (C_2H_5OH) Nominal heat re-lease: approx. 1.5 MW
=3 m/s	120	150	2 x 1 m² fire fuelled by diesel pool; each comprising 10 litres of diesel and 5 litres of petrol Nominal heat re-lease: approx. 3.5 MW

With the new ventilation systems featuring large fire dampers, the exact identification of the site of the fire is critical to control the setting and opening of the dampers nearest to the fire. Therefore, the fire detection system must be able to localise the site of the fire with an accuracy of 20 m.

Beside the automatic fire detection capability, which basically responds to an increase in temperature, the detection of smouldering fire in the road tunnel is also considered of eminent importance. Requirements to be met by such systems - which have only recently become commercially available - have already been defined. The system must be able to distinguish between smoke emanating from a fire and other factors such as dust or exhaust fumes.

Another important point in tunnel risk management is automatic monitoring of dangerous goods transports. Here, too, some first proposals have been made and tests conducted. The guidelines specify the standards to be met by an automatic monitoring system. The system must automatically provide data to the control centre whenever dangerous goods pass specified points, such as tunnel entrance, tunnel exit, ventilation and smoke extraction zones.

3.3 Video system

Traffic is monitored and controlled by means of a video system. Such a system is required to enable complete surveillance of the roadway. Cameras should preferably be positioned in emergency niches, lay-bys, crossover passages and portal areas. All camera signals are to be transmitted to the control centre in live image format.

In addition to video surveillance, video image evaluation standards have been defined to cover developments in this area by the guideline. Video image evaluation allows existing video systems to be used for the detection of congestion and vehicles positioned in lay-bys etc, and may thus replace other operating or safety systems. Video image recording, which has recently been implemented in a number of tunnels, is defined as a video capturing application. This involves recording television camera images for documentation purposes cation. This involves recording television camera images for documentation purposes and as a basis for the initiation of special measures.

3.4 Emercency call -boxes

Emergency call-boxes are provided to enable user to report dangers and accidents in the tunnel and thus to contribute to the rapid initiation of emergency response measures. Like all safety installations, such systems are classified by the new RVS guideline according to the hazard class of a tunnel. Tunnels are grouped into 4 hazard classes based on traffic density, uni- or bidirectional traffic, additional points of conflict in the tunnel (e.g. merging lanes or intersections) and the frequency of dangerous goods transports.

The new guidelines differentiate between emergency and help systems, with emergency systems being required to meet higher fail-safe standards. Emergency call-boxes are thus required for hazard classes 3 and 4, while tunnels exposed to lesser hazards may be equipped with help call-boxes. As a general rule, emergency call-boxes have to be installed in accessible niches to permit users proper communication with the control centre. The doors have to be fitted with safety glazing. Emergency call-boxes with simple bus structure are allowed only for hazard classes 1 and 2, while hazard classes 3 and 4 require a ring-topology bus structure.

3.5 Radio system

In case of accidents or major emergencies, effective communication between emergency response personnel, tunnel users and the tunnel control centre is of key importance. Therefore, significant changes have been incorporated into the new guideline in this regard, which, overall, result in additional costs. For the tunnel radio system, 3 categories have been specified: in category 1, the entire system is allowed to break down if the HF radiation system (leaky feeder cable or antenna) or the amplifier is damaged. The system uses antennae with L-feeding or T-feeding (from the middle of the tunnel).

In the next-higher category 2, radio reception is allowed to fail ...

– over a distance of not exceeding 500 m if the leaky feeder cable is damaged
– over a distance of not exceeding 3000 m if an amplifier unit fails or the transport cable is damaged. The system is designed
– partial radiant emittance with cascading supply
– radiant emittance with feed from backside in case of failure
– parallel leaky feeder with antiparallel feeding or partial feeding.

In the highest category 3, radio reception is allowed to fail over a distance of not exceeding 500 m if the leaky feeder cable or the transport cable is damaged or the amplifier unit fails. The system may be designed with feeder cables strung in star configuration or with redundant tunnel transmitters and receivers, transmission amplifiers and transmission cables with appropriate failure surveillance. Every tunnel radio system has to feature a traffic information capability allowing messages broadcast from the control centre to override other channels. This enables control centre staff to inform tunnel users in case of accidents or fire in the tunnel and provide information about the appropriate action to take.

3.6 Information transmission time

In case of accidents or fires in a tunnel information has to be communicated very quickly, e.g. from an emergency call-box or a response unit. For this purpose, RVS 9.282 defines maximum permissible times for information transmission. This includes the specification of maximum transmission times for messages, i.e. the time from receipt of the information by the remotest activating device to its arrival at the operating or control centre, as well as maximum permissible information transmission times for commands, i.e. the time from issuance of a command in the operating or control centre to its receipt by the activating device and feedback from the device, depending on the hazard class.

3.7 Cables and wires

Particularly the Tauern tunnel fire showed that cables and wires laid in the kerb are protected even in the case of very long fire exposure times. In the road tunnel itself, it is of course not possible to protect all wires in the event of a major fire. Nonetheless, the RVS guideline specifies more stringent requirements in order to prevent a need for additional repair work, and thus closure to traffic, in the event of smaller fires, which occur quite frequently. Cables and wires are therefore not allowed to be laid in the road tunnel, as a matter of principle, except where this is necessary due to the nature of the installation (e.g. radio equipment, fire alarms). For reasons of operational safety, they should be placed, uncut, in the kerb or in cable ducts. They should, moreover, not contain any halogens; neutral and earthed wires should be separated. In addition, maintenance of E 30 operability is required as defined in the standards ÖNORM DIN 4102-12 and insulation should conform to FE 180 (according to ÖNORM E 3653)

– for cables strung uncovered in the road tunnel over a length of more than one metre or, in exceptional cases, in fresh-air ducts; for power cables providing safety power supply between operating centres, the operating station and electric niche, and
– for operating and safety installations required to meet higher standards (e.g. power cables feeding louvres) and
– for transport cables for the fire detection system.

3.8 Structural safety

Structural safety specifications are currently defined in guideline RVS 9.281. These include, most importantly, easier access for emergency services (fire-fighters) in case of fire. With two-bore tunnels, crossovers should be provided from every second emergency call-box niche, which corresponds to a spacing of 500 metres. Unlike in the past, these cross passages are accessible for emergency response vehicles. Passages every 1000 metres can be used by all lorries. In tunnels with high congestion frequency, such as tunnels in urban areas, crossovers are to be provided at shorter intervals. In Austria, this requirement practically applies only to tunnels built according to the cut-and-cover method.

To prevent accidents, particularly head-on collisions in tunnels with bidirectional traffic, an experts committee specifically set up for this purpose has proposed measures including rumble strips in the middle of the roadway and clear marking of the hard shoulder with light-emitting diodes. These measures will be discussed in detail in a separate presentation.

FRESH SOLUTIONS NEW CHALLENGES - MANAGING THE RISKS INHERENT IN NEW TUNNEL SAFETY SOLUTIONS

Arnold DIX
Phillips Fox Lawyers, Australia

ABSTRACT

There are no solutions which provide absolute tunnel safety for users, operators, owners and insurers of transportation infrastructure - tunnels are no exception.

There are however developments in tunnel safety which can alter the probability of an incident occurring and/or the consequences of such an incident. This paper explores the dangers of categorising developments in tunnel safety as providing solutions to 'problems' when in reality all that usually occurs is an alteration of the probability and consequences of an incident.

In a world where community, political and legal expectations change, often independently to the evolution of the engineering expertise which underlies the performance of infrastructure, it is inevitable that there will be a tension between the expectations of those who:

- *use, maintain and operate facilities*
- *design, develop and promote new developments in tunnel safety*
- *insure the ultimate risks.*

The challenge is to manage these tensions.

Legal Overview

It is useful to briefly mention some legal principles with respect to potential liability for engineers in tunnel safety design - thankfully the broad principles can be summarised and have global application.

For the design engineer the task is simple to state in broad terms.

- An engineer must bring to the design task such skill as would be expected of a competent engineer expert in the task engaged to perform.

This is generally the test in all countries, see for example:

- German Federal Court of Justice (BGH) 31 January 2002 4 StR 289/01 (Wuppertaler overhead railway deaths)
- American Case - City of Mounds View v Waligarui 263 N.W.2d 420,424 (MINN 1978)
- English Case - Gagne v Bertram 1934 43 C.2d 481, 275 p2d15

Having articulated this broad principle the more difficult question is determining - upon the particular facts - what was appropriate.

In all jurisdictions the test is <u>not</u> with hindsight - it is on the basis of the state of knowledge at the time the experts skills were used. As explained by an English court:

> 'In this world there are few things that would not have been done better if done with hindsight. The advantage of hindsight include the benefit of having a sufficient indication of which are unimportant … the standard … to be expected of a professional man must be based on events as they occur and not in retrospect' (Dutchess of Argyle v Beuselinck (1972) 2 Lloyd's Rep 172p185).

The recent catastrophes at Mont Blanc, Gotthard, Kaprun and the tunnelling component of the World Trade Centre collapse have contributed to changes in what is expected of the engineering expert.

Spare a moment to consider the position of parties after an incident.

For the insurers of infrastructure representations (warranties) about the physical safety characteristics of the tunnel and the way it is operated go to the heart of their preparedness to take the risk - misrepresentations about the characteristics of a particular tunnel to an insurer can in some circumstances allow the insurance company to avoid the obligations under the contract of insurance - Even if the owner made the representations without knowing they were wrong.

While for an operator they may find themselves at the forefront of liability in the event of an incident - because like the driver of a car - there is a universal presumption the exercise of their judgement and skill directly effects the consequences of an emergency/safety incident.

The engineers are caught somewhere in between the parties - and it is for this reason they must be careful to document their professional deliberations.

Factual Examples

In recent years I have been fortunate enough to conducted independent (and often confidential) reviews of the systems, operations and procedures of existing transportation tunnel systems. My views are founded not upon the promises of new or emerging technologies, the undertakings of those who promote it or the excitement of the latest research, but in the often mundane expression of all that work which has gone before as evident in an operational system.

For example I am consistently reminded of the gulf between those who designed the hardware and operational controls that provide the safety and ventilation systems on the one hand, and those charged with the responsibility of operation, maintenance and day to day revision of the procedures. All too often the intimate understanding of the safety solutions touted during the early stages of a project (and often at least in part responsible for the success and funding of the project) have been lost as the project makes the transition between commissioning and operation. This problem can be particularly acute if the safety measures add significant costs to the operation of the tunnel after commissioning.

This observation is equally true for upgrades of old systems, where new technologies are often blended with old to provide an enhanced operational environment. Once again the translation of the theoretical benefits of the new technology are often distorted and diluted in the transition to what is often a comparatively mundane operational environment.

For the purpose of illustrating my argument let me reflect briefly on a number of case studies from my work over the last six months or so.

1 Urban rail tunnels - New York, World Trade Centre Underground

As part of my review of an urban underground rail system's safety management practices I was required to attend the World Trade Centre in the weeks following its collapse and discuss the effectiveness of the emergency procedures in the minutes following the terrorist attack.

By way of brief overview the New York ‘subway’ system is a blend of previously, separately run, cut and cover railway tunnels which have been bought together as one in recent years and provide a high frequency and high density service under the island of Manhattan. Those portions under the World Trade Centre were purpose built comparatively modern - integral components of the World Trade Centre.

Inspection of the network revealed comparatively old infrastructure with a ventilation and control network system which bears little or no resemblance to that expected in a new project. In other words the New York underground system is typical of that found in most major cities which evolved during the earlier part of the 20^{th} century. It has variously been estimated that to bring the ventilation system up to a standard which is comparable to that of new projects would cost tens of billions of US dollars.

When the terrorist attack occurred on September 11, 2001, an emergency response was initiated which either removed, or stopped entering, in the order of ten thousand people from the underground system, and despite the destruction of much of the underground rail network resulted in the deaths in the order of only 10 people.

In other words the operational response of those responsible for train control in the New York city underground was such that there was a significant number of lives saved and property (trains) protected.

In this instance almost no amount of investment in infrastructure could have saved the physical infrastructure but operational effectiveness reflected in both egress design and operational response was able to save thousands of lives.

Compare that scenario where the safety outcome was highly effective notwithstanding old and what might be argued to be inferior technology with the circumstances of an emergency exercise conducted on another rail network utilising state of the art communications, tunnel ventilation and emergency response systems.

2 Urban Metro System (anonymous)

A pre-arranged emergency scenario (scripted) involving the immobilisation of a single train in a segment of modern rail tunnel (modern signalling, communications, jet fans, etc and evacuation of passengers along a pedestrian ‘friendly’ track.

The train driver attempted to communicate the fact that his train was disabled to the appropriate authority using modern communication technology. The control centre, after hearing a lengthy description of time, train type and location replied that they didn’t understand what the train driver was saying. When an alternative means of communication to the emergency services was used the alternative emergency service refused to take the call seriously thinking it was hoax and terminated the communication. Communication of the incident was eventually communicated - the exercise began.

After thirty minutes the emergency ventilation system was activated (after prompting by embarrassed exercise supervisors).

Discussion - these examples

In the first instance in New York it was not the latest technology which saved thousands of lives but the ability of those responsible for the control of the network to make rapid decisions on comparatively little information and for those decisions to be followed. In other words there was a chain of command which was understood and respected.

In the second instance - although admittedly only an exercise - the existence of highly sophisticated technologies to assist in the event of an emergency were not used, the chain of decision making, command and response failed. Had it been a real incident the likelihood is many people would have died.

The implications of these comparatively simple observations are many - in fact too many to be fully explored in a short paper such as this. But let me briefly further explore some of them.

3 Incremental components in a safety system

Each engineering development contributes to the overall performance of tunnel safety. That contribution can effect the performance of other safety components in the system.

3.1 Refuges

A simple example is the development and refinement of refuges in tunnels. As an alternative to points of actual tunnel egress they provide a place of comparative safety by providing a tenable environment for human beings which is longer than that expected within the tunnel itself. For this reason their contribution to tunnel safety only arises when people are able to properly access them and then their benefit is measured by the additional time they maintain a tenable environment.

Clearly they provide an improvement in tunnel safety for those people whom are able to access them. But in order to avail themselves of their sanctuary citizens must both be willing to, and able to, make the journey from the vehicle in which they are travelling to the points of refuge. Therefore the change in tunnel safety achieved by building the refuges will be optimised only if:

(a) People want to enter the refuges

(b) People can enter the refuges

(c) People do enter the refuges

On the other hand the existence of the refuges may be used as justification to place less emphasis on in tunnel tenability of atmosphere.

Once again this comparatively simple observation has highly complex implications for tunnel safety. For example in a multi-lane urban road tunnel the lane widths may be critical for commuters to exist their cars. If they are not wide enough, commuters simply can’t open their doors.

Having opened their doors and got into the tunnel environment are we confident that they will overcome their natural urge to go back in the direction they have come (or head in the direction they are going) and make their way to the refuges? Will they overcome their fear of the unknown and enter the refuge? And even if they want to do all of these things are the dimensions of the walkways and the physical obstructions such as barriers, steps or the like such that will not literally be a second jam of human beings? What will the consequences be if there is a disabled person, someone trips, or someone is simply too fat to get through the door?

Risks of 'improved' design

A further complication of improved emergency designs and philosophies for apparently similar infrastructure is that within a localised area there may be significant variations in the way infrastructure safety systems have to be operated, maintained and used during an emergency.

Examples of this can be found in most major cities. Whether it be in road or rail tunnels, infrastructure built at different times has different features, notwithstanding that it preforms the same primary function of facilitating transportation.

Example 1 - Emergency Egress (Broad discussion):

It is not only common - it is almost expected - in the international tunnelling community that in an underground rail system there will be variations in the means of egress from different types of rolling stock. Once egress is achieved the means of passage in the underground rail system tunnels on foot will vary for dedicated walking paths, to walking up the track. While in many systems no egress will be permitted at all because of the third rail.

In road tunnels, within the one city, there may be examples of transverse, semi-transverse, longitudinally ventilated, longitudinally ventilated with dedicated smoke extract and more recently longitudinally ventilated with parallel tube recirculation.

The design of emergency egress from the affected tube may also be extremely variable - the experience for citizens varying between a short flight of stairs to the surface, a very long set of stairs to the surface, a refuge, a cross passage, a dedicated escape tunnel or the opposing tube with traffic still flowing.

Because of this each project must be viewed not only from the perspective of the new piece of infrastructure but also from the perspective of what the implications will be for safety as a consequence of its installation given the context of other infrastructure serving the same purpose within the region. In other words - how will people react to the new design in this particular location.

Example 2 - Emergency Egress (Specific discussion):

Once again I'll use an anonymous but nonetheless tangible example is useful in this regard. An existing urban rail network with components of both underground and air right development running rolling stock of varying age and design and then embarking upon a new extension and upgrade programs.

It is proposed that in the new parts of the underground network dedicated passenger egress ways will be incorporated in the tunnel design - this is not the case in any other part of the network.

There will be an emergency smoke management system installed as is the case with other new sections of the railway network. This will impose an additional smoke management systems on the network - with its own control system and operational requirements.

In such circumstances developments in our understanding of tunnel safety have provided new tools to increase the safety of the system, but through incremental installation into the network they have introduced new control systems with differing design and operational characteristics. The challenge is in ensuring that notwithstanding the new developments in tunnel safety the delivery of the system is integrated with other safety systems in a way which does not result in a degrading of the overall safety of the network.

Conclusion

Ultimately for there to be positive improvements in safety with respect to tunnel safety technological achievements and improvements must be coupled with a conscious effort to integrate and understand the implications of those new systems on the safety of existing infrastructure.

After project construction or upgrading the systems must serve their functions in a world of changing technical and social expectations. We must ensure that knowledge of past safety incidents are translated into a form understood by safety engineers to citizens. Insofar as passive systems can be employed to enhance safety they should be, and where active systems are required or installed appropriate effort should be made to ensure that they are understood and properly utilised by operators, emergency services and the citizens who use these underground transportation corridors.

What cannot be overlooked is the importance of sound communication, command and response on the part of those whom operate and respond to emergencies on the one hand, and informed and active participation by the community whom use these facilities when there is an incident notwithstanding what technology is used in a tunnel.

Having an informed public able to make considered and rapid decisions about their own safety in the event of an emergency remains one of the great areas of tunnel safety available for rapid and comparatively cost effective safety improvements.

For engineers it is essential that they acknowledge new developments in tunnel safety may have unforeseen or even negative implications. However the overall positive contribution to the safety outcome of new initiatives must be identified - and the basis for such conclusions articulated.

It must be recognised that there are some events which cannot reasonably be anticipated or engineered for. The challenge is to learn from past events how to better contemplate and control incidents of the future. The difficulty with proactive incidents and consequences reducing measures is that their effectiveness is difficult to quantify.

It is an extremely difficult task when considering low probability high consequence events to differentiate the non occurrence of ‘incidents’ from effective incident control. The two are <u>not</u> the same, and easily confused.

With fresh solutions come the new challenges of placing the ‘solution’ in context and ensuring that the merits of the changes are both documented and rationally articulated.

In the event that there is an ‘incident’ such documentation will stand the engineer well in demonstrating the appropriateness of his advice. This will also serve the owner, operators, users and insurers well in the event of an incident.

PSYCHOLOGICAL ASPECTS OF TUNNEL SAFETY

Prok. Dipl.-Ing. Gerhard Eberl
Österreichische Autobahnen- und Schnellstraßen AG, A 1010 Wien, Vorlaufstraße 1

ABSTRACT

After the big fire incidents in the Mont Blanc Tunnel, the Tauern Tunnel and the St. Gotthart tunnel we are thinking about psychological aspects of tunnel safety. We all saw, that people did not react in an expected way.

Our recent activity in this topic is, that we investigate how people could react in the case of a catastrophe and we also want to investigate how we can help people to react in the right way.

We therefore started an investigation project in co-operation with traffic-psychologists to find out how the behaviour of the tunnel users can be improved by the design.

Test persons had to drive at a section of a highway with 5 tunnels, each tunnel with other characteristics.

After the test persons had passed the testing section of the highway they had an interview with a psychological background.

1. INTRODUCTION

A large fire occurred in the Mont Blanc Tunnel on 24 March 1999, car accidents led to fire disasters in the Tauern Tunnel on 29 May 1999 and in the St. Gotthard Tunnel on 23 October 2001.
A number of accidents and fires in tunnels occurred in Austria in summer 2001 in addition to these three incidents. Human error was usually involved to a certain degree in all these incidents.

These errors can be roughly divided into three groups:

1. Errors made by a driver who causes an accident – like in the Tauern Tunnel and possibly in the Gotthard Tunnel.
2. Errors made by the operating staff who, from a retrospective perspective, serviced the ventilation system adversely or incorrectly – like in the case of the fire in the Mont Blanc Tunnel.
3. Errors made by tunnel users who are trying to flee – or who rather do not escape or try to escape too late. Examples of this are, on the one hand, the tunnel users of the Tauern Tunnel fire who remained seated in their vehicles and, on the other hand, those people fleeing from the Gotthard Tunnel who ran past the escape tunnel.

In our responsibility for the planning, construction and operation of tunnel systems, we need to deal intensively with this "weak human link". We need to provide drivers with a tunnel that does justice to their requirements whilst driving and that does not make excessive demands of them. We need to create ideal preconditions for tunnel users so that they can react correctly in an emergency situation. And finally, we need to ensure that our employees are able to intervene correctly and efficiently in an emergency.

2 PERCEPTUAL PSYCHOLOGICAL INVESTIGATIONS INTO TUNNEL SAFETY

Together with psychologists from the Institute of Traffic Psychology of the Austrian Road Safety Board, ÖSAG has started processing a topic area from the field of perceptive psychology.

According to reports, one of the reasons for the severity of the disaster in the Mont Blanc Tunnel was the fact that lorry drivers did not observe the traffic lights that had changed to red after the fire had started. For this reason, we approached the psychologists from the Austrian Road Safety Board with the following question:

How can we ensure that a red light by a tunnel portal or in a tunnel is better obeyed?

A further question that we wanted an answer to was the placement and optical design of freely programmable information boards before a tunnel portal. One reason why we were particularly interested in these questions was that we were in the process of establishing tunnel chains on the Semmering and, in particular, on the Pyhrn Motorway in Upper Austria, which were about to have equipment of this kind installed.

The traffic psychologists from the Austrian Road Safety Board then complied a report that was used as the basis for the planning of the equipment of the two above-mentioned projects.

I would like to mention a few of these recommendations here:

- Early advance announcement of red light, if possible 1 to 1.5 km before the entrance to the tunnel.
- Repeated advance announcement of red light.
- No fixed advance announcements of red light, but flexible announcements that can be particularly emphasised if required – i.e. in the case of a red traffic light. The comment that LED displays attract greater attention was also seen in this context. Another possibility of flexible announcements consisted of flashing yellow lights on the advance announcement that only flash when the traffic light is red.
- A further recommendation was to place as little information as possible in the area of the tunnel portal. This area starts about 150 to 200 m before the portal. This affects, for example, the signposting of the name and length of the tunnel. This information should be provided earlier on and not – as has been the case so far – immediately by the portal.

As a consequence, the planning of the guidance equipment of the two above-mentioned projects was arranged in collaboration with the ladies and gentlemen of the traffic psychology department of the Austrian Road Safety Board.

3 EMPIRICAL OBSERVATIONS ON THE PYHRN MOTORWAY

In order to test the efficacy of the recommendations that were implemented in the planning, the Austrian Road Safety Board was commissioned, in May 2001, to carry out a test programme, which took place in autumn 2001 during the renovation work in the Bosruck Tunnel in September and October.

The aim of this test programme was:

- To work out psychologically meaningful and perceptually appropriate design criteria for designing tunnels
- To recognise perceptual defects and emotional disturbance factors
- To increase the objective and subjective safety of drivers
- To encourage desired driving behaviour

The project was carried out in five stages:

- General preparation stage
- Preparation phase for field inquiry
- Implementation of field inquiry
- Evaluation of journeys and people surveyed
- Reporting

The test was carried out as follows:

Of the 69 test subjects, 23 were inexperienced tunnel drivers, 23 were experienced tunnel drivers and 23 were senior citizens.

36 test subjects drove during the day and 33 test subjects drove at night. Every test subject drove for 1 – 2 hours and was interviewed for about 1 hour.

The test section was on the Pyhrn Motorway and was 70 km long. It started in Spital/Pyhrn, then went north to St. Pankraz, where people turned round and drove south to Rottenmann and then back to Spital.

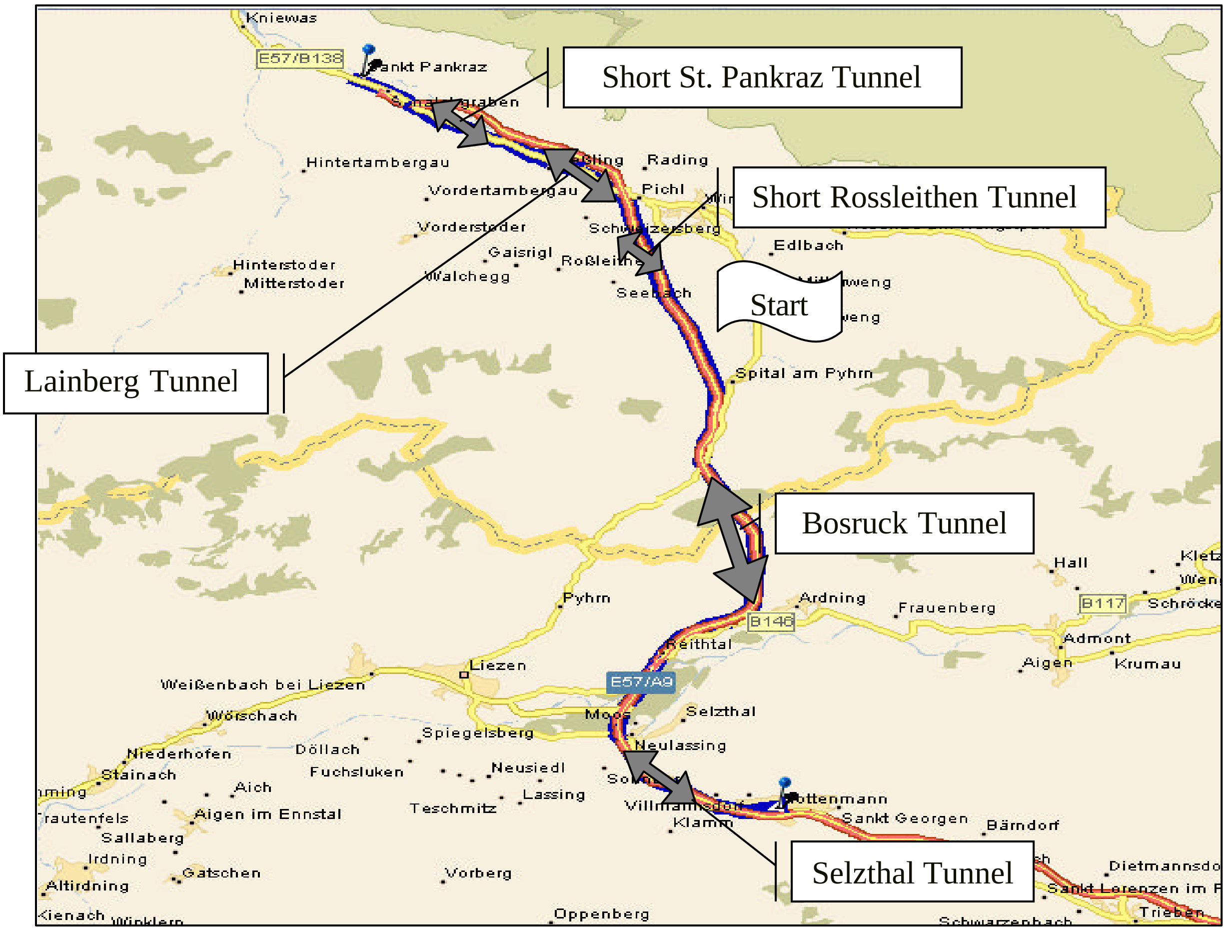


Illustration 1: test section

The following tunnels formed part of the test drive: short St. Pankraz Tunnel, Lainberg Tunnel (length about 2.8 km), short Rossleiten Tunnel, Bosruck Tunnel of about 5.5 km length and Selzthal Tunnel (1 km in length).

The test subjects essentially had to deal with the following test conditions:

- They had to drive through a building site with stop signals before the tunnel
- Some tunnels on the test section had one tube and others had two tubes
- The test subjects also had to drive through washed and unwashed tunnels
- There was also a tollbooth on the test drive

The SAF program (driving behaviour analysis system) and comments on the drive were used as test methods.

The SAF program (driving behaviour analysis system) allows the investigation of individual behaviour when driving cars in field experiments.

The main characteristics of SAF are:

- It is a system that is easy to install; in this case it was installed in a small car belonging to the Austrian Road Safety Board that the test subjects were driving.

- An observing passenger compiles complicated behavioural and situational characteristics and enters these into the computer by means of a click of the mouse
- The apparative data serves to complement the observations of the passenger.

Data analysis then occurs based on the recorded speed, the longitudinal and transverse acceleration, the status signals of the vehicle and the keyboard entries of the observer.

Ill. 2: Recording of the test results

Ill. 3: Video image - 4 camera positions

4 video cameras were used for the video analysis to record the face, the feet when using the pedals and the road in front and behind. These recordings are made using split screen technology.

The comments on the drive are based on a special interview technique where questions are asked on certain topics after the test drive is over:

Questions are asked on following thematic points of focus in this test:

General section:

- Sociodemographic data
- General questions about tunnels and the test drive

Specialised section:

- Questions about traffic signals
- Tunnel entrance
- Lighting
- Tunnel walls
- Road markings
- Safety equipment
- Tunnel exit
- Tollbooth
- Building site
- Behaviour in an emergency
- General safety questions

Characteristics to be observed:

- Subjective perception
- Subjective driving quality
- Subjective safety
- Orientation
- Taking in information
- Registration of tunnel design elements
- Acceptance
- Visual conditions
- Recollection
- Distinctive features

4 RESULTS OF THE INVESTIGATIONS

Here, I would only like to emphasis a few significant results:

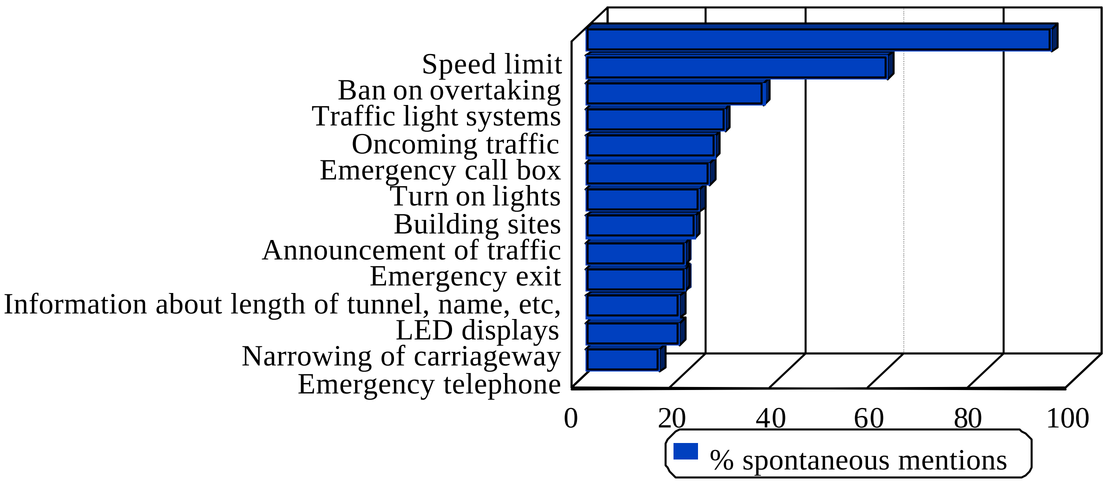
4.1 Perception of the test subjects

93% of the test subjects responded to the question “How did you perceive this drive?” with positive or very positive.

74% of the drivers responded to the question about whether the test person felt safe during the drive with at least quite safe.

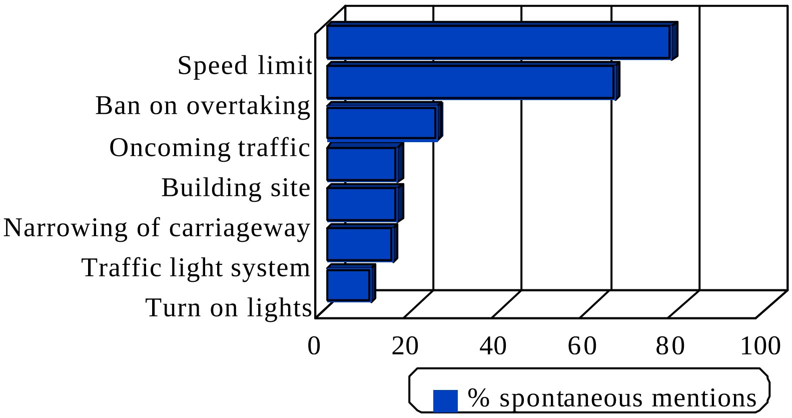
Assessment of traffic signals

The question about which traffic and warning signs the test subjects felt were important in the tunnel area led to a sobering result. Over 90% of the test subjects thought the speed limit was important, however, only 36% considered the traffic light system to be important, which allows conclusions to be drawn about the acceptance of traffic light systems.



Ill. 4: Important traffic and warning signals in the tunnel area

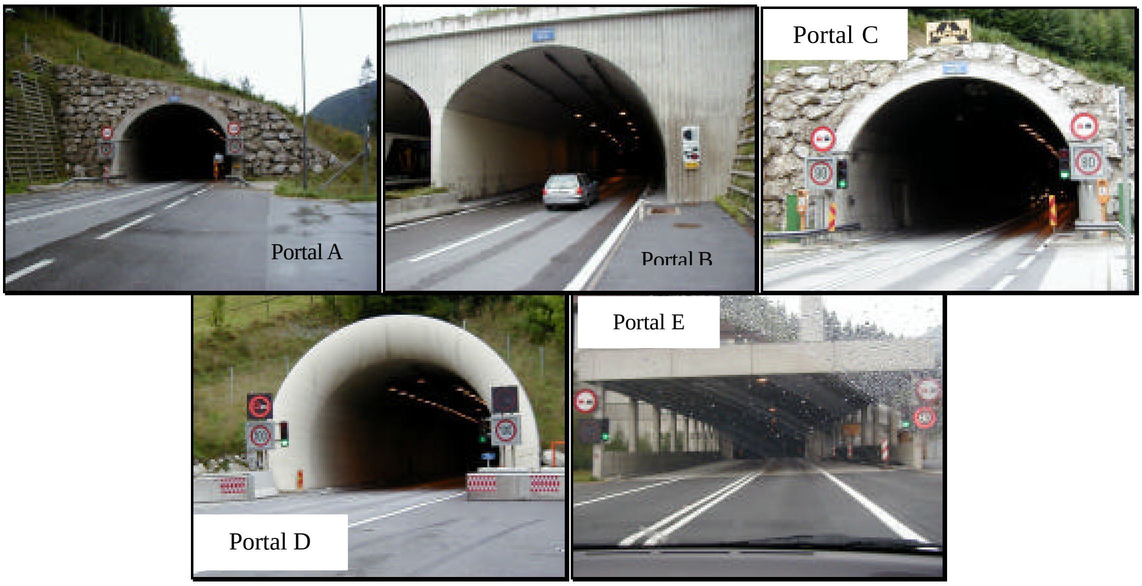
Only about 15% of the test subjects thought that non-observance of a traffic light system was of great importance, while about 75% of them attributed great danger to non-observance of the speed limit. It is also interesting that the ban on overtaking was assessed as less important than the speed limit.



Ill. 5: Danger caused by non-observance of traffic signals

4.2 Tunnel entrances

The tunnel entrances were also assessed. Of the five entrances displayed here:



Ill. 6: Tunnel entrances

- Entrance D was seen as the most informative, clearly laid out and as having the best guiding properties
- Entrance B was assessed negatively in terms of being informative, clearly laid out and having good guiding properties
- Entrance A was mentioned most frequently in the context of having a slowing down effect, being confining and dangerous
- Entrance E was also assessed as having a slowing down effect, without, however, the terms confining and dangerous being applied
- Entrance B was rated as having the least slowing down effect
- Entrance E was not assessed as confining
- Entrance D was named as the least dangerous

In summary, it can be said that Entrance C was assessed in the most neutral terms and that Entrance E has a special position in that it was assessed as having a slowing down effect, but not as being confining.

4.3 Speed developments

Essential insights:

- Drivers who approached at speeds below the speed limit, drove faster in the tunnel, while drivers who were above the limit slowed down.
- It was observed that speed limits were broken more frequently in bidirectional tunnels than in unidirectional tunnels.
- The test subjects' assessment of the effect of the design of the tunnel entrance on speed – use of "having a slowing down effect" – correspond to the speed developments actually observed

4.4 Lighting

Lighting was seen to be of great significance in terms of driving behaviour. However, the test subjects also recognised that a tunnel that is too light can lead to excessive speed. The distance behaviour is also different in dark tunnels to in light tunnels.

4.5 Reflectors

The kerbs that were illuminated with LED were assessed as much more visible and with better guiding properties, while the fear that they might distract or disturb was not confirmed.

4.6 Dirty walls

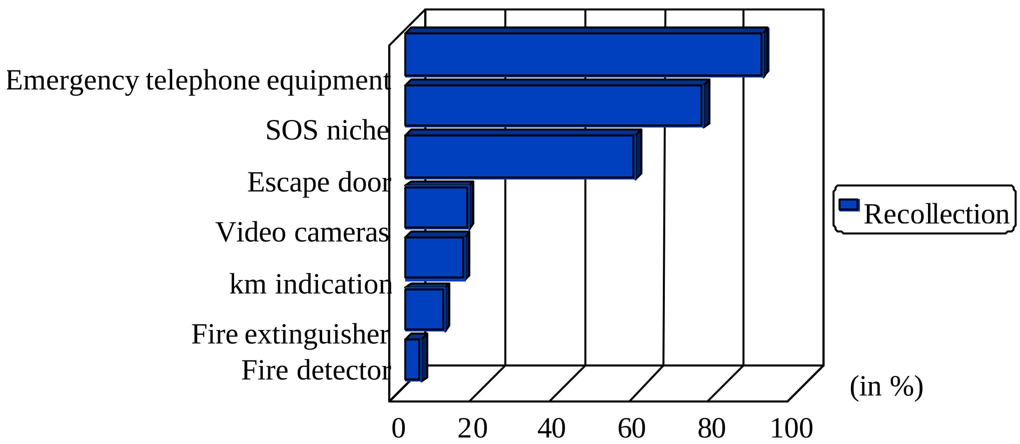
In this context, it was noted that lane adherence errors occurred more frequently in unwashed tunnels than in washed tunnels. It was also ascertained that there was no significant difference between the number of times the speed limit was exceeded between the washed and the unwashed tunnel.

4.7 Height of light spots

A comparison was made between driving behaviour in tunnels with an intermediate ceiling (light spots at a low height) and in tunnels without an intermediate ceiling (light spots at a great height). The only significant difference was the greater number of times the speed limit was exceeded in the tunnel with the interim ceiling.

4.8 Perception of safety installations

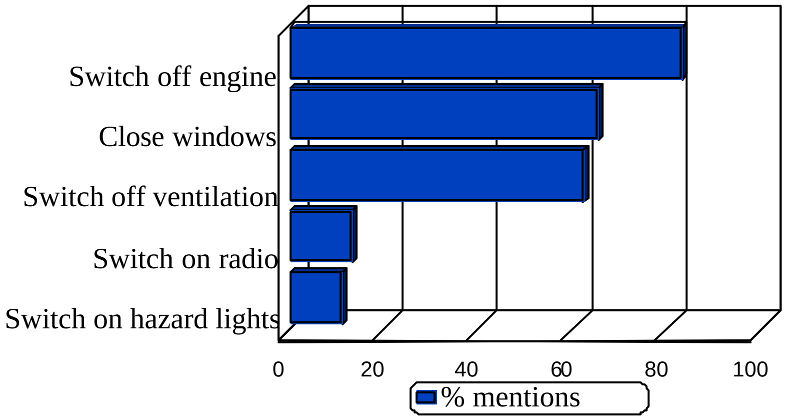
The following diagram shows which safety installations the test subjects could remember after the drive.



Ill. 7: Safety installations recalled from the tunnel

90% of the test subjects can remember the emergency telephone equipment, while only 4% remember fire detectors and 10% fire extinguishers.

83% of the test subjects answered the question about how they would behave in the case of smoke development by saying they would switch off their engine, about 65% would close the window and switch off the ventilation in the vehicle. Only 11% thought of switching on the radio, between 1 and 4 % thought of alerting the fire brigade, switching their lights on/off, turning off the heating, switching on their mobile phone or waiting for instructions.



Ill. 8: Behaviour during a traffic jam in the tunnel area with strong smoke development

4.9 Unidirectional vs. bidirectional traffic

As expected, the test subjects felt considerable safer in unidirectional tunnels (97%) than in bidirectional tunnels. 69% felt that speed limits were better adhered to in bidirectional tunnels. However, in bidirectional tunnels, the speed limit was exceeded significantly more frequently than in unidirectional tunnels. It was also noted that lane adherence errors and distance errors occurred more frequently in bidirectional tunnels.

5 CONCLUSIONS

The study shows that tunnel operators in Austria have been heading in the right direction over the past years, but that there are still possibilities to improve tunnel safety through design. Drivers perceive many tunnel characteristics extremely consciously and also react to the different design of tunnels in terms of their behaviour. The lack of recognition of the significance of traffic light systems on the motorway shows a perceptual superimposition through routines. Things that are required to drive through a tunnel under normal conditions are perceived, while the emergency installations are not. There is a particular need for tunnel operators to take action in this area by passing on the corresponding information to drivers whether on the spot or through the media and via driving schools.

In connection with the testing of the tunnel portals it was shown that what is experienced as positive leads to positive and safe reactions. The aim must be to use design to achieve a homogenous and appropriate speed. Because this alone will probably not be adequate, this speed will also need to be monitored.

Drivers desire a comfortable tunnel. Tunnels that are assessed as positive by drivers, e.g. through good lighting or good guiding properties by means of illuminated kerb reflectors, do not have a negative effect on driving behaviour.

I believe that the unanimous opinion is that tunnel safety is an extremely important topic.

It must, however, be emphasised again and again that there is no absolute safety in tunnels – the same applies outside tunnels, too. Ultimately, human beings play an extremely decisive role. Technicians can, to a considerable degree, contribute to improved safety, but this can become even more successful in collaboration with other specialist areas!

BEHAVIOUR OF SMOKE DURING THE SELF-RESCUE PHASE OF A FIRE EMERGENCY

Norman Rhodes & Hing-Wai Wong,
Hatch Mott MacDonald
49 West 37th Street
New York, New York 10018-6216
USA

ABSTRACT

The first actions carried out by the users and the operators of a tunnel can have a significant effect on the outcome. Most minor tunnel fires are dealt with by application of a pre-planned response procedure without injury or serious damage. On the rare occasions when a serious fire breaks out the dynamics of the situation are different. This paper sets out some of the technical questions which need to be addressed in understanding emergency response; how quickly smoke moves, the effect of wind and traffic-induced air flows, tunnel slope and the time response of the ventilation system.

A three-dimensional, transient CFD model has been developed and applied to study these effects. Validation has been obtained previously by way of comparison with both laboratory and full-scale fire experiments. The methodologies developed during validation studies have been applied so that the level of confidence in the parametric studies reported in this paper is very high.

The objective of the paper is to stimulate discussion on what advice to give to tunnel operators with regard to how the initial response to a fire emergency should be managed.

1 INTRODUCTION

Tunnel operators handle many minor incidents involving vehicle breakdowns and small fires and these are largely unrecorded. However, contrasting a small vehicle fire with the events of, say the Mt Blanc fire, it is self-evident that the smoke produced in a small fire and the hazards which they represent are of minor significance in comparison with larger magnitude events. The smoke produced by a small fire is quickly diluted by the air movements in a tunnel, be they driven by ventilation or traffic movement. Larger fires can, by virtue of the energy produced, have a greater influence and the higher concentrations of smoke lead to life-threatening situations. It is important, therefore, to understand the dynamics of flow, particularly in the self-rescue phase. During this period, shortly after the beginning of an incident, the traffic in a tunnel will stop, the operator will become aware that there is a problem and will begin a process of evaluation to determine response. The tunnel users, meanwhile, will encounter an unfamiliar set of circumstances and will not know what action to take.

This general problem requires a consideration of information that can, perhaps, be divided into two forms, that which is scientifically quantifiable, such as airflow rates, smoke concentrations and temperature, and that which is uncertain and difficult to predict, namely, the area of human response.

Much work has been done to evaluate the technical aspects of tunnel behaviour with respect to fire. However, the knowledge of the combination of effects is probably not complete. Smoke behaviour in a tunnel fire might be affected by:

- The growth rate and ultimate size of the fire; this would depend on the type of vehicle involved in the fire, its load etc.
- The tunnel air velocity; this would be affected by the initial traffic speed, ventilation design and environmental effects such as wind or buoyancy effects due to differences between tunnel temperature, ambient air temperature and slope of the tunnel.
- The speed with which the operator can identify the fire location and take appropriate action.
- The speed of response of the tunnel ventilation system.

It is probable that the fatalities which occur in a fire do so in the earliest stages of an emergency in most cases. However, note that fatalities themselves are relatively rare and more likely to occur in more severe fires, when the situation in the tunnel can quickly become untenable.

The purpose of this paper is to firstly attempt to define the effect of variable parameters which affect smoke movement. Three-dimensional CFD simulations have been carried out to illustrate the effect of air velocities induced by the various mechanisms mentioned above. The second purpose here is to pose the question ~ what should the tunnel user do? The question needs to be thought about in two parts; what does the tunnel designer/operator want the tunnel user to do, and what will the tunnel user actually do. Human behaviour is unpredictable, and there is ample evidence of motorists ignoring stop-lights and entering tunnels when forbidden to do so. Motorists are inclined to stay in their cars, and if asked to leave them unlocked, are unwilling to do so.

However, consider firstly the conditions which users might experience in fire situation. This is controlled by the dynamics and timescale's of air behaviour in tunnels.

2 DYNAMICS OF AIR BEHAVIOUR

The air velocities in tunnels will vary in magnitude and direction due to the influence of traffic movement, natural and mechanical ventilation effects and the particular geometry of the tunnel components. Superimposed on these, smoke from a fire will tend to stratify and progress along the tunnel on either side of the fire source. The behaviour of the smoke will be predominantly affected by the longitudinal velocity in the tunnel. Bearing in mind that to control the smoke a longitudinal critical velocity of about 3 m/s has to be achieved, the following values can be considered as potential initial values prior to the implementation of control measures:

- Wind effects: pressure differences between tunnel portals give rise to longitudinal velocities. Day et al, reference 1, quotes measured values of up to 3 m/s in the 19.05 km long Vereina Tunnel in Switzerland, this velocity arising due to pressure differences between portal of 200 to 300 Pa.
- Geothermal: the differences between tunnel wall temperatures and ambient air can give rise to a stack effect in a sloping tunnel. A 15 C temperature difference in a tunnel sloping at 3% would result in a mean velocity of about 1 m/s.
- Traffic: The motion of vehicles through a tunnel will impose forces which push air in the same direction. In a rail tunnel with relatively little clearance, this would dominate other effects, including that of mechanical ventilation, less so in road tunnels. However, velocities in excess of critical value could easily be generated by moderate road traffic.

Consider now the effect of smoke movement, firstly without the above effects.

Figure 1 shows the predictions of a CFD model of a rectangular tunnel having a length of 1000 m, a height of 3.8 m and a width of 10 m. The fire size is 10 MW, developing in a time of 1 minute – a rather fast development time, but considered to be a worst case.

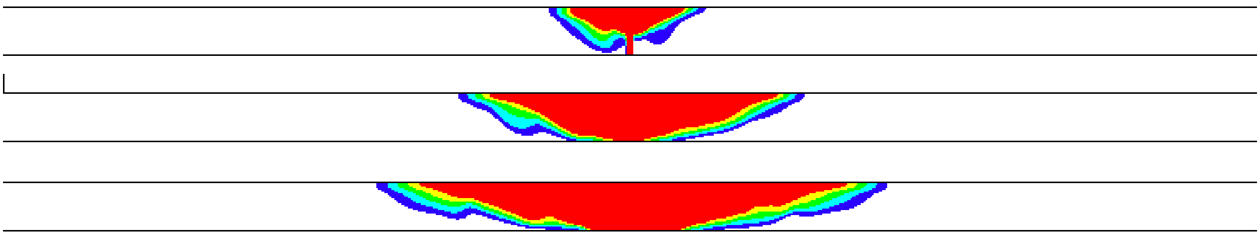


Figure 1: Progress of smoke in a horizontal tunnel 1000 m long – zero slope; 1, 2 and 3 minutes

In this figure, the outer contour represents a 1% smoke concentration, defined simply as the mass concentration of the combustion products. It can be seen that smoke has travelled about 220 m on either side of the fire source within 3 minutes. Contrast this with a tunnel having a 4% slope in Figure 2.

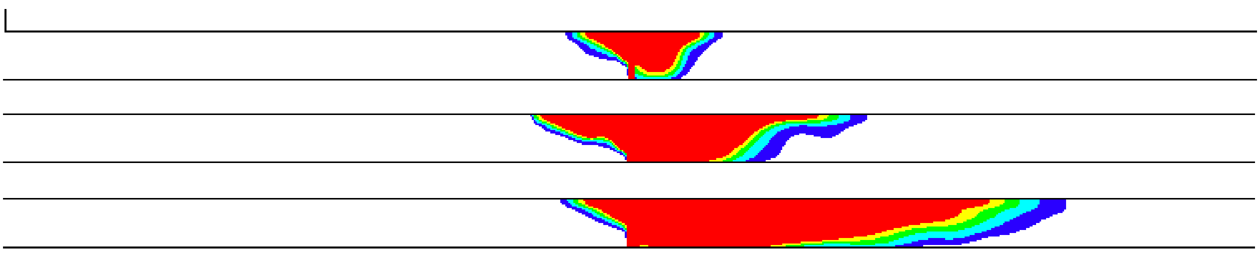


Figure 2: Progress of smoke in a tunnel having a slope of 4%

In this case, it can be seen that after only 3 minutes, smoke has progressed about 350 m from the fire source. This shows how influential the effects of slope might be. This type of behaviour was observed in the Memorial Tunnel tests, reference 2, which had a slope of 3.2% and in the absence of ventilation the uphill section of the tunnel could become smoke logged in 2 or 3 minutes. It is interesting to note that on the down-slope side of the fire, the length of the smoke backlayer diminishes as the buoyancy-induced flow increases.

This type of result can be represented in a more quantitative way. In the following graphs the edge of the smoke layer is defined as the distance from the fire source to the points on either side where the concentration falls below 1%. Plotting these distances as they vary with time provides a means of comparing the effects of the different variables which affect the longitudinal flow. Figure 3 represents a case where traffic has been assumed to move downhill (positive to negative distance in the figure, and the origin coincides with the fire source), causing a longitudinal velocity in that direction, but is stopped by the incident fire; note that traffic would be backed up behind the fire, i.e. uphill. There is no effect of wind this case. It can be seen that the residual velocity transports the smoke downhill for about the first 130 seconds, after which the buoyancy effects take over and begin to move smoke back over the stalled traffic. Bear in mind that the region between the curves is smoke-filled.

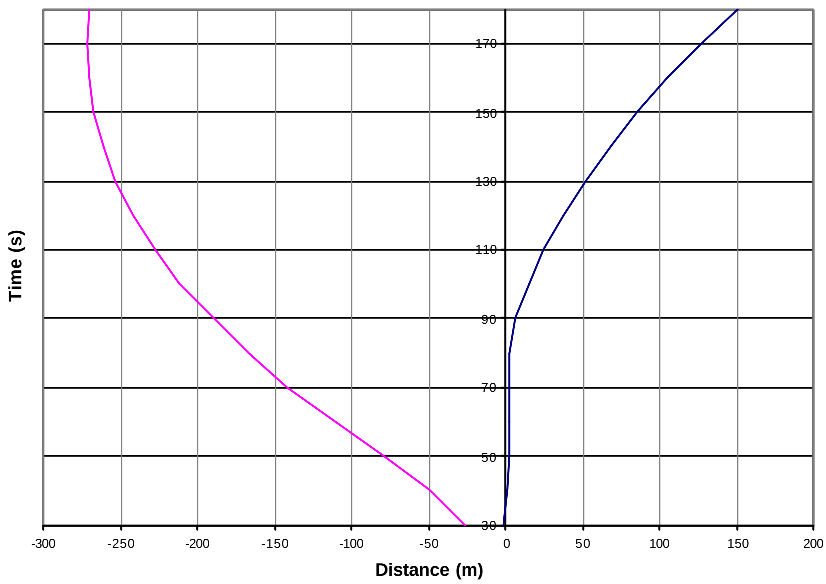


Figure 3: 1% smoke concentration positions on either side of the fire source – 4% slope

Had the residual velocity been cancelled by wind and stack effects, the smoke behaviour would have been as shown in Figure 4, with smoke progressing over the stalled traffic at a much earlier time.

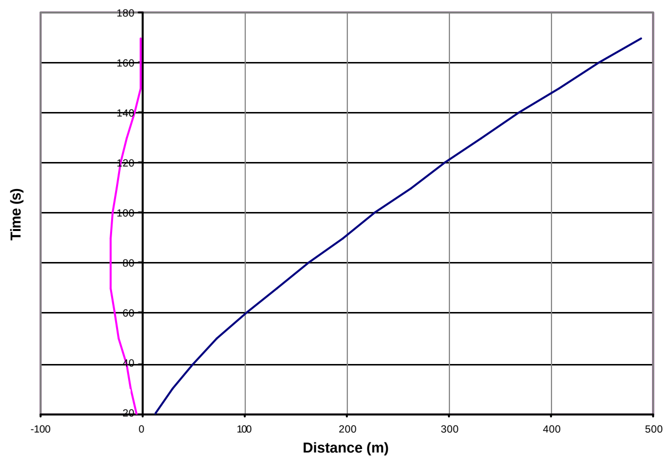


Figure 4: 1% smoke concentration positions – wind effect cancels residual traffic-induced velocity

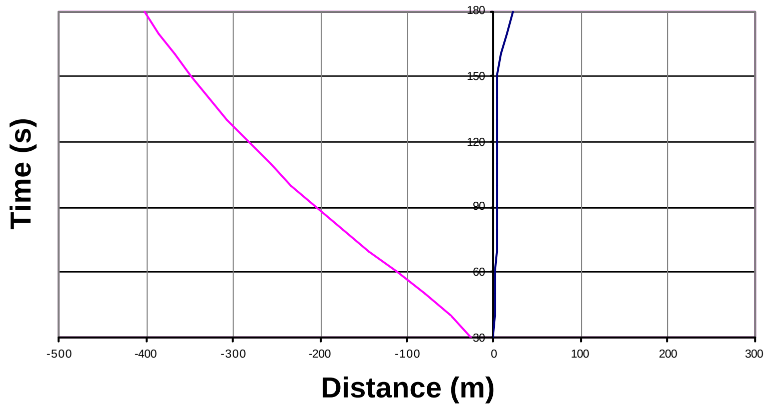


Figure 5: As for the case in Figure 3, but with ventilation implemented after 60 seconds

Figure 5 shows a more ideal case where control of the smoke is exercised after 60 seconds, and the smoke continues to move in a downhill direction, away from the stalled traffic.

The above results are presented to indicate possible scenarios which would result in less desirable conditions for tunnel users. They show that a very rapid response might be required in order to bring smoke under control and provide a safe environment. Numerous other scenarios are possible and exercises of the kind outlined above are useful for any particular tunnel geometry and specific conditions. The objective is to provide an initial database for designers and operators to understand the predicament of tunnel users in an incident situation, and then to consider the rescue and evacuation procedures that need to be put in place.

3 THE TUNNEL USERS PERSPECTIVE

The question of response of the user is uncertain. Muir, reference 3, provides a summary of possible behavioural responses under the headings of fear, anxiety, disorientation, depersonalisation, panic, behavioural inaction, affiliative behaviour, focused attention and enhanced physical performance. Her work has researched evacuation from aircraft. However, it is quite probable that similar responses might be expected from tunnel users.

Now imagine that you are in your car, stopped in a traffic queue in a tunnel and you see a blanket of smoke moving steadily towards you. You have no knowledge of tunnel infrastructure or ventilation and have no idea whether anyone "in control" even knows about the accident. This is the situation to be imagined by the designer. Emergency response procedures may be active, but how will the communication be made with the user, how effective will that communication be?

The European research program 'Fires in Tunnels Thematic Network', details of which can be found on http://www.etnfit.net, is focussed on bringing together current knowledge of fires and behaviour in tunnels, as well as the techniques and technical information available for the study of this subject. If you can propose an answer any of the questions noted above, then please make contact.

The issues that need to be considered in the future include the education of tunnel users, the interaction between possible behavioural modes and tunnel infrastructure, such as signing. Tunnel evacuation modelling, training exercises and full scale trials would be required to define the complex interface between the user and the operator.

Acknowledgement

The authors would like to acknowledge the assistance of Mr. Gavin Butcher and CFX International, AEA Technology for their assistance in executing this work.

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PRACTICAL ASPECTS OF TUNNEL DAMPER INSTALLATIONS IN FALSE CEILINGS

Fathi Tarada*, Barry Trewhitt*, Michel Jeangros+
* Trox (UK) Ltd, Caxton Way, Thetford, Norfolk IP24 2XF, United Kingdom
+ Trox Hesco (Schweiz) AG, CH-8630 Rüti, Switzerland
Email: ftarada@troxuk.co.uk

ABSTRACT
This paper focuses on some of practical aspects of selecting and installing these dampers into false ceilings with both transverse and semi-transverse ventilation systems.

Starting with the issue of damper selection, the paper discusses the temperature criteria required of the damper/actuator assembly for both operational security and structural integrity. The size and number of damper modules is determined by a variety of practical considerations, and these are reviewed both from a commercial and from an engineering perspective.

The issues of damper orientation and installation (recessed or proud within the duct) are addressed from an aerodynamic pressure drop and an installation / maintenance perspective, and new cost-effective proposals are presented. The paper also reviews the issue of aerodynamic fairings and discusses their cost / benefit relationship.
Key words: Ventilation, tunnel, fire, smoke, installation, commissioning

1 INTRODUCTION

The highly destructive recent tunnel fires in Europe have given further impetus to upgrade the road tunnel ventilation systems to enhance the safety of the travelling public. The newly designed ventilation systems can be significantly more effective in exhausting smoke from tunnel fires, primarily because of the increase in ventilation capacity and through localising the exhaust flow through large tunnel dampers.

However, there is evidence that international 'best practice' relating to tunnel damper selection and installation is not necessarily being followed in recent refurbishment and new-build projects being undertaken in Alpine countries. This paper addresses some of these issues for the purpose of enhancing the debate regarding life safety in traffic tunnels.

2 TUNNEL DAMPER SELECTION

Selection of the appropriate tunnel damper is a key instrument to enhance life safety in tunnels, achieving reliable ventilation operation and holding down both the initial and running costs of mechanical and electrical services in tunnels.

Unfortunately, only a few product standards for tunnel dampers are available to assist the tunnel designer in the selection of appropriate tunnel dampers for installation in false ceilings. In the absence of such standards, engineers in Alpine countries have tended to use prior local practice, rather best international practice, to specify tunnel dampers for the large number of refurbishment and new-build projects currently underway there. An overview of prior Alpine and international best practices is presented in Table 1.

Why do Alpine countries diverge from international best practice, and what are the consequences of these differences on their tunnel damper selections?

Specification	Alpine Prior Practice	International Best Practice
Blade Actuation	Parallel bladed, to enable an aerodynamic air-stream from traffic space to ventilation duct.	Opposed-blade or parallel bladed operation, depending on specific requirements (see below)
Pressure Loading	Typically 2 to 10 kPa, comprising the sum of maximum static (fan) pressures and dynamic event (e.g. sudden shut-off) pressures to generate no more than a specified blade deflection (e.g. 2 mm).	Maximum static (fan) pressures to produce blade deflection < blade span/250. Repetitive cycling allowed for through fatigue-life specification. One-off dynamic events allowed for through stress considerations.
High-temperature cycling	Various ad-hoc requirements, with temperatures between 250 to 400 ºC for 1 to 2 hours.	French standard 2000-63 calls for a cycling requirement of 400 ºC for 2 hours.
Fire integrity requirements	None specified.	Dampers form an integral part of the false ceiling and should therefore be covered by fire integrity specifications such as BS 476-20, or more demanding national standards such as the hydrocarbon curve for the UK.
Leakage requirements	Only cold-flow (not hot flow) leakage rates through the blades (not case) are specified.	Cold-flow leakage rates as per UL555S Class 1 [71 $l/s/m^2$ @ 3 kPa], hot-flow leakage rates as per BS EN 1366-2 [360 $m^3/h/m^2$ @ 300 Pa].

Table 1: Prior Alpine and International Best Practices relating to Tunnel Dampers

It is the authors' contention that the reason for this situation is the limited size of the tunnel damper market in Alpine countries prior to recent catastrophes including the Mont Blanc and Tauern Tunnel fires. This small market size reduced active competition, and local manufacturers developed their own standards to satisfy the small demand for tunnel dampers in Alpine countries.

After the safety reviews undertaken by tunnel safety authorities in Switzerland, Austria and Germany (amongst others), large public works programmes were initiated to replace the slot extracts in existing road tunnels with multi-bladed tunnel dampers. Such large exhaust openings, set every 50 to 100 m in the false ceiling, were shown by the Memorial Tunnel experiments in Boston, USA to be significantly more effective in limiting smoke movement than the slot extracts.

However, the Alpine safety reviews did not encompass the detailed tunnel damper specifications, which for the greater part were carried over from the earlier phase. This has the unfortunate consequence that the new dampers installed do not fully conform to international best practice, and furthermore may be somewhat more expensive because of this nonconformity. We now turn to some of these selection issues in detail.

2.1 Blade actuation

Prior Alpine practice calls for parallel-bladed dampers, presumably to enable an aerodynamic air-stream from traffic space to the ventilation duct. Opposed-blade dampers are hence strictly ruled out of most Alpine tunnel projects. However, this specification does not take the following considerations into account:

- Parallel-bladed dampers cannot achieve any fire integrity under hydrocarbon or BS 476-20 conditions, since they cannot be designed with any blade interlocking.
- The pressure drop difference across a parallel-bladed damper as opposed to an opposed-bladed damper is negligible in comparison to the total fan head (of the order of 10 Pa compared to 1 kPa). The pressure difference reduces even further when the blades of the opposed-blade damper are oriented parallel to the tunnel axis.
- Opposed-blade dampers can control the flow far better than parallel-bladed dampers, since they can generate higher pressure drop coefficients at smaller blade angles (see Figure 1). The problems of commissioning tunnel dampers to achieve uniform flow through all dampers during normal operation would therefore be significantly reduced, since the opposed-blade dampers can be set over a wide range of angles. Parallel-bladed dampers are restricted typically to the last 15° of movement in order to adequately throttle the flow.

None of the above discussion should be taken to imply that opposed-blade dampers are always superior to parallel-bladed ones, only that more care should be taken to consider all factors into account when specifying such dampers.

Figure 1: Measured Pressure Drop Factors for Opposed versus Parallel Bladed Dampers

2.2 Fire integrity requirements

Certification to a standard fire integrity requirement means that a damper will withstand a fire without extensive gaps appearing between the blades (hydrocarbon curve or the cellulose curve according to BS 476-20), or will leak less than 360 m^3/h per m^2 damper area at 300 Pa suction pressure (BS EN 1366-2) for a specified length of time. These are onerous constraints – during fire integrity tests to the hydrocarbon curve, temperatures rise above 1000 ºC after 5 minutes (Figure 2).

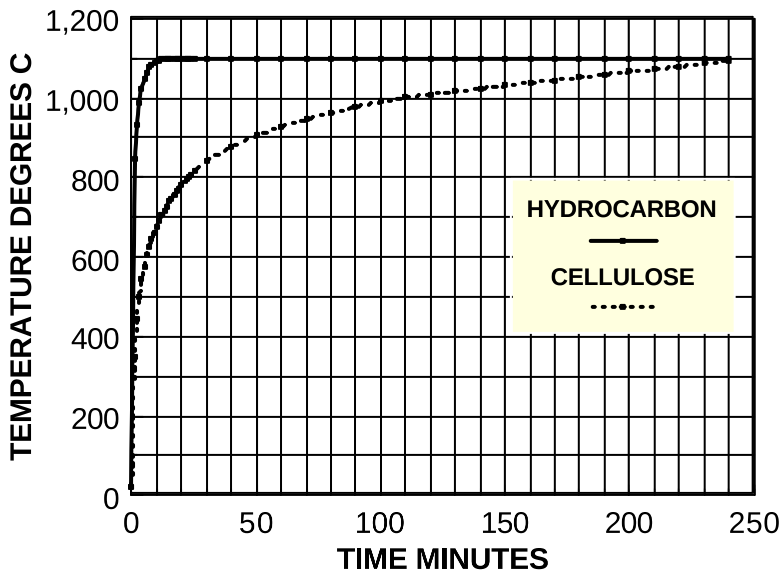

Figure 2: Time-Temperature Curves for Fire Integrity

At a time when significant amounts of engineering effort are undertaken to specify the fire integrity of the false ceilings in tunnels with transverse and semi-transverse ventilation systems, it seems odd that no such considerations have been given to tunnel dampers, which are an integral part of the tunnel structure. Would the collapse of tunnel dampers in a fire cause a collapse of the false ceiling? This issue requires further investigation.

Additionally, further fire scenarios have to be considered which may well highlight the need for damper fire integrity for smoke containment. For example, in the initial stages of a fire, hot smoke may spread bi-directionally and damage dampers either side of the fire, which effectively causes the affected dampers to behave ‘open’ rather than ‘closed’. This prejudices against concentrating the exhaust air flow through the dampers immediately next to the fire, and hence cause smoke to spread over a wider tunnel extent, possibly endangering human lives.

For dampers located between cut-and-cover metro tunnels or in the cross-passages in bored railway tunnels, the case for dampers that are properly certified for fire integrity is very clear: passengers and rolling stock in the non-incident tunnel must be protected from the fire in the incident tunnel.

2.3 Size Considerations

Dampers are normally sized according to their emergency ventilation duty. An estimate of their cross-sectional area can be obtained from the formula below:

$$A_d = \frac{2V_c A_T}{N_d V_d} \qquad \text{Equation 1}$$

where

A_d	=	Damper gross internal cross-sectional area (m^2) = B x H
V_c	=	Critical velocity to avoid the backflow of hot smoke in the traffic space (typically about 2 to 3 m/s)
A_T	=	Cross-sectional area of tunnel traffic space
N_d	=	Number of dampers to be opened simultaneously (typically 2 to 4)
V_d	=	Maximum allowable velocity through the dampers (typically 10 to 20 m/s)

Note that the above formula does not take the production of hot smoke from the fire source into account.

Having obtained an estimate for the damper cross-sectional area, it is important to specify the breadth (B) and height (H) dimensions such that:

- The static integrity of the false ceiling is not compromised due to the concrete cut-out.
- The breadth dimension reflects the fire integrity and high-temperature cycling tests for reputable damper manufacturers, in particular with respect to the maximum allowable unsupported blade length (approx. 1.5 m for Trox JFP dampers). Failure to heed this requirement will lead to significantly increased damper cost, since additional damper modules may have to be built.
- The false ceiling can support the weight of the dampers. As a rule of thumb, Trox JFP dampers weigh about 65 kg/m^2 damper area.
- The dampers can be fed through the concrete cut-outs from the traffic space into the overhead ventilation duct. This check is normally carried out using Computer-Aided Design, using the minimum size of cut-out and the maximum size of damper within the prescribed tolerances (Figure 3).
- The dampers can be realistically loaded onto a heavy goods vehicle trailer for delivery on site. A standard trailer is 2.4 m wide, 12 m long and can stack up to 2.4 m high. Allowing for clearances between the trailer sides, palettes and the dampers, this implies a maximum damper breadth of about 2.3 m across the flanges, when the actuators are supplied separately.

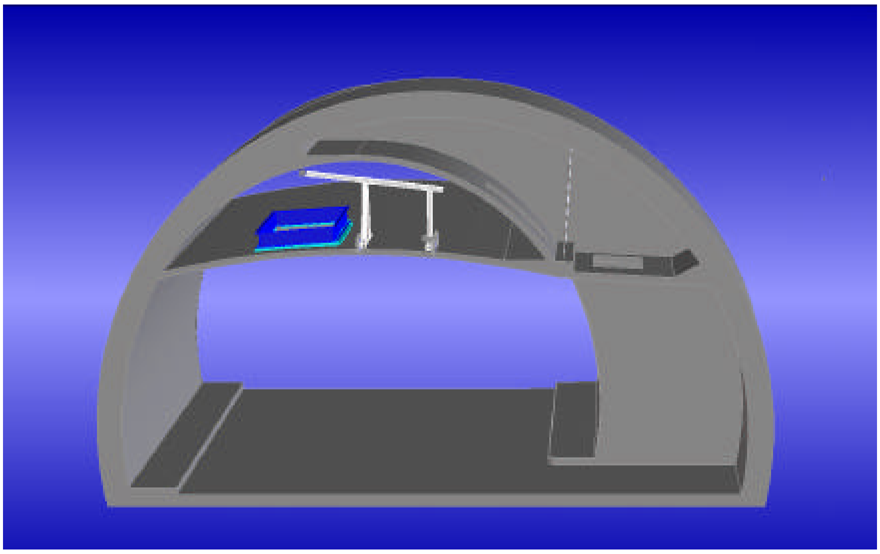

Figure 3: Three-Dimensional CAD Representation of Damper Installation

3 TUNNEL DAMPER INSTALLATION

3.1 Proud or recessed?

Currently, the accepted method of installing tunnel dampers in false ceilings is to drop them into the concrete cut-out. This recessed installation (Figure 5) has the advantage of minimising the pressure drop in the ventilation duct due to the disturbance of the flow by the dampers.

It may be beneficial to critically question the extent to which the pressure drop increases due to the presence of dampers mounted proud in the ventilation duct, and also investigating the additional benefits to be gained by such a 'proud' installation.

Assuming a distance of 100m between adjacent dampers, a damper depth of 300 mm, a damper breadth of 3 m, a duct cross-sectional area of 8.7 m^2 and a duct velocity of 10 m/s, we can show that the form drag due to the dampers will generate an additional 10 Pa of pressure drop per 100 m of tunnel length. This should be compared to a typical fan head of 1 to 2 kPa.

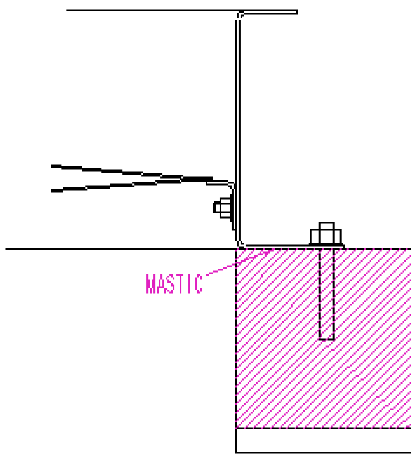

Figure 4: 'Proud' Damper Installation (on top of opening)

The *benefits* of a 'proud' damper installation include:

- Simpler maintenance and repair of the damper bearings, including lubrication and occasional replacement, without the necessity of lifting the whole damper off its mounting. This is a significant consideration during the expected 25 to 30 year life of the dampers.
- The actuator drive system is significantly simpler, meaning a cheaper installation and fewer bearing surfaces subjected to wear.
- Smaller concrete cut-outs are possible in the false ceiling for the same damper sizes, which can significantly assist in maintaining the static integrity of the false ceiling.
- If the same sizes of concrete cut-outs are chosen as for a recessed installation, lower flow velocities can be generated through larger damper sizes, which tend to offset the form drag losses calculated above.

The selection of a recessed or proud installation should therefore be undertaken only after consideration of these issues.

3.2 Methods of damper mounting

False ceilings normally have a significant degree of curvature (radii of 20 to 30 m are not uncommon), so there is no flat surface onto which to lay down the dampers. It is important however that the damper casing is held flat, or else any resulting distortion may lead to the damper blades seizing. Another important consideration is that the junctions between the damper casing and the false ceiling should be sealed, to prevent air leakage through any gaps. Such air leakage would reduce the effectiveness of smoke exhaust in a fire emergency, and complicate the commissioning of the ventilation system for normal operation.

The first dampers in refurbished false ceiling installations used a separate installation frame onto which the dampers were mounted, with a clamp arrangement to hold the damper in place (Figure 5). These installations required the use of soft concrete to provide two support plinths either side of the damper. However, most tunnel operators have now moved away from the use of soft concrete due to the risks of damaging the road surface, and installers have recognised the cost and expense of this solution.

The authors have developed a better solution that has eliminated the use of a separate mounting frame and the use of concrete plinths, whilst still maintaining the flatness of the dampers and minimising the air leakage around the damper frame. This method is simple to install and reduces the overall cost of the damper, since the mounting frame is eliminated.

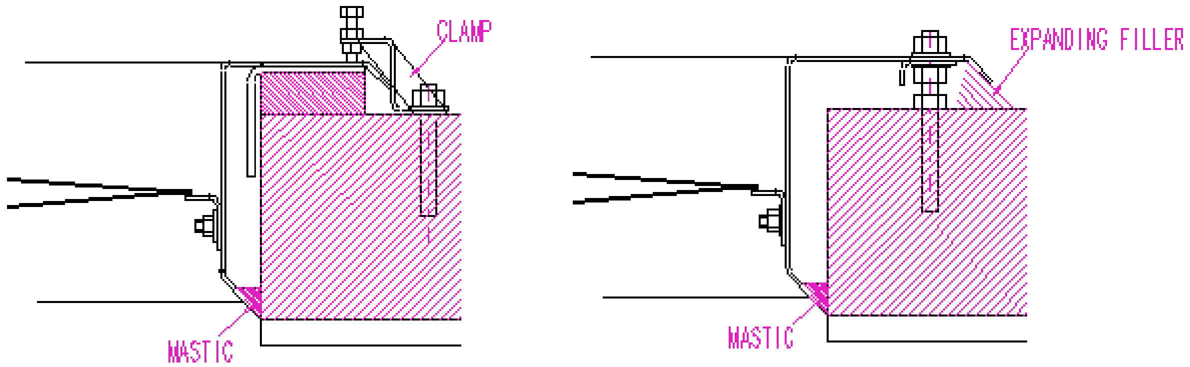

Figure 5: Recessed Damper Installation with (left) and without (right) a Concrete Plinth and Installation Frame

3.3 Aerodynamic fairings

Some tunnel dampers in Austria have been specified with aerodynamic fairings within the duct (to reduce the form drag due to the protrusion of the dampers within the duct) and also on the underside of the dampers (to reduce the contraction losses of the flow).

As in any other kind of capital investment, careful consideration must be taken to ensure that these aerodynamic fairings give value for money and can give a measurable financial return to a commercial investor.

From the calculations in section 3.1, it was seen that form drag losses due to the projection of the *full* damper height (i.e. for a ‘proud’ damper installation) within a duct are small. It follows that form drag losses for a *partial* damper projection (i.e. for a recessed damper installation) are proportionally smaller. The pressure drop reductions, and hence the potential fan energy savings, in providing aerodynamic fairings in recessed damper installations are smaller still.

Similar considerations can be brought forward for damper inlet fairings. Typically, one velocity head (½?V^2) is lost at discharge from a damper, and about half a velocity head is lost at entry to a damper (in the absence of any fairings). Assuming a velocity through each open damper of 10 m/s in a fire scenario, this implies that 25 Pa is lost at entry to the dampers (which are open in parallel). Even if this pressure drop figure is reduced in half by entry fairings, the projected savings are small compared to the overall fan head of typically between 1 to 2 kPa.

4 CONCLUSIONS

Through our experience in supplying and installing tunnel dampers for false ceiling applications in Alpine countries, we have identified potential improvements in the specification of these dampers to bring them up to international best practice. In particular, we have identified the importance of fire integrity as an important consideration for tunnel dampers.

Through our continuous design and innovation, we have made several suggestions to significantly reduce the cost of these damper installations and hence improve the commercial return of these projects to public and private investors. These proposals include dispensing with damper installation frames, concrete plinths and aerodynamic fairings.

5 ACKNOWLEDGEMENTS

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ADJUSTABLE TUNNEL DAMPERS- -AN ESSENTIAL COMPONENT FOR SMOKE-EXTRACTION DURING FIRES

Dipl.-Ing. Michael Speiser;
SIROCCO Luft- und Umwelttechnik GmbH; Vienna / Austria; E-mail: office@sirocco.at
em. Univ. Prof. Dr. techn. Karl Pucher; TU Graz / Austria

ABSTRACT

Requirements on tunnel ventilation systems (and thus on extraction dampers as well) have become markedly more stringent in the past years, due to increased knowledge and a great deal of experience. In Austria, these requirements (primarily leakproofing and temperature resistance) are defined by the applicable project-inspection directive RVS.
However, aspects of flow technology, choice of materials, processing guidelines and experience in technical production must also be taken into account when conceiving, manufacturing and selecting extraction dampers.

As the European market's leader in tunnel extraction dampers, Sirocco presents in the first part of this discussion a detailed, practically-oriented look at the way the requirements are met, indicating the essentials of an extraction damper.

During normal operation, the settable extraction damper's suctioning (the aperture angle of which can be reset depending on the distance from the ventilator) is markedly technically advantageous in terms of flow (pulse effect). The pulse effects have been proved in comprehensive model testing, in which the resistance coefficient ? of an extraction damper was determined with respect to an aperture angle.

Key words: leakproofing, temperature resistance, stainless steel, pulse effect

1. INTRODUCTION

Modern concepts of transverse-ventilated roadway tunnels evince that extraction dampers built into the intermediate ceiling are an essential component for a ventilation system to function efficiently.

The great advantage of this ventilation concept lies in the fact that, in cases of fire, smoke-gases can be pinpointed and suctioned off in the vicinity of the fire. In ideal cases, this results in only a short section of the traffic area becoming filled with smoke, and fresh air flows to the fire location from both sides. Thus, the danger that tunnel users will be enveloped by smoke gases is markedly reduced.

Since, in this type of fire ventilation, smoke gases flow through the dampers unrarified, i.e. at a very high temperature, the dampers must be able to withstand very great temperature stress.

Furthermore, aiming for maximum suction performance during fire-ventilation operations requires that the extraction dampers be leakproof and facilitate flow.

2. TUNNEL DAMPER REQUIREMENTS

2.1. Requirements set out in the applicable project inspection directive RVS

The Austrian project inspection directive on tunnel ventilation equipment, decreed by the Federal Ministry of Transport, Innovation and Technology, was amended per January 2001 by Inspection RVS 9.261 after the fire in the Tauern tunnel and in the light of new knowledge gained in past years. This amendment imposes even more stringent requirements on ventilation equipment – and extraction dampers in particular – than were formerly the case with Austrian tunnel-ventilation units.

In cross-ventilated tunnels, the minimum extraction capacity was increased to 120m³/sec.; this extraction quantity must be attained in a section of 150 m at any point in the air duct.

In order to make this extraction quantity economically viable, the leakage requirements for air ducts and extraction dampers were markedly increased.

The following maximum allowable leakage values apply:

air duct:	5 m³/ sec km
extraction dampers:	0.10 m³/sec m² at 2500 N/m²

Measuring data must confirm that both the shutters and the air duct are leakproof.

Extraction dampers must be designed to be as wide as possible (ideally, 3 m) and the total surface area of the cleared concrete openings for the dampers must be at least the same size as the air-duct surface at a length of 150 m.

For extraction ventilators, the requirements for temperature resistance were increased to 400° C during 60 minutes, implying that this minimum requirement for temperature resistance also applies to extraction dampers.

2.2. Materials and Processing

Due to the stringent requirement for temperature resistance (400° C) and the demand for functional safety over decades in extreme ambient conditions (exhaust gases, roadway salt, high dirt build-up), only top-quality stainless steels may be used to make extraction dampers.

The basic component in stainless steel corrosion resistance is a chrome conduct of at least 15%. At 18% chrome and 8% nickel, the steel becomes resistant to rust and acid, and by further adding molybdenum, it is resistant to holing caused by corrosion. Unfortunately, in practice it is not possible to use the optimally resistant steel, since – apart from the high cost of the material – it is no longer ductile if the molybdenum content is greater than 5%. Furthermore, the more the steel is alloyed, the less it can be welded.

Therefore, Stainless Steel 1.4571 (X 6 CrNiMoTi 17 12 2) has proved to be the best type for use in tunnel construction.

In order to keep the Stainless Steel 1.4571 corrosion-resistant and impervious to pitting, the engineering rules corresponding to construction and processing directives must unconditionally be taken into account (cf. also Quality Standard DIN 8563; EN 25817); otherwise, the steel will not be corrosion-resistant and functional safety cannot be guaranteed.

The two essential stainless-steel processing rules are:

- All weld seams are to be made continuously and on both sides, without exception. Tack and spot welding are not permissible, since they inevitably entail corrosion because, on the one hand, no passive layer can form in the narrow gaps around a weld seam and, on the other hand, subsequent mordant treatment and passivation are not possible (the acid used for mordant treatment cannot be removed without a trace from the gaps).

- All welded parts, just as all parts tooled with non-stainless utensils, must be given mordant treatment after processing to clean them, following which they must be protected by passivation (passive layer build-up on the metal's surface). If the passive layer has been damaged chemically or mechanically, local corrosion develops.

Of course, complying with the processing rules involves expense, some of which is not inconsiderable. Mordant treatment and passivation by qualified companies alone is time-consuming (reacting duration) and cost-intensive (approx. 7% of total manufacturing costs).

However, it is mandatory that the applicable regulations, standards and necessary quality requirements be observed without compromise.

2.3. Flow-Technical Requirements

During normal ventilating operation, the extraction dampers must be set so that smooth suctioning is assured throughout the entire tunnel. This means that, the closer the dampers are to the exhaust ventilator, the smaller the aperture angles of the vanes (free cross-section surface) are.

In order to ensure that this is so and, simultaneously, to assure the best possible flow even at small aperture angles, the following points must be taken into account:

- vanes must run equally (pulse effect)
- mechanical and electrical hysteresis when starting up intermediate positions must not exceed 1%
- small aperture angles must be capable of being set stably. This means that there must be only very little vane (and rod assembly) play
- vane geometry should be favourable to flow even at small aperture angles and produce the least possible whistling noise, even at high flow speeds, by using rigid, stable vane-ends

In general, one should strive for low resistance, minimal reduction of cross-sectional surface in the exhaust duct and construction favourable to flow.

Major flow-technical characteristics:

- Extraction dampers should be built into the intermediate ceiling and, when closed, protrude into the exhaust duct as little as possible.
- All parts which protrude into the exhaust duct must be panelled with flow-past profiles.
- On the roadway side, the extraction dampers should be outfitted with inflow nozzles, in order to reduce the resistance coefficient.
- Vane geometry should be favourable to flow (low resistance coefficient).

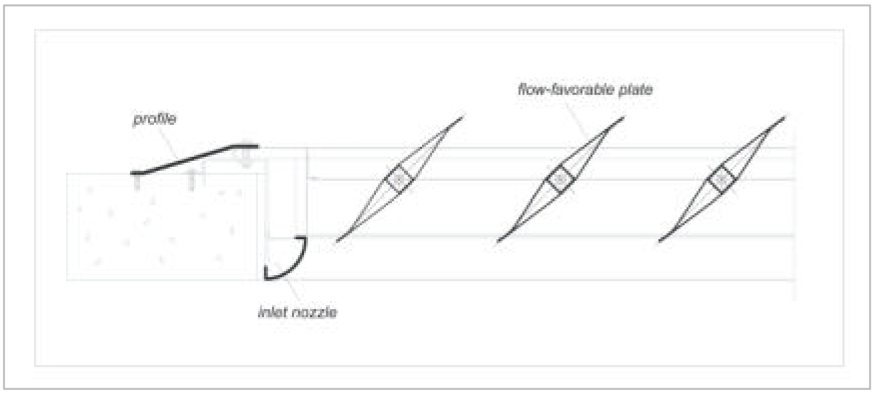

Figure 1: flow-technically optimised extraction damper

3. DELOPING AN EXTRACTION DAMPER WHICH CONFORMS TO REQUIREMENTS

Together with leading tunnel planners and building firms, the Austrian Sirocco Company has been working for decades on improving tunnel ventilation systems. For more than 20 years now, Sirocco has been involved in developing and producing stainless steel extraction dampers. The result of these years of experience is a high-quality product which conforms to all requirements and which has made Sirocco the market-leader.
The essential characteristics of Sirocco extraction dampers are described below.

3.1. Flow favourability

The fish-belly vane developed by Sirocco has been optimised according to flow-technical standpoints, the result of which is, on the one hand, only slight cross-sectional narrowing when the damper is open and, on the other, efficient, flow-through of the vanes, low in both resistance and turbulence. Both of these features assure improved suction performance in cases of emergency.
In the course of this development, the vanes' overlapping ends were designed so that labyrinth-sealing occurs when they are closed.

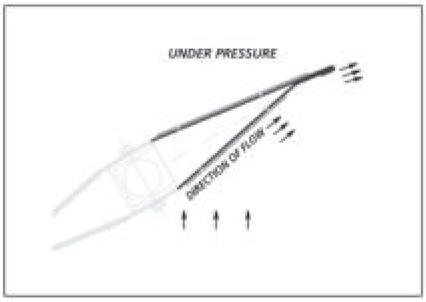

Figure 2: flow-favourable vane

3.2. Leakage prevention

The stringent requirements for preventing leakage and the simultaneous demand for temperature resistance can only be met by using metal sealing systems. Furthermore, they must be impervious to dirt, corrosion-resistant and must maintain their sealing effect permanently.
The sealing system developed at Sirocco fulfils these criteria.
A springing seal is placed on every damper vane (Fig. 3), which covers the gap (necessary for thermal expansion) between the vane and the frame, thereby assuring a high degree of sealing, both during normal operation and in cases of fire alike.
By bending the closed vanes through under high partial-vacuum air pressure of approx. 4000 Pa, gaps occur on the first and last vane between the rabbet and the bent-through vanes. The new rabbet (Fig. 4), protected throughout Europe, seals this variable gap, corrosion-free and with no wear and tear.

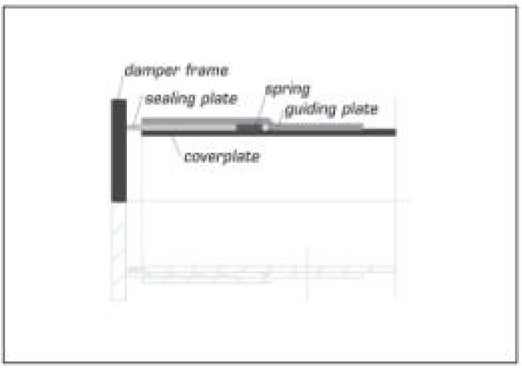

Figure 3: metallic vane sealing

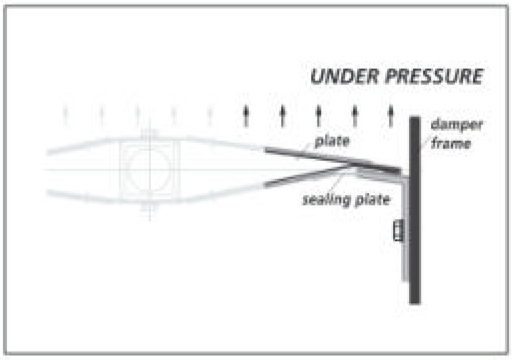

Figure 4: suction rabbet on the longitudinal shutter-frame

3.3. 400° C temperature resistance

Not only must stringent temperature requirements (400° C/60 min.) be taken into account when selecting the materials to be used (temperature resistance, solidity), but they also demand targeted construction procedures.
In order to ensure that the dampers function under temperature, the individual components' varying longitudinal expansion must be considered, with the following results:

- the entire damper must be capable of expansion in the concrete cut-out; it must not be rigidly connected to the concrete. Therefore, Sirocco dampers are fastened (clamped) to the concrete with U-bolts; they can expand when temperature-stressed.
- The vanes, surrounded by flowing smoke gases, heat up markedly sooner than the vane frame. Here, relative temperature difference between the vanes and the shutter frame must be taken into account by the use of sufficient gaps, so that the vanes remain mobile under temperature.
- Correct functioning under temperature influence should be obligatorily evidenced in a fire-test through cyclic opening and closing. Furthermore, fire-testing should include optical checking (light gap) of whether the vanes are completely shut when in the closed position.
- In general, the start-up motor is outfitted with an electronic control unit, which results in a maximal permissible temperature stress of 80° C. Thus, the drive must be thermally protected against hot smoke gases. There are two options:
  If a separate air-feed duct is available, the drive is installed in the cold air-feed duct and connected with the extraction damper via a drive shaft. It is essential at this point that, on the one hand, the wall-piercing (drill-hole) is thermally (and, of course, hermetically) bulkheaded and, on the other hand, that the drive shaft is outfitted with a thermal coupler.
  If the drive has to be installed in the exhaust duct, a thermal casing is mandatory. For physical reasons, such a casing can only keep temperature away from the drive for a limited time. Sirocco has developed a stainless-steel casing lined with various insulating materials separated by air cushions and certified for 400° C / 90 min.

As a general rule, more stringent the extraction dampers' temperature requirements, the more complex it will be to achieve optimal leakage prevention. Sirocco extraction dampers have been fire-prevention certified (400° C/120 min.); the certificate also covers function-testing under temperature and visual checking for leakage. In addition, Sirocco has its own certified leakage-testing shop, where extraction dampers can be tested and optimised up to dimensions of 4.0 m x 3.0 m.

4. TECHNICAL ASPECTS OF VENTILATION

4.1 Concentrated smoke suctioning

We now come to the question, „Why are extraction dampers and ventilator cowls needed in the first place?" Isn't it enough to have large openings in the intermediate ceiling in cross-ventilated or semi-cross-ventilated tunnels to suction off smoke in a case of fire?

In Fig. 5, you can see a schematic rendering of an extraction duct, with the intermediate ceiling and the traffic area below. There are openings of the same size at specific intervals in 4the ceiling. An exhaust ventilator is indicated at the end of the extraction duct; the ventilator suctions off exhaust out of the extraction duct. When the ventilator is switched on, the exhaust is distributed as shown here, due to local pressure conditions. s_A is the dimension-less suction volume, that is, the ratio of local suction volume to the mean value, and ξ is the dimension-less duct length, that is, the ratio of the running length to the duct length. You can see that a large quantity is suctioned off in the ventilator's vicinity, whereas very little is suctioned at the end of the extraction duct. However, during normal operation (especially at full load), it is necessary to assure smooth exhaust suctioning (i.e. $s_A = 1$) throughout the duct's entire length, since otherwise high concentration peaks can occur in the tunnel. Smooth suctioning can be achieved by mounting chokers, that is, ventilator cowls and/or extraction dampers at each opening. Near the ventilator, this choking must be very great, whereas it need only be very slight at the end of the exhaust duct, in order to achieve smooth suctioning.

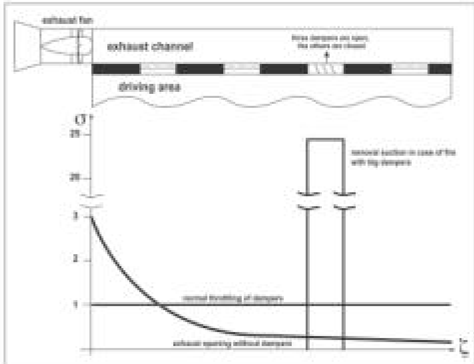

Figure 5: schematic rendering of an extraction duct

Bear in mind, however, that every choking is a loss of pressure which must be compensated by the exhaust ventilator, and entails more expense when operating the ventilating equipment. Pressure loss in the exhaust openings is absolutely necessary to achieve smooth exhaust suctioning; thus, it cannot be reduced. On the other hand, pressure loss in the exhaust duct must be kept to a minimum. This is why it is necessary to fully exploit the inflow pulse of the exhaust, that is, the exhaust must be fed into the duct at a very small angle. Pure choking of the inflowing exhaust without using the inflow pulse – as shown in Fig. 6 , leads to large pressures losses in the exhaust duct and to high costs of operating the ventilation equipment.

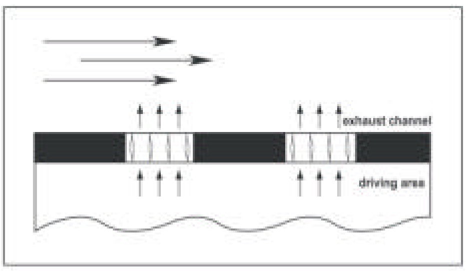

Figure 6: inflowing exhaust without using the inflow pulse

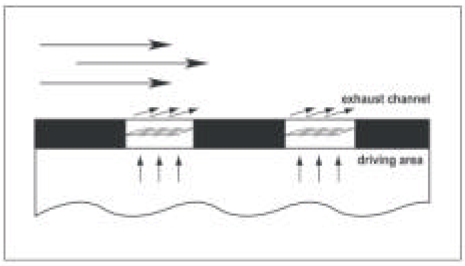

Figure 7: inflowing exhaust using the inflow pulse

During fire operation, an extraction damper near the fire’s location is opened fully, whereas all the others are shut tight. This allows the greatest possible volume of smoke gas to be suctioned off through the open extraction damper. The ventilator’s entire suction effect is concentrated on the area of the fire, where s_A is very large; by contrast, it is zero throughout the rest of the duct.
Optimal aerodynamic designing of the extraction dampers ensures a large suctioning volume. This begins as early as the stage of determining the size of the concrete openings for the extraction dampers. They should be large enough so that the flow speed in the open damper is not much larger than in the cross-section of the exhaust duct. In significantly smaller openings, the flow is initially greatly accelerated, which means it must be strongly detained in the exhaust duct which, in turn, leads to major losses of pressure.

4.2 Theoretical calculations

Thus, there are three ducts in cross-ventilating (traffic area, exhaust duct, air-feed duct) and two interconnection openings, viz. the extraction dampers and the fresh-air blower. Therefore, the pressure progression in the exhaust duct and the traffic area are also influenced by the flow conditions in the air-feed duct. This results in a very complicated system of equations – six paired, non-linear differential equations – for the progressions of pressure and speed in the individual ducts.
Here, for instance, you can see the differential calculations for the progressions of pressure and speed in the traffic area (equations 1 and 2).

Equation 1

$$\frac{dp_v}{dx} = -l_v \cdot \frac{1}{D_v} \cdot \frac{r}{2} \cdot u_v^2 \cdot sign(u_v) - r \cdot k_v \cdot u_v \cdot \frac{du_v}{dx} + \frac{r}{2} \cdot c_w \cdot \frac{F_F}{F_v} \cdot \frac{1}{\Delta L_1} \cdot \left[(V_1 - u_v)^2 \cdot sign(V_1 - u_v) - \frac{\Delta L_1}{\Delta L_2} \cdot (V_2 + u_v)^2 \cdot sign(V_2 + u_v) \right]$$

Equation 2

$$\frac{du_v}{dx} = -\frac{1}{F_v} \cdot \left(F_z \cdot \frac{du_z}{dx} + F_a \cdot \frac{du_a}{dx} \right)$$

Equations 3 and 4 show the progression of pressure and speed for the fresh-air duct.
Equation 3

$$\frac{dp_z}{dx} = -l_z \cdot \frac{1}{D_z} \cdot \frac{r}{2} \cdot u_z^2 \cdot sign(u_z) - r \cdot k_z \cdot u_z \cdot \frac{du_z}{dx}$$

Equation 4

$$\frac{du_z}{dx} = -\frac{f_z^{'}}{F_z \cdot \sqrt{V_{T2} + \sum V_{sek} + V_D}} \cdot \sqrt{(p_z - p_v) \cdot \frac{2}{r} + (1 - V_{T1}) \cdot u_z^2}$$

Equations 5 and 6 show the progressions of pressure and speed for the exhaust duct.
Equation 5

$$\frac{dp_a}{dx} = -l_a \cdot \frac{1}{D_a} \cdot \frac{r}{2} \cdot u_a^2 \cdot sign(u_a) - r \cdot k_a \cdot u_a \cdot \frac{du_a}{dx}$$

Equation 6

$$\frac{du_a}{dx} = \frac{F_a^{'}}{F_a \cdot \sqrt{1 + V_a}} \cdot \sqrt{(p_v - p_a) \cdot \frac{2}{r} + u_v^2}$$

This entire system of equations must be solved numerically, taking marginal values into account.

For example; the progression of pressure in an exhaust duct 1370 metres long was calculated for normal operation, if the exhaust is suctioned vertically into the exhaust duct without exploiting pulse (α = 90°). The partial vacuum at the end of the duct amounts to 1100 N/m^2. By contrast, if the exhaust is fed into the exhaust duct in the flow direction (α = ~ 0°) and the pulse is fully exploited, the partial vacuum at the end of the duct is only 650 N/m^2. At a maximum exhaust volume of 110 m^3/s, this results in increased exhaust ventilator output of 70 kW in a tunnel 1375 metres long, without exploiting inflow pulse.

4.3 Model testing

The Sirocco company commissioned model tests in order to achieve the most favourable flow conditions in a case of fire at a fully-opened extraction damper in the Plabutsch tunnel. Testing was conducted with the authorisation of the Office of the Styrian Provincial Government in the tunnel's winch house.

In Fig. 8, you can see the model of the exhaust duct, approx. 15 metres bng. The exhaust duct, modelled in wood construction, is at the front, and the exhaust ventilator's drive-motor and the soundproofing are visible in the background.

Pressure losses in the extraction damper were calculated at four different vane angles, α = 60°, α = 75°, α = 90 ° and α = 115° in the exhaust duct, thereby determining the resistance coefficient ζ (zeta) for the entire inflow.

Figure 8: model of exhaust duct

Fig. 9 shows the results of measuring. We can see that the lowest resistance coefficient is achieved (zeta = 1,3) at an inflow angle of α = 90°. Although less exhaust flows into the traffic area at smaller inflow angles, a certain amount of pressure is recovered through the inflow pulse aimed in the direction of the exhaust duct; however, the resistance coefficient is higher than at α = 90°. But if the exhaust is suctioned in the direction opposite to that of the flow (α = 105°), the negatively aimed inflow pulse leads to additional drop in pressure in the exhaust duct, which sharply increases the resistance coefficient.

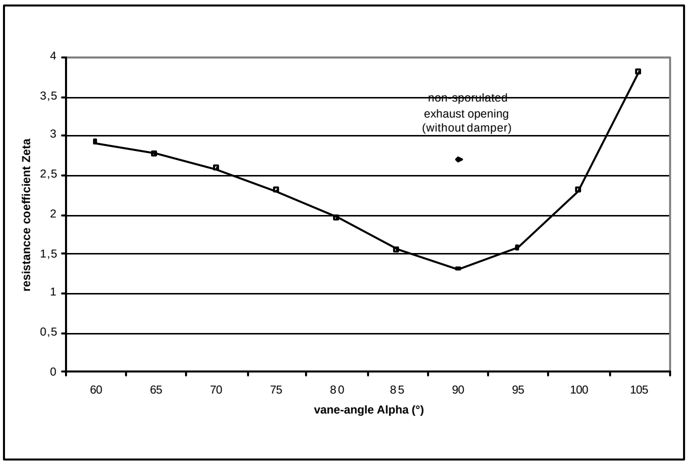

Figure 9: resistance coefficient – model testing in Plabutschtunnel

After measuring, the vanes and the central stay were taken out of the extraction damper, so that only the large non-sporulated exhaust opening remained, as it appears with an exhaust slide-gate. Measurements showed that the resistance coefficient of the unchoked opening is about 2.7, that is, it was larger than the coefficient of a fully-opened extraction damper.

SMOKE STRATIFICATION EVALUATION IN CASE OF TUNNEL FIRE

O. Vauquelin, D. Telle, E. Casalé* & D. Gabay**
University of Valenciennes, France
* Scetauroute DTTS, France ** RATP, France

ABSTRACT

This paper presents the results of a parametric experimental study carried out on a scaled down tunnel model (scale reduction 1 :20). Several tunnel fires have been simulated for different ventilation conditions in order to quantify the smoke layers stability. Visualization and local measurements have allowed to bring to the fore the flow pattern and a dimensionless parameter associated to the «stratification level » have been derived from experimental data.

Key words : fire-induced smoke, scale down model, longitudinal ventilation, stratification.

1. INTRODUCTION

When a fire occurs in a tunnel, the existing ventilation system has to be able to control the fire-induced smoke propagation. In both cases of longitudinal and transverse ventilation systems, one of the main aspects deals with the preservation of the smoke natural stratification. Keeping a correct stratification of smoke layers allows :

- to preserve a clean air layer in the lower part of the tunnel, which is crucial in order to facilitate the users evacuation,
- to increase the extraction efficiency of the vents located in the ceiling.

The major cause of smoke non-stratification downstream the fire is due to the interaction between the longitudinal airflow and the thermal plume. Large eddies develop and then mix both the air and the smoke [1]. In the case of a strong interaction, the buoyant forces become too weak in comparison with the turbulence being convected within the longitudinal flow : The mixing process continues and no stratification can appear downstream. From a practical point of view, it might be quite useful to be in a position to define (for a standard tunnel and a given fire heat release rate) a boundary value of the longitudinal velocity which would thus allow to preserve a suitable stratification.

From a more general point of view, two additional non-thermal causes likely to alter the layer stability can also be defined : The air motions due to the extraction duct operating process, or also, whirlwinding flows likely to appear if the fresh air blow down the walls is too important.

Before studying all that particular aspects, it is necessary to know how the stratification of a smoke layer can be quantify. The aim of the work presented in this paper is to characterize and quantify the effect of a forced longitudinal airflow on a stratified layer flowing through a tunnel. A set of experimental tests have been carried out on a scaled down tunnel model Several fires have been simulated for different ventilation conditions and then, velocities and densities in the flowing smoke layer have been measured. The first objective is then to use these local measurements to describe the flow pattern. The second objective is to build a layer « stability parameter » using bulk quantities easily measurable in practical conditions.

2. EXPERIMENTAL SET-UP

The experimental set-up is a 10 m long channel with a 250 mm high and 500 mm wide rectangular cross-section. These dimensions approximately correspond to a standard road tunnel with a scale reduction of 20. The latter will then be used in order to determine a correspondance between the full scale values and the scaled down values.

As shown on Fig. 1, a longitudinal air flow is created by a fan located at the channel end. The fire-induced smoke is simulated by a continuous release of an air/helium mix. For all the experiments, this buoyant source is placed 4.5 m from the channel entrance and the instrumentation station is located 2 m downstream the source. Both velocity and density are measured along a vertical line in the symmetry plan of the channel.

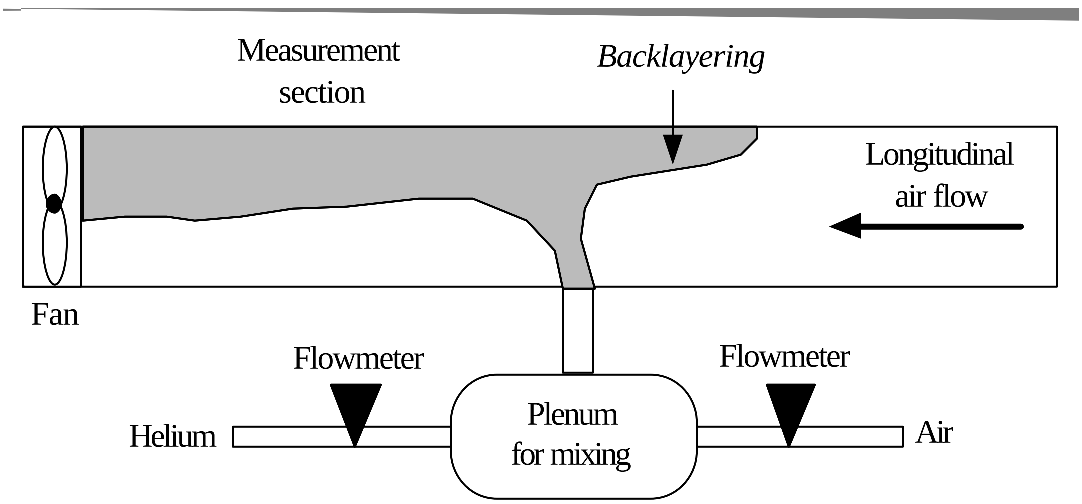

Fig. 1 : Experimental set-up

Froude and Richardson similitudes are kept in order to represent correctly the duality between the buoyant and the inertia forces in the smoke layer. Similarity rules then impose a strict conservation of the density values. As regards the other variables, a scale reduction α imposes an $\alpha^{1/2}$ reduction for velocities and an $\alpha^{5/2}$ reduction for mass flow and heat release rates.

Practically speaking, the experimenatl procedure cab be defined as follows : The value of the heat release rate to be simulated is chosen in the first instance. This value then imposes the source size, the mass flow rate and the density of the air/helium mix, according to the model developed by Mégret *et al.* [2]. More details about the fire simulation principle on this scaled down isothermal model are given in [3].

3. TESTS AND RESULTS

3.1. Tests description

For all the tests presented in this paper, the heat release rate being simulated is 4 MW (full-scale value). According to the model [2] for fire characteristics, the mass flow rate and the smoke temperature are then 20 m^3/s and 350°C respectively, for the corresponding full-scale configuration. Similarity rules for a scale reduction of 20 impose an air-helium mix flow rate of 650 l/mn with a 62% helium proportion.

Velocity profiles are obtained using Particle Image Velocimetry (PIV) and densities are measured by a local oxygen analyser. Density is related to the oxygen percentage χ_{O2} by :

$$r = r_{air} - \left[\left(1 - \frac{c_{O2}}{0.21}\right)\left(r_{air} - r_{helium}\right)\right] \tag{1}$$

The density can be associated to a «virtual temperature » T admitting the hypothesis of perfect gases. We can then write :

$$\frac{T - T_{air}}{T_{air}} = \frac{r_{air} - r}{r} \tag{2}$$

Five tests are carried out for five different values of the extraction mass flow rate. The first one is carried out without forced longitudinal air flow (noted Q_0) and the others are carried out for the mass flow rates Q_1, $Q_{3/4}$, $Q_{1/2}$ and $Q_{1/4}$ corresponding respectively to the critical mass flow rate, 3/4 of Q_1, 1/2 of Q_1 and 1/4 of Q_1. The critical mass flow rate [4] is associated with the critical velocity [5] needed to prevent the backlayering occurrence.

3.2. Local analysis

The vertical evolutions of density and velocity are presented on Fig. 2 and Fig. 3. We can observe that for the whole range of the mass flow rates tested, the density profiles are quite similar in the lower part of the tunnel. Differences appear within the layer *stricto sensu* and quite noticeably they are characterized by a clear decrease in the temperature close to the ceiling whenever the longitudinal airflow increases.

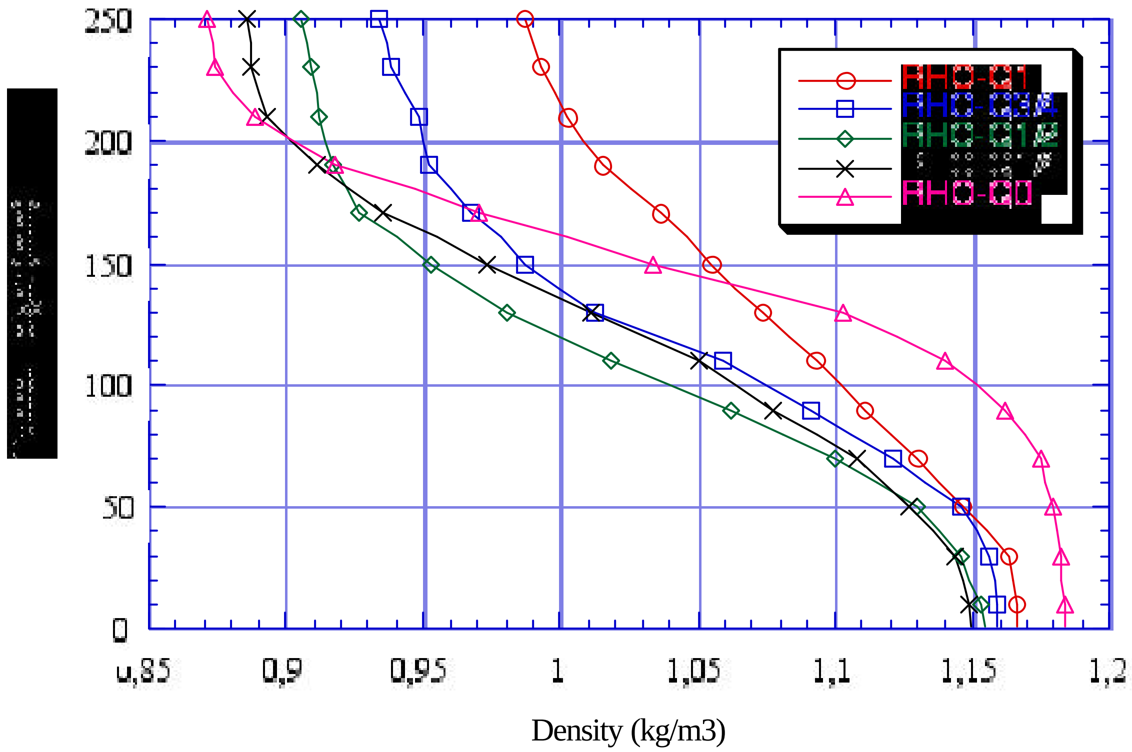

Fig.2 : Density vertical evolution for different extraction flow rates

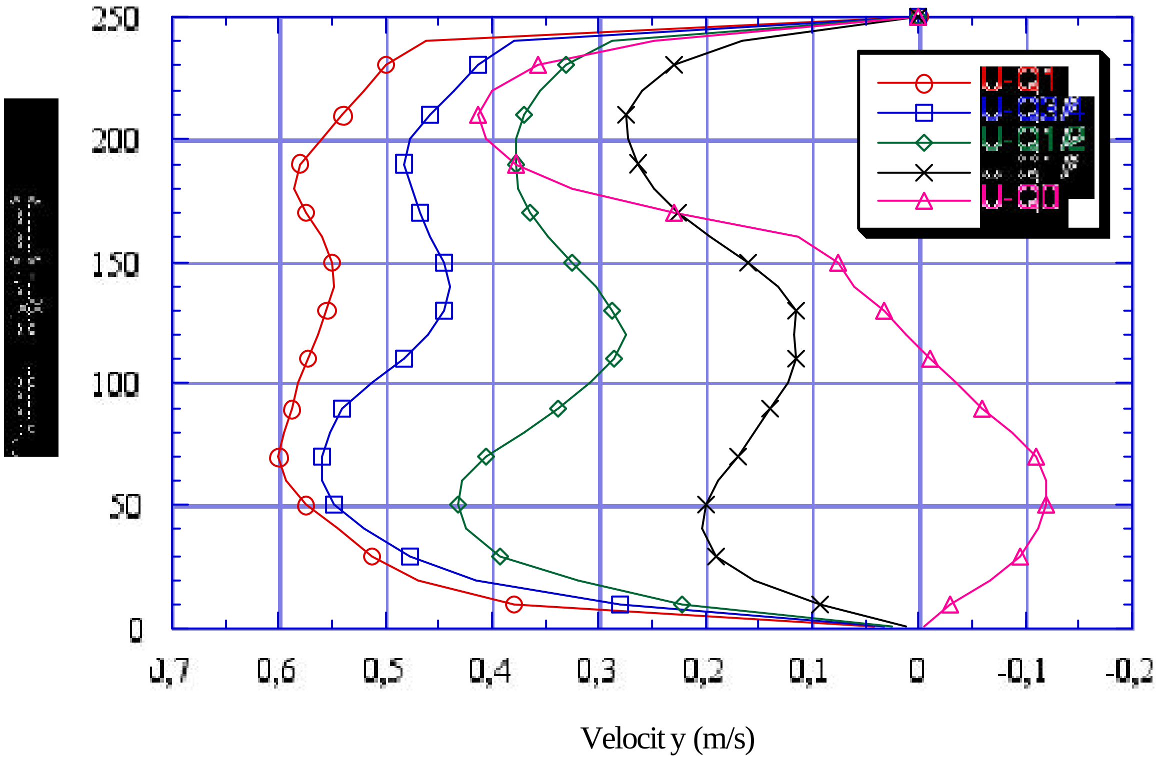

Fig. 3 : Velocity vertical evolution for different extraction flow rates

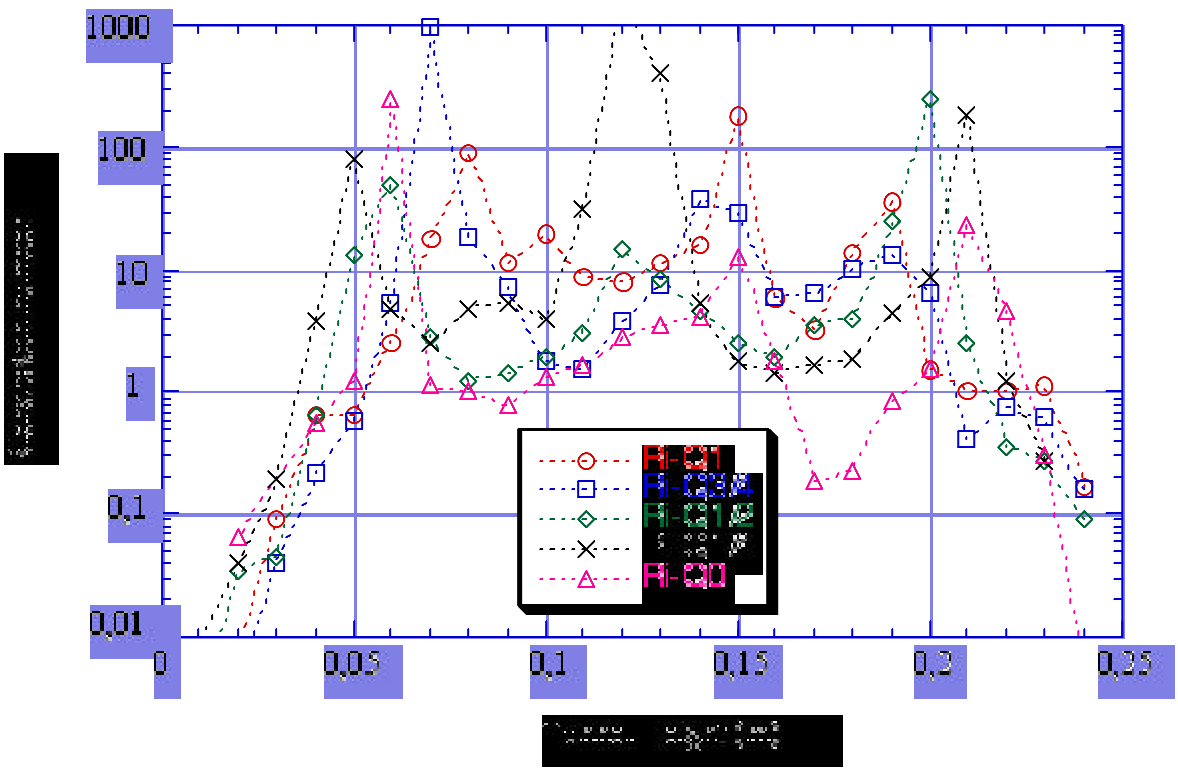

Fig.4 : Vertical evolution of the local Richardson number for differnet extraction flow rates

On the velocity profile curves, the smoke layer and the fresh air layer below are quite conspicuous since the interface area can easily be identified by the velocity trough. The bigger the flow, the thicker the interface area. A standart turbulent velocity profile in a channel is then reached for high velocity.

These vertical evolutions allow the calculation of the local derivative values for density and velocity [6]. It is then possible to calculate the vertical evolution of the local Richardson number as defined by :

$$Ri = -\frac{g(d\rho / dz)}{\rho_{air}(dU / dz)^2} \qquad (3)$$

The vertical Richardson number evolutions are presented on Fig. 4 display three peak values. These peak values can be associated, on the one hand to the maximum velocity in the smoke and the fresh air layers, and on the other hand, to the minimum velocity characteristics of the interface area between the two layers.

It can be noticed that the distance between the peaks associated with the maximum velocities sightly decreases when the extraction flow rate increases. This can be explained by a progressive disappearance of the interface area.

3.3. Overall analysis

The overall quantification of the stability of a flowing stratified layer has been studied by Newmann [7] and Xue *et al.* [8] in the specific case of a tunnel fire. These authors propose to use a dimensionless parameter S called « stratification parameter » and defined by the ratio between $?\rho_{gc}$, the density difference calculated between the ground and the ceiling and $?\rho_m$, the mean density difference calculated for the whole tunnel heigth.

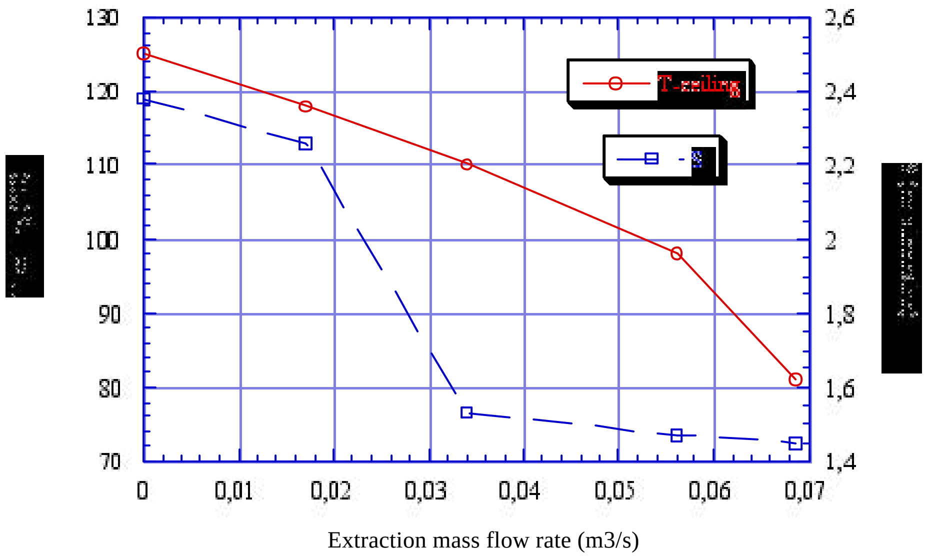

Fig.5 : Evolution of the temperature at the ceiling and of the « stability parameter » as a function of the extraction mass flow rate (for the corresponding full-scale values)

For a practical application in a tunnel, what we can easily obtain in real time are : the bulk velocity and the temperature close to the ceiling. It is then interesting to see if a correlation exists between these two parameters and the stability parameter S.

In the graph on Fig. 5, The virtual temperature close to the ceiling $T_{ceiling}$ and the stability parameter are plotted as a function of the longitudinal mass flow rate Q. This graph shows that a simple correlation can be set up between S and $T_{ceiling}$ since the latter keeps a higher value. However, when $T_{ceiling}$ decreases (or alternatively when the extraction flow rate increases) we can observe a sharp discontinuity in the curve representing the stability parameter S. Beyond this discontinuity, the layer is then in an « unstable » configuration : S slightly varies with the other parameters and its numerical value remains below 1.7 according to the results obtained by Newman [7].

4. CONCLUSIONS

The tests presented in this article were carried out in order to find a simple way to quantify the stability of a stratified flowing layer within a tunnel.

On the one hand, these tests have allowed to reveal the existence of a dimensionless parameter S called « stratification parameter » whose value abruptly falls at a certain condition when the bulk velocity in the tunnel increases. This discontinuity in the evolution of S allows to define two flow behaviours : In the first one, the smoke layer will be considered stratified and stable (S > 1.7) and in the second one (S < 1.7) the natural stratification of the smoke layer can be supposed to be noticeably damaged. The separation between these two flow behaviours can be associated with the bulk velocity value within the tunnel or with the temperature value close to the ceiling : These are two parameters easily mesurable in real time in a tunnel in use.

On the other hand, local measurements have allowed to plot the vertical evolution of the Richardson number along the whole height of the tunnel. These vertical evolutions have put to the fore the distribution of the stability areas but they do not allow to simply quantify the smoke layer stratification rate.

The future prospect mainly include other tests for other values of the fire heat release rate in order to give the observations made in this particular study a wider scope.

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FIRE MODELLING IN TUNNELS - CRITICAL PARAMETERS

Arthur A. EISENBEISS,
Helmut PEHERSTORFER, Thomas TRAUNER
IBS – Institute For Technical Fire Protection And Safety Research Ltd.
State Accredited Testing And Supervising Institute

ABSTRACT

The public discussion about safety in tunnels is leading to improved passive and active safety requirements. As a consequence increased performance data for the construction material, equipment and protection coverage have to be specified as a reasonable optimum of safety and economical feasible requirements. Calculations based on fire models are applied to the specific parameters of a particular tunnel in order to figure out such a tunnel specific optimum.

Based on the results of the sensitivity analysis the philosophy of a tunnel standard is discussed. To introduce a fire scenario together with fire resistance levels instead of definition of a temperature curve is recommended.

Sensitivity of temperature values calculated by modeling of a fire scenario in a tunnel geometry has been investigated. Critical parameters have been filtered out and are discussed in this paper. The presentation includes discussion of meteorological parameters, sensitivity to train length, to influence of tunnel geometry, remaining oxygen concentration and durability of the fire.

As a consequence of model calculation on sensitivity analysis temperature distribution in concrete and the corresponding fire resistance is discussed.

This paper is concentrated on safety requirements with respect to the stability and does not refer to personnel safety

Key Words: *Sensitivity Analysis, Temperature Distribution, Fire Scenario*

1. Introduction

Tunnel accidents in the past (e.g. Mont Blanc accident, Tauern tunnel accident, Kaprun accident, Gotthard accident) caused improved methods and intensified investigation of fire safety in planning and design of tunnels.
Improved fire resistance of a tunnel is connected with cost enhancement. As a consequence increased performance data for the construction material, equipment and protective coverage have to be specified as a reasonable optimum of safety and economical feasible requirements.

2. Temperature Curve and Modeling on the base of a defined fire scenario

A defined fire scenario leads to various fire growth scenarios in terms of heat release rate as a function of time and in terms of temperature as a function of time due to the dependance on

e.g. tunnel´s cross section, tunnel length, longitudinal air stream, forced ventilation, meteorological environmental conditions, blocked cross section by vehicles.
Determination of a fire curve as a standard implies the applicability to all, or at least to a very wide range, of tunnels. To cover all, or at least most of the tunnels, worst case conditions have to be considered for the choice of parameters influencing the fire growth.
Applying worst conditions to all tunnels delivers different safety levels for the tunnels. Those tunnels which are far beyond the worst case conditions exhibit a higher safety level than those which meet the worst case condition.
Preferring the approach to have the same safety level for all tunnels a common agreed fire scenario is needed to be defined. For the structural consequences different resistance levels for tunnels as they have been proposed by Lacroix /1/ shall be added. Such a differentiation covers different economical aspects of a break down of a tunnel (importance of the route, reconstruction time, reconstruction costs, subsea tunnels, ...).

Definition of a common agreed fire scenario together with needed resistance levels offer the advantage of harmonized safety levels and an optimized economical approach. Austria has formed a standardization team including representatives from the Authorities, the Fire Brigade, the Industry and Test Institutes to establish a Standard which contains

a) safety objectives with respect to risc classes (in the sense of resistance levels according to /1/
b) a fire scenario from which a particular can be calculated and designed in order to achieve the safety objectives
c) a temperature curve for 2 or 3 types of “typical” tunnel configurations with precisely defined limits of application. These limits shall define exactly what characterizes a “typical” tunnel. For all other tunnels a detailled analysis has to be carried out.

The following sensitivity analysis shows the wide range of fire temperatures under steady state conditions of one fire scenario applied to different tunnel parameters showing the difficulty to define a standardized temperature curve.

3. Sensitivity Analysis

3.1. Fire Model

The objective of the model IBSTUN02 was to utilize a model as simple as possible, able to run on a PC within a relatively short processing time and as complex as necessary to use the model as an engineering tool.
IBSTUN02 is based on the calculation of the energy balance considering enthalpy of the chemical equation, air supply due to tunnel geometry, longitudinal air flow, convective heat losses, radiation losses to the tunnel wall, bypass air and remaining oxygen content in dependence of the scenario’s geometry in order to calculate steady state conditions of temperature.
As a compromise there is no description of the temperature behavior in the initial fire growth phase.

In parallel the calculated results have been confirmed by the results of a CFD model /4/ and by experimental data acquired in fire tests and by experimental data documented in the literature /5/.

3.2. Fire Scenario

As there is currently no international definition of a "design fire scenario" for tunnels a quasi heuristic approach was taken to define fire scenarios.

For liquid fires Diesel was taken as a leading substance. The fuel is assumed to be spilled by an opening with a spilling rate of 7ls-1, which corresponds to an accidentally removed filling device.

To represent solid goods a carrier loaded with car tires was taken. Tiers as burning material have been chosen as the burning properties (calorific value and burning rate) are within the upper third of values for solid goods documented in the literature /2/ and /3/.
In the first approach the fire scenario was restricted to one carrier.

In particular the initial fire growth rate depends on the type of burning material (liquid fire of Diesel compared to a carrier with car tires). The amount of temperature variation relative to the absolute steady state temperature has been found to be comparable in many aspects for liquid and solid fire scenarios.

4. Results

The absolute temperature values under steady state conditions vary between 800°C and more than 1300°C for a multiple track section (cross section 250m²) according to the input parameters. The absolute values are not considered and discussed in this paper as the absolute temperature values are dominated by the individual tunnel geometry and environmental conditions and vary in dependence of the specific tunnel parameters (train length, meteorological pressure difference, tunnel length, cross section, remained oxygen concentration).

In the standard scenario non critical values are used as entrance parameters (leading to relatively low absolute temperatures) in order to demonstrate the influence of each individual varied parameter solely. Sensitivity analysis is performed either for a one track train tunnel (lower absolute temperature values) showing a cross section of around 40m² or for a two track tunnel showing a cross section of around 75m². Tunnel length is assumed to exceed 5000m.

As this paper focuses on the relative influence of specific parameters on the steady state condition temperature independent of the absolute temperature value. Despite the approach of relative temperature differences which would rather demand percentages than absolute temperature values the differences are given in degrees as the relevance of the values in degrees is much more obvious.

4.1. Sensitivity to Meteorological Pressure Differences and Longitudinal Air Speed

Meteorological pressure differences at the tunnel portals in a distance of 10 km are considered up to 100 Pa. A difference of 100 Pa corresponds to weather conditions which can be found sometimes a year /6/. The pressure difference varies linear with the tunnel length except for tunnels through the alps. As an extreme under very heavy storm conditions 200 Pa as an order of magnitude can be achieved. These high differences must also be considered for tunnels crossing the alps as totally different weather conditions north and south of the alps can lead to such high values. /6/.

The temperature variation due to air pressure differences of approximately 100° is cross section dependant. In case of a single track tunnel the temperature difference will decrease by 20% and will decrease furthermore in case of derailed and crashed wagon blocking most of the cross section.

The pressure difference is correlated to a non forced longitudinal air speed. For a double track tunnel and a 10000m long tunnel 50Pa relate to approximately 2ms-1 and 100Pa relate to approximtely 4,5ms-1.

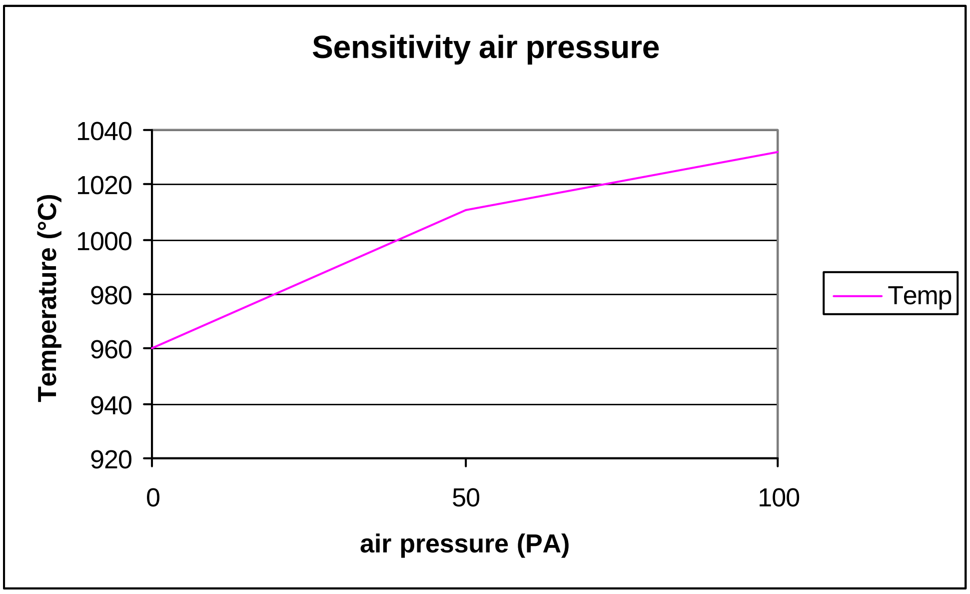

Fig. 4.1.1 Influence of air pressure difference between the tunnel portals on the steady state temperature 30 min after ignition.

4.2. Sensitivity to Train Length

The sensitivity to the train length is more relevant in one track tunnels as the resistance of the train against the longitudinal air flow is dominant there. In a one track tunnel the temperature varies within a range of approximately 100° between a 3 wagon and a 10 wagon long train.

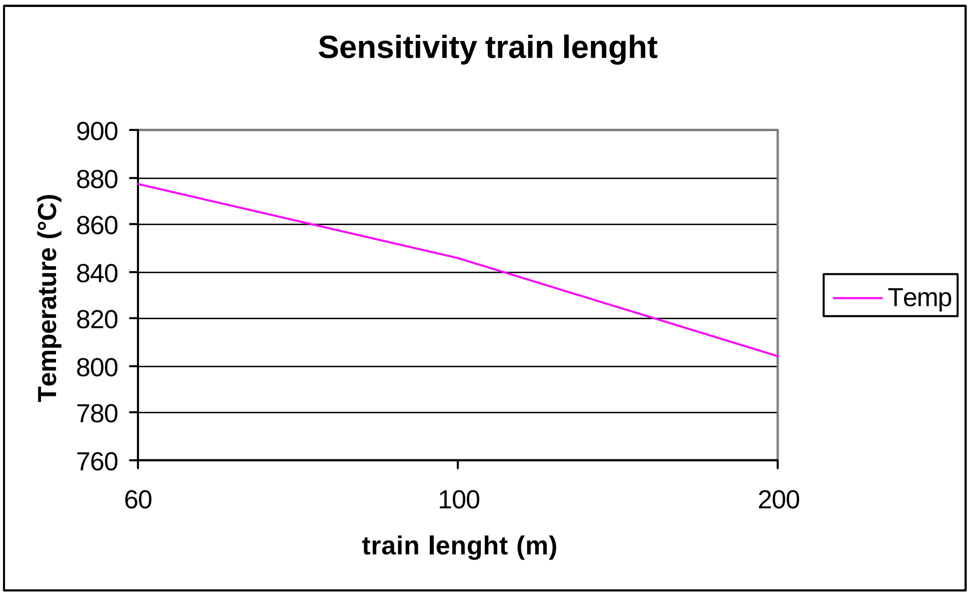

Fig. 4.2.1: Sensitivity to train length in a single track tunnel (20m correspond to one wagon)

In a double track tunnel the influence is approximately half of that in a single track tunnel and gets negligible in a multi track tunnel.

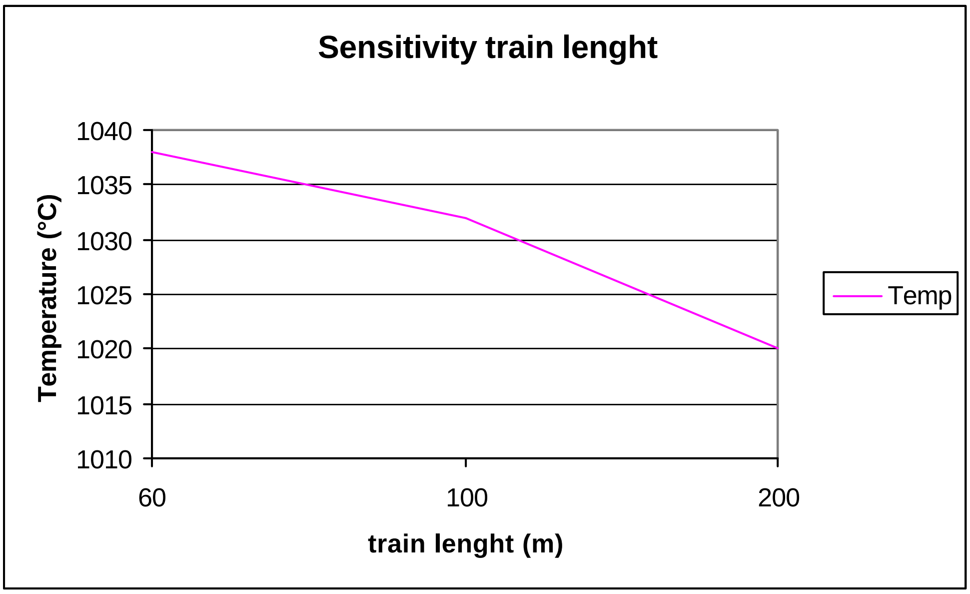

Fig. 4.2.2: Sensitivity to train length in a double track tunnel (20m correspond to one wagon), showing much less influence compared to a single track tunnel in Fig. 4.2.1

4.3 Sensitivity to Remaining Oxygen Concentration

The variation on steady state temperature is strongly influenced by the remaining oxygen which passes by the fire without participation in the chemical reaction.
There are two approaches from experience to define the range in which the remaining oxygen content should be considered:

a) A value between 12% and 15% of oxygen concentration is required to fulfil the design rules of gas extinguishing systems for the majority of liquid and Feststoffen, providing an inert atmosphere. For diesel and fuel the maximum oxygen concentration is 13,8% /7/

b) A minimum of 4% oxygen content is required for test furnaces to provide realistic conditions to represent fully burning conditions /8/

It should be noted that the values noted in a) are given for fires in an initial phase but not for longer lasting fully developed fires. The value noted in b) covers hot circumstances as the test conditions represent fully developed fires.

Up to our knowledge the literature does not report about experimental values about the remaining oxygen content in tunnel fires.
Therefore the range for the remaining oxygen concentration was considered between 4% and 12% remaining oxygen concentration leading to a temperature variation of approximately 400°.
Comparison with real 1:1 scaled fire tests in tunnels performed by our test institute and recalculation of the tests carried out in the firetun project /5/ showed a best fit for a remaining oxygen concentration of 8%.

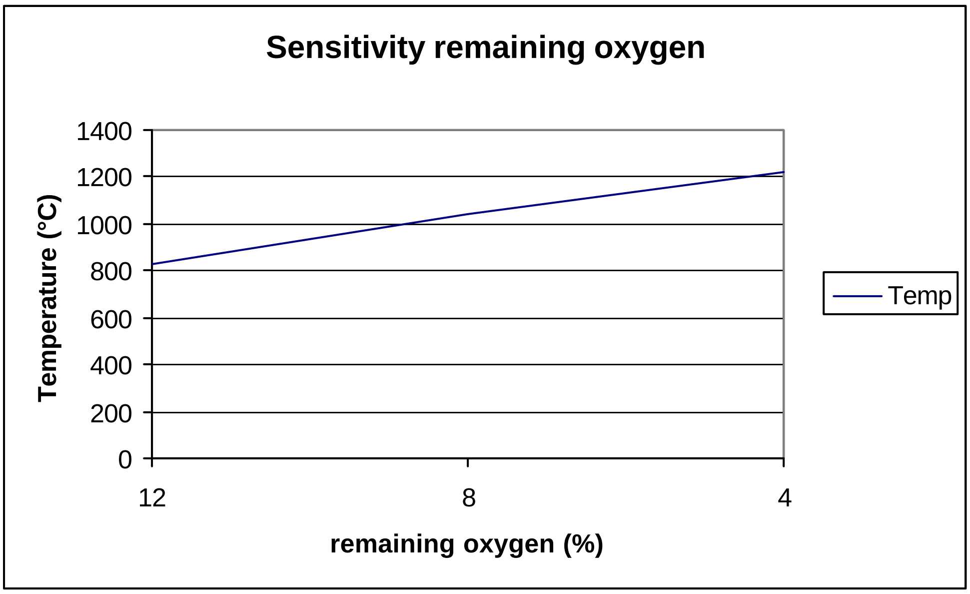

Fig.4.3.1 Sensitivity to remaining oxygen content

4.4 Long lasting fires

For fires lasting more than 2 hours the tunnel walls have been heated in a way that reduces the heat transfer by radiation. As the radiative heat losses can be typically in the order of magnitude of 30% in the beginning of a fire the decreasing heat loss of radiation can lead to an increase in temperature by up to 200° for fires lasting long compared to 2 hours.

6. Temperature Distribution within the Concrete and Fire Resistance

The calculated temperature progress in a depht of 40mm inside the concrete at the tunnel ceiling as a function of time is shown in Fig 6.1. Parameter is the steady state temperature caused by a fire in the tunnel. The horizontal line at a temperaturelevel of 500°C is a guide for the eye representing the critical steel temperature.

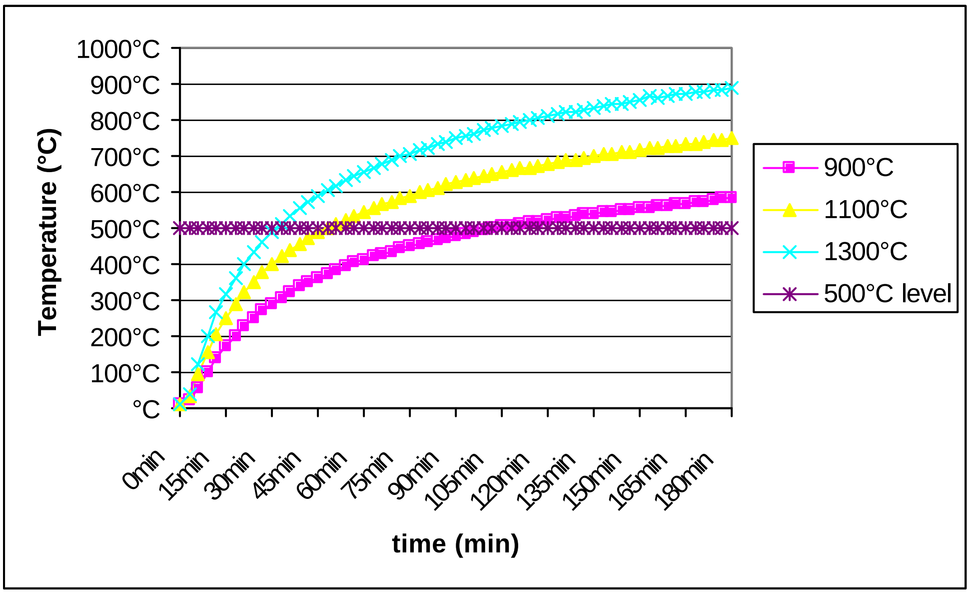

Fig.6.1: Time dependent temperature development in concrete for a 900°C, 1100°C and 1300°C temperature load in a depth of 40mm calculated with IBSTUN02

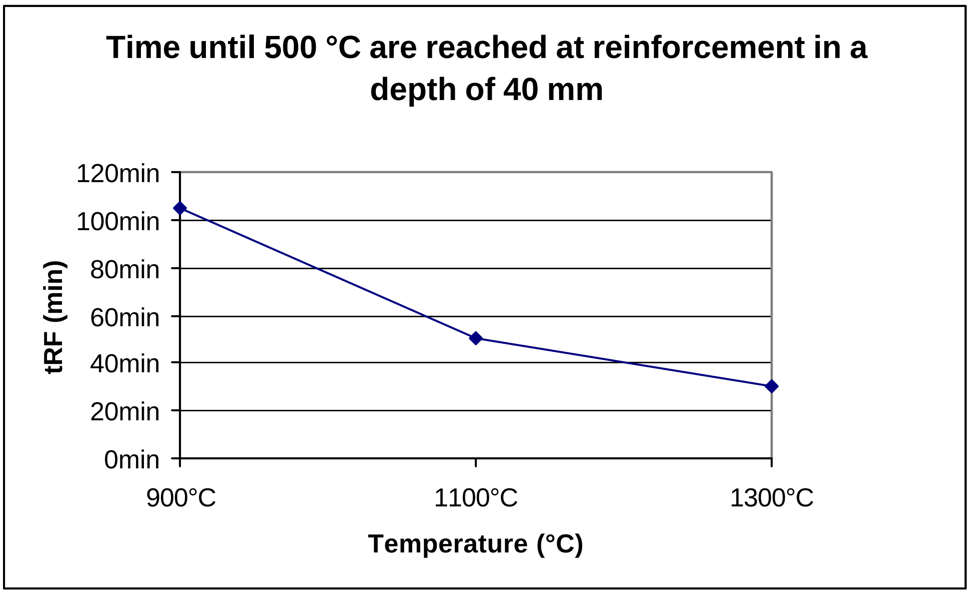

Fig.6.2: Time before structure fails (t_{RF}-time when 500°C are reached at the reinforcement in depth of 100mm)

As the critical steel temperature is around 500°C with minor variations due to different steel types the time of resistance is derived and plotted for an assumed depth of the reinforcement of 40mm in Fig. 6.2. The critical steel temperature provides a reduction of strength therby reducing the safety coefficient from 1,7 to 1,0. The temperature of the steel/concrete can rise up to around 500°C before the structure fails e.g. /9/.

7. Conclusion

Any temperature curve is a result of a fire scenario and cannot act a basic design requirement unless a worst case based fire curve is chosen.
Sensitivity analysis shows remarkable differences for different tunnels. Combination of varied parameters cannot be arithmetically added. Adding the variations resulting from sensitivity analysis and including variations in cross sections of a single track tunnel (40m²) and a multi track tunnel (up to 280m²) covers a temperature range between 800°C to more than 1300°C.
Results of modeling and sensitivity analysis inform of resistance times against a fire and combined with demanded risk levels (fire resistance) levels which take into account the surrounding importance can and shall be used to influence the tunnel design in order to establish a high safety level in the light of reasonable construction costs.

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SIMULATION OF ESCAPE FROM ROAD TUNNELS USING SIMULEX

Arthur G. Bendelius, Senior Vice President
Silas K. Li, Supervising Mechanical Engineer
and William D. Kennedy, Vice President

Parsons Brinckerhoff Quade & Douglas, Inc.
One Penn Plaza, New York City, NY10119, USA

ABSTRACT

The 2001 Edition of NFPA 502 requires emergency exits to the surface or a point of safety or that tunnel-to-tunnel cross-passages be provided throughout the tunnels. Their maximum spacing is 600 m (travel distance to an emergency exit shall not exceed 300 m therefore 600 m between exits) or 200 m (between cross-passages). The distances stated in the standard are more of a matter of experienced opinion than being developed from a rigorous engineering analysis. The tunneling environment (rock, soft ground, etc.) can make cross-passages very expensive. Therefore, there is an ongoing interest to determine the most appropriate distance between emergency exits and the width of walkways and cross-passages.

This paper discusses the use of an emergency evacuation computer program, SIMULEX, to simulate the emergency exiting of people from road tunnels to a point of safety. The program algorithms for the movement of individuals are based on real-life data. The program shows the evacuation process graphically on the screen, with the plan view of passengers moving towards emergency exits, showing the constraints on the exiting flow. Options were added to the program including the simulation of curbed walkways in road tunnels.

The egress times computed by the program were used to evaluate alternate distances between emergency exits and to provide comparisons among alternate widths and heights of walkways and cross-passages. The paper includes the results from 16 separate analyses.

1. INTRODUCTION

The 2001 Edition of NFPA 502 [Ref. 1] requires a maximum travel distance to an emergency exit of 300 m (600 m between exits) to the surface or a point of safety or 200 m between tunnel-to-tunnel cross-passages be provided throughout the tunnels. European practice is to use 200 m to 300 m spacing between cross-passages. In some countries, a spacing of 500 m between cross-passages is acceptable. NFPA 502 /101 [Ref. 2] requires cross-passages with a minimum width of 1100 mm and a minimum walkway width of 1000 mm. Walkways shall be protected from oncoming traffic by either a curb, or change in elevation or barrier. Raised walkways that are more than 760 mm above the road surface shall be provided with guards to prevent falls over the open side.

This study is part of an ongoing study on escape from road and rail tunnels [Ref. 3]. The findings are based solely upon occupant evacuation to the nearest exit. All of the tunnel occupants are assumed to have health and ability to exit the tunnel. But in reality people who are unable to self-rescue may be present in the tunnels and an allowance of some sort must be made for them. Further, other factors are involved in the design of cross-passages, such as tunnel ventilation, smoke and visibility.

2. DESCRIPTION OF SIMULEX

The exiting program, SIMULEX [Ref. 4], is an existing Program developed for buildings and modified by the original developer for tunnels, both road and rail. The program simulates the emergency exiting of people from large, geometrically complex building space to a point of safety. The program models the escape movement of each individual person instead of using mathematical formulae for uniform flow rates and average speeds of groups of people. The program displays the building plan and the position and progress of individual people as they walk towards emergency exits and shows choke points in the exiting flow.

The program algorithms for the movement of individuals are based on real-life data and predicts realistic people flow rates [Ref. 5]. The program assigns body dimension, position, angle of orientation, occupant type and a walking speed for each person. The simulation of escape movement includes distance mapping, wayfinding, overtaking, route deviation, response time and adjustments to individual speeds due to the proximity of crowd members.

The computer program takes the building plan data file and generates a “distance map” for that space. A “distance map” is a fine mesh of spatial blocks which covers the floor plan. The numerical value assigned to each block in the mesh is equal to the optimal travel distance from the center of that block to the nearest available final exit. The “distance map” is then used by the program to assess escapes routes throughout the floor plan.

It is important that the program predicts realistic people flow rates over a range of different exit widths. Unrealistic people flow rates will produce unreliable results when calculating the total evacuation times for different floor plans. Therefore, a set of tests was carried out to calibrate the program [Ref. 6]. This form of testing was useful because the motion of individuals, moving in close proximity through a restricted opening, invoked all the decision and movement algorithms.

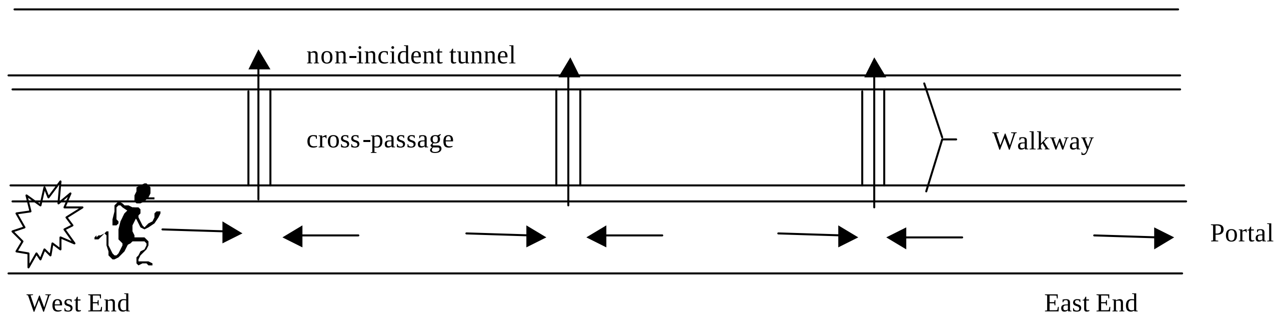
At Parsons Brinckerhoff's request, SIMULEX has been modified for road and rail tunnel applications. The road tunnel modifications include the simulation of curbed walkways. The rail tunnel modifications include, as an option, the simulation of people walking at a constant speed of 1 m/s as stipulated by NFPA 130 [Ref. 7]. The special people type of 1 m/s can be used in road tunnel simulations.

3. ROAD TUNNEL PROBLEM

3.1 Description of Problem

The road tunnel consists of 2 bores, 1000 m long, each carrying 3 lanes of uni-directional traffic. Intermittent cross-passages with access steps provide emergency egress between the bores. Further, an elevated walkway of 900 mm in height is located adjacent to the cross-passages. Figure 1 depicts a schematic of the tunnel, including the fire incident location at the west end of the tunnel. The tunnel occupants will move toward the nearest cross-passage even though in some tunnel sections they will move toward the fire. To make them do this, proper signs are needed on tunnel walls to clearly show the exit direction to the nearest cross passage.

Figure 1 : Road Tunnel Schematic



3.2 Input Data

The traffic mix comprises of 10 percent of trucks, 5 percent of buses, and 85 percent of minivans and cars. Vehicle occupancy comprises of 2 people in a car, one person in a truck, 30 people in a bus, and 4 to 6 people in a minivan. The total number of individuals in the 3-lane tunnel is 1513 or a population of 50 people per 100 lane-meters.

The SIMULEX simulations used "Commuter" mix and walking speeds for people movement to predict more realistic people flow. The commuters consist of 50 percent male, 40 percent female and 10 percent children. Each type of commuters has its own body size and normal walking speed. The mean speeds of male, female and child are 1.35 m/s, 1.15 m/s and 0.9 m/s, respectively.

The response time of people in the tunnel was staggered in such a way that people near the incident will react quicker than those further away from the incident. The maximum response time was assumed to be 2 minutes.

4. SIMULATIONS PLANNED

A total of 16 simulations was planned for the road tunnel problem. The simulations included:

- two cross-passage widths (1100 mm and 2100 mm),
- four cross-passage intervals (125 m, 250 m, 375 m and 500 m),
- elevated walkway and low curb walkway,
- two and three traffic lanes.

The first series of runs kept the cross-passages 1100 mm wide and changed the spacing of cross-passage in each run. The second series of runs repeated the previous runs with 2100 mm wide cross-passages. The third and fourth series of runs repeated the runs without walkway and changed the 3 lanes tunnel to 2 lanes.

5. RESULTS OF SIMULATIONS

The results of simulations were animated. The playback feature of the program displayed the movement of people as they evacuated the tunnel. At the end of a simulation, the total exiting time was predicted. The exiting time included 4 time elements: 1) people response time to an incident, 2) walking time to the nearest cross-passage/portal, 3) waiting time at the entrance of cross-passage, and 4) walking time to a point of safety. As people passed the fire doors at the end of the cross-passages they have reached a point of safety. Table 1 shows the exiting times for the 16 simulations.

Table 1: Exiting Times for Road Tunnel Problem

Run Number	Cross-passage Width (mm)	Cross-passage Spacing (m)	Number of Cross-passages in Tunnel	Walkway Type	No. of Lanes	Exiting Time (min.: sec.)
1A	1100	125	7	Elevated	3	4:26
1B		250	3			7:53
1C		375	2			9:39
1D		500	1			15:03
2A	2100	125	7	Elevated	3	3:19
2B		250	3			4:47
2C		375	2			6:38
2D		500	1			9:33
3A	1100	125	7	Low Curb	3	4:14
3B		250	3			7:41
3C		375	2			9:25
3D		500	1			14:33
4A	1100	125	7	Low Curb	2	3:25
4B		250	3			5.37
4C		375	2			7:41
4D		500	1			10:16

Figure 2 shows two snapshots of the simulations, one at the start of the simulation (time = 0) when the incident has been recognized but the tunnel occupants have not yet responded to the emergency. In the second snapshot the tunnel occupants have had 14.7 seconds to begin their flight from the tunnel.

Figure 2: Snapshot of a Simulation at Time = 0 Second

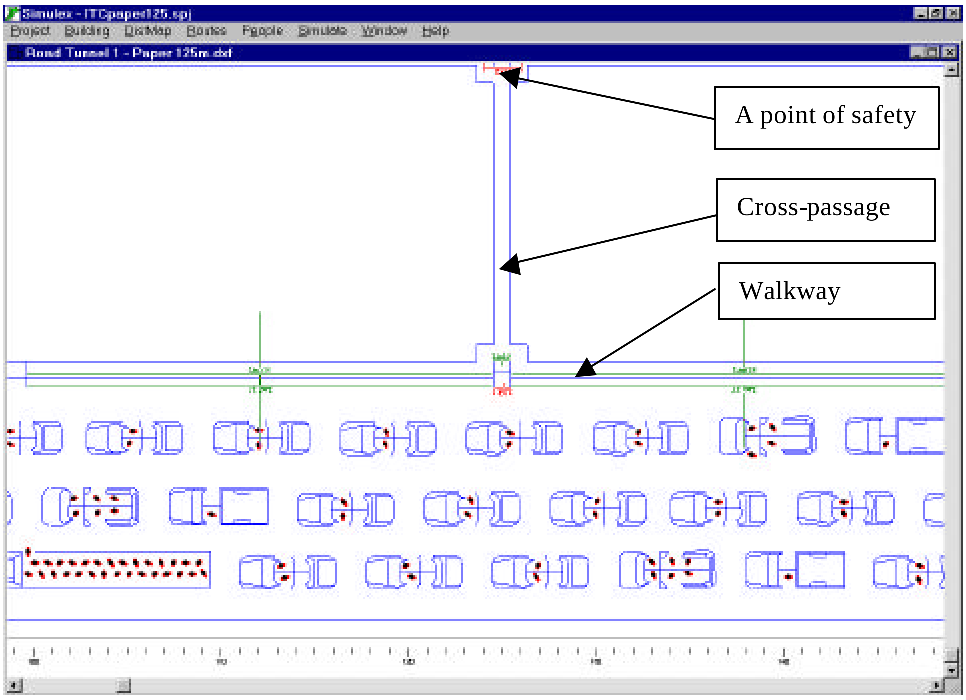
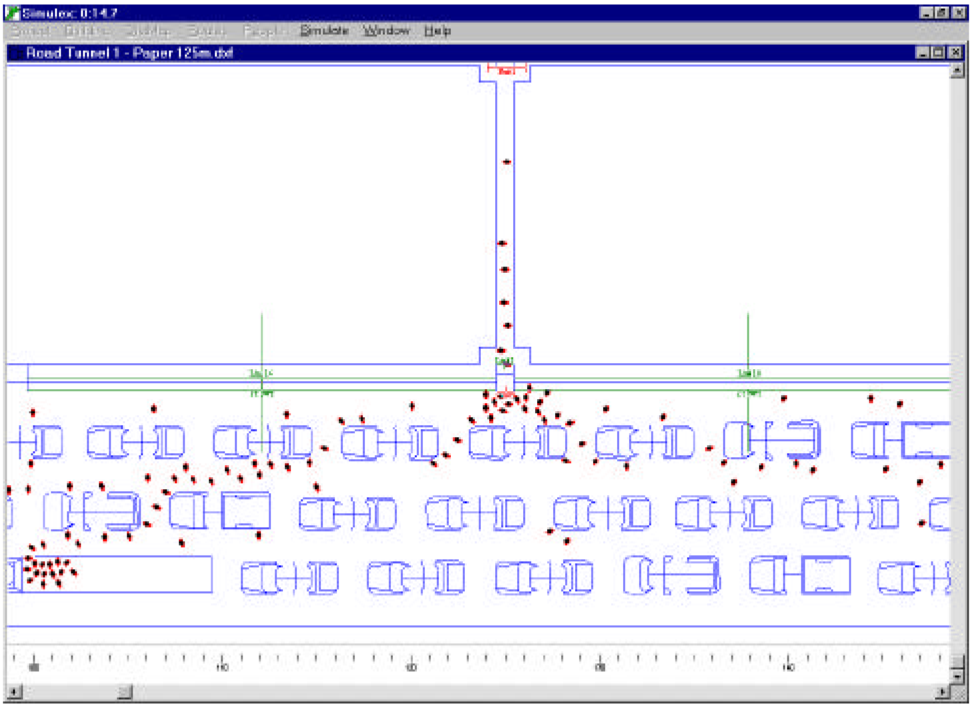


Figure 3: Snapshot of a Simulation at Time = 14.7 seconds



Effect of Cross-passage Spacings

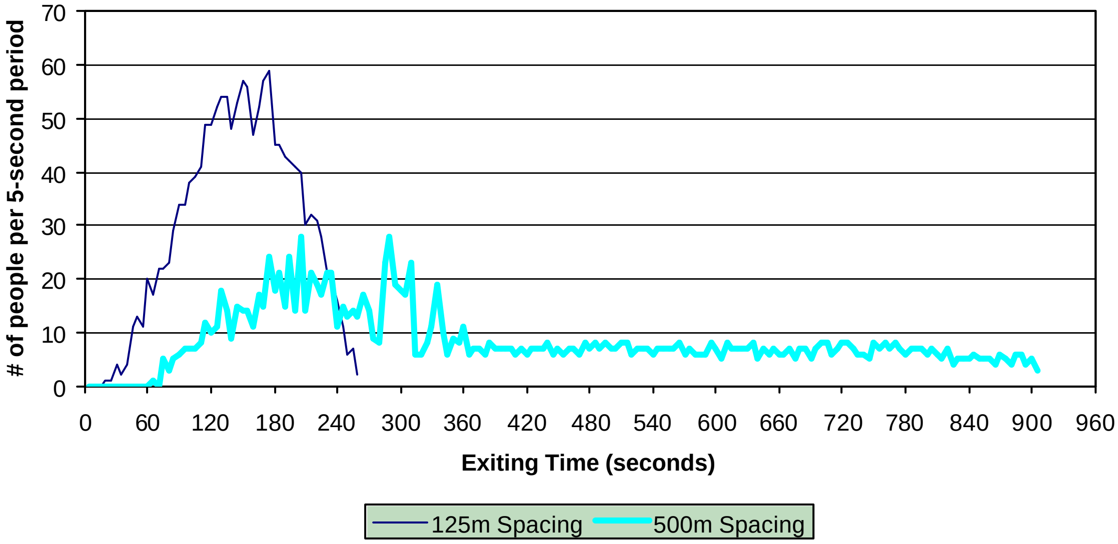
The first series of runs predicted an increase of exiting time as the spacing of cross-passages increased as shown in Table 2. When the distance of cross-passages increased, people had to walk a longer distance to the nearest cross-passage and wait a longer time to exit through the cross-passage.

Table 2: Effect of Cross-passage Spacings

Run Number	**Cross-passage Spacing (m)**	**Exiting Time (min. : sec.)**
		1100 mm Wide
1A	125	4:26
1B	250	7:53
1C	375	9:39
1D	500	15:03

It is interesting to note the number of people reaching all exits (including portal) during the evacuation period. A comparison was made between 125 m and 500 m intervals. As shown in Figure 4, the number of people through all exits gradually increased and then decreased. The roughness of the curves was caused by slow persons temporarily slowing the cross-passage flow. This is different from many manual calculations assuming a constant people flow rate. Figure 4 also shows that shorter spacing between cross-passages allows a greater number of people through the exits because of more available cross-passages.

Figure 4 : Number of People through All Exits (1100 mm width)



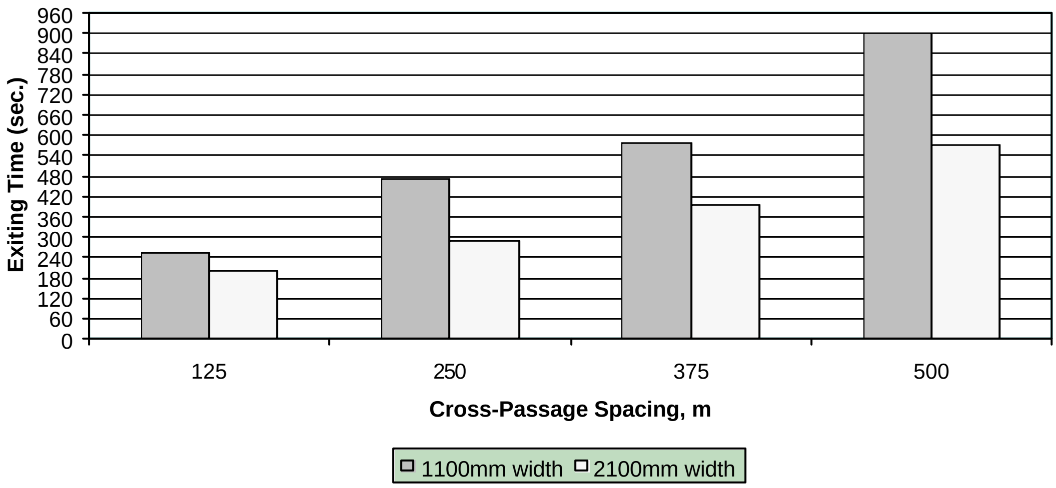
Effect of Cross-passage Widths

Widening cross-passages increases people flow rate and reduces waiting time at the cross-passages, hence decreasing exiting time. Table 3 compares the exiting time between 1100 mm and 2100 mm wide cross-passages. Although the cross-passage width was increased by 90 percent, the exiting time was reduced by 15 to 40 percent. Increasing cross-passage width will reduce waiting time at cross-passages, but not the walking time. So a relatively small reduction in exiting time was realized with a 125 m spacing, while the reduction in exiting time was more significant when the spacing was 500 m, as shown in Figure 5.

Table 3: Effect of Cross-passage Widths

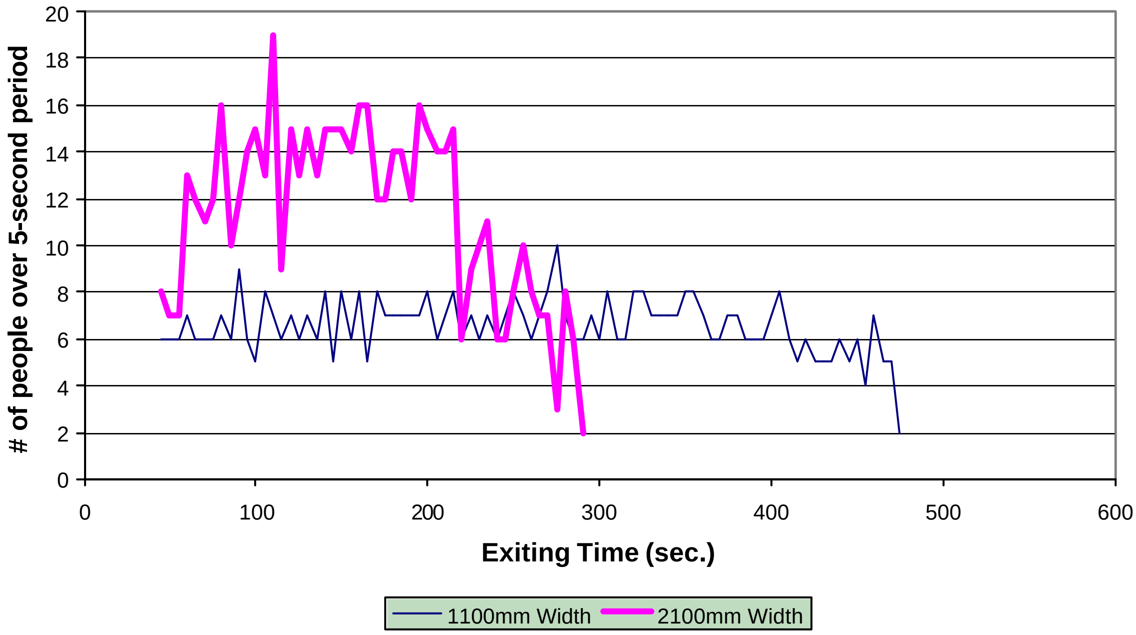
Run Number	**Cross-passage Spacing (m)**	**Exiting Time (min. : sec.)**	
		1100 mm Wide	**2100 mm Wide**
1A & 2A	125	4:26	3:19
1B & 2B	250	7:53	4:47
1C & 2C	375	9:39	6:38
1D & 2D	500	15:03	9:33

Figure 5 : Exiting Time for Road Tunnel



To compare the number of people walking through a 1100 mm wide cross-passage with that through a 2100 mm cross-passage, results of the simulation with 250 m spacing cross-passages were plotted in Figure 6. The average number of people walking through 1100 mm and 2100 mm wide cross-passages were about 79 and 137 people per minute (or 1.1 and 1.2 persons per meter width per second), respectively.

Figure 6 : Number of People Through a Cross-Passage



Effect of Walkway Heights

Four simulations were performed to study the effect on exiting time by changing walkway height from 900 mm to zero. Table 4 indicated only a minor improvement in exiting time. A playback of the simulations confirmed that the cross-passage was the bottle-neck in the evacuation path. The curb walkway will not greatly improve exiting time. It was assumed that all tunnel occupants have the ability to step up the walkway and exit the nearest cross-passage. For high-level walkways (over 1 m), elderly, children and their parents may choose to bypass cross-passages and evacuate through tunnel portals. That may result in longer exiting time.

Table 4: Effect of Walkway Heights

Run Number	Cross-passage Spacing (m)	Exiting Time (min. : sec.)	
		Medium-height Walkway	**Low-level Curb Walkway**
1A & 3A	125	4:26	4:14
1B & 3B	250	7:53	7:41
1C & 3C	375	9:39	9:25
1D & 3D	500	15:03	14:33

Effect of Walkway Widths

Based upon previous simulations for alternate walkway heights, the restriction at egress flow is at the cross-passages, not the walkways. There is an "optimal" ratio between the walkway width and the cross passage width. If the ratio is optimal the increasing the cross-passage width will not decrease exiting time since the walkway width will then become the choke point. Similarly, increasing the walkway width will not decrease the exiting time since the cross-passage will become the choke point. So if the ratio is optimal, once has to increase both cross-passage and walkway widths to decrease exiting time.

Effect of Tunnel Occupant Load

Reducing people load in the tunnel will speed up the total exiting time. Results in Table 5 confirmed that understanding. To achieve a similar exiting time, the cross-passages in a 2-lane tunnel could be placed 100m to 125m further apart than those in the 3-lane tunnel.

Table 5 : Effect of Number of Lanes

Run Number	**Cross-passage Spacing (m)**	**Exiting Time (min. : sec.)**	
		3 lanes	**2 lanes**
3A & 4A	125	4:14	3:25
3B & 4B	250	7:41	5:37
3C & 4C	375	9:25	7:41
3D & 4D	500	14:33	10:16

6. CONCLUSIONS

Egress simulations provided more details and insights on road tunnel exiting. The egress times computed by computer program could be used to evaluate alternate distances and widths of cross-passages and to provide comparisons among alternate walkway heights and widths. Using the results of the road tunnel problem, to achieve an exiting time of 6 minutes, the designer could further study the cost implications of two options: 1) 1100 mm wide cross-passages spaced at 125 m and 2) 2100 mm wide cross-passage spaced at 250 m. Furthermore, to achieve a similar exiting time in a 3-lane tunnel with 250m cross-passage spacing, cross-passages in 2-lane tunnels could be placed further apart (375 m).

As the distance between cross-passages increased, people had to walk a longer distance to the nearest cross-passage and waited a longer time at the cross-passage. It was interesting to note that the number of people through all exits gradually increased and then decreased. This highlighted the limitations of many manual calculations assuming a constant people flow rate.

Widening cross-passages increased people flow rate and reduced exiting time. Only the waiting time at the cross-passage was reduced, while the walking time to the cross-passage remained the same. People would predict that doubling the width of cross-passages would reduce exiting time by half. However, simulations revealed that a relatively small reduction in time was realized with a closer spacing (125 m). The reduction in exiting time was more significant when the spacing was 500 m and the waiting time was the longest.

The playback of simulations confirmed that the cross-passage was the bottle-neck of egress flow. The effect of walkway heights was minimal. The simulations assumed all tunnel occupants have the ability to step up the walkway and exit the nearest cross-passages. People will not bypass the walkway because of the walkway height. Similarly, when the restriction of exiting flow occurs at the cross-passages, the effect of walkway widths was minimal. If the ratio of cross-passage width to walkway width is optimal, once has to increase both cross-passage and walkway widths to decrease exiting time.

7. RECOMMENDATIONS

Applicable standards and codes for road tunnels should consider the approval of using validated computer exiting program to determine the most appropriate width and spacing of cross-passages. Similar to NFPA 130 for station design, a maximum exiting time and a methodology to compute design occupancy should be developed for road tunnels.

Further studies should superimpose the exiting results of these studies on the movement of smoke and heated gases within the road tunnel during a fire incident. The evacuation speed depends on smoke movement and visibility. This will then bring tunnel grade into the evaluation.

8. ACKNOWLEDGMENTS

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CERBERUS: A NEW MODEL TO ESTIMATE SIZE AND SPREAD FOR FIRES IN TUNNELS WITH LONGITUDINAL VENTILATION

R.O. Carvel, A.N. Beard & P.W. Jowitt
Department of Civil and Offshore Engineering,
Heriot-Watt University, Edinburgh EH14 4AS, Scotland, UK

ABSTRACT

A new fire model is presented. This model, CERBERUS, combines the results and findings of three previous research projects carried out at Heriot-Watt University. Each of the three projects is briefly described. Combining the results of these three projects, together with knowledge of fire behaviour in the open air, enables the estimation of the maximum fire size of a fire in a tunnel and the conditions under which it might spread to an adjacent vehicle, for a given longitudinal ventilation velocity. To enable these results to be easily used by a wide audience, they are being combined in a single, user-friendly, computer model. The current version of this model (a1.0) is limited to considering fire spread between HGV objects in a single lane tunnel, dimensions based on the Channel Tunnel rail link (UK/France). Future versions of the model will allow for different types of fire and different sizes of tunnel to be considered. Some preliminary results are presented and discussed.

Key words: Fire size, Heat Release Rate, Fire spread, Longitudinal vent., Probabilistic model

1. INTRODUCTION

In the past, the heat release rates of experimental fires in tunnels have sometimes been observed to be significantly higher or lower than expected, but these effects have rarely been quantified or even commented upon. Heat release rate (HRR) is a measure of the size of a fire and is a crucial factor contributing to the severity of that fire. In 1976 it was estimated that a heavy goods vehicle (HGV) fire in a tunnel would have a HRR of about 20 MW[1] and this has tended to become a value used by many risk assessors and tunnel designers. However, the only real HGV fire test carried out in a tunnel exhibited a peak HRR of over 120 MW[2] – the huge difference between the estimate and reality may be due to (a) the influence of the forced ventilation on the fire and (b) the influence of the tunnel geometry on the fire.

In recent years computer technology has advanced to the stage that complex Computational Fluid Dynamics (CFD) models can be used to simulate the effects of a fire in a tunnel and predict the movement of smoke and the zones of high temperature. These models are frequently used at the design stage to test various ventilation strategies and investigate smoke behaviour in tunnels. However, one of the limitations of these models is that they are unable to predict the rate of burning or HRR of a fire in a tunnel, the HRR data must be input by the user, so predictions of temperature conditions in the tunnel may be used only as a rough guide. If a CFD model user bases the model inputs on the 1976 estimate, the model may produce results which are unrealistically mild, however if the inputs are based on the experimental data (from a small tunnel with a high air velocity) then the model might produce results which are unrealistically severe. A better method of estimating the HRR of a fire in a tunnel, under specified ventilation and geometrical conditions is desirable.

Much of the experimental and modelling research into fire phenomena in tunnels has only been concerned with smoke movement and control, as smoke is the main cause of fatalities in enclosed fire incidents. However, smoke is not the only important factor when considering tunnel fires – the temperature of the fire, its probability of spreading to other vehicles or objects and the effect it will have on the integrity of the tunnel itself are not directly dependent on the smoke produced by the fire, but they are dependent on the energy produced by the fire and the rate at which that energy is released. Many fire safety engineers hold that the HRR of a fire is the single most important factor contributing to its severity.

A model that predicts the heat release rate of vehicle fires in tunnels is currently in development at Heriot-Watt University. At present the model is restricted to only considering HGV fires in a single lane tunnel, but it is intended that future developments to the model will enable a variety of tunnel and vehicle configurations to be tested. The model takes into account the shape and size of the tunnel and the ventilation conditions and adjusts the HRR of the fire accordingly. The model also predicts the conditions under which the fire will spread to an adjacent HGV. The outputs from this model may be used as input for CFD or other models in order that more realistic simulations of fires in tunnels may be made.

The model has been named "CERBERUS" after the three headed dog that guarded the entrance to the underworld in ancient Greek mythology. In this instance, CERBERUS is an acronym for Computer Estimate of the Rate of Blaze Enlargement and Risk of Underground Spread. The model, like the mythical dog, is three headed – it combines elements of three separate research projects carried out at Heriot-Watt University. The results from each of these three projects will be briefly discussed here.

2. DESCRIPTION OF THE COMPONENT PARTS OF CERBERUS

2.1. Variation of HRR with ventilation velocity

It is well known that gently blowing on a fire will tend to fan the flames. It is also well known that one can blow some fires out. Blowing air on a fire has two conflicting influences: more oxygen is available to the fire so it might burn faster (that is, its heat release rate will increase), but the air may also take heat away from the fire source, cooling it and possibly making it burn slower (that is, its heat release rate will decrease). Under certain conditions the former influence will dominate, under different conditions the latter influence might dominate.

A research project was carried out to investigate the influence of longitudinal ventilation on fire size (HRR) for fires in tunnels. The project investigated five different cases: fires involving HGVs, passenger cars and three different sizes of pool fire. The study was probabilistic in nature, producing a probability distribution of fire size for each of the cases at four different longitudinal ventilation velocities (2, 4, 6 & 10 m s^{-1}). The fire size is defined in terms of the coefficient k, defined by:

$$HRR_{vent} = k\, HRR_{nat} \quad [1]$$

where HRR_{vent} is the heat release rate of a fire in a tunnel with longitudinal ventilation of a specified airflow velocity and HRR_{nat} is the heat release rate of a similar fire in a similar tunnel subject to only natural ventilation. In this way particular uncertainties relating to the exact nature of the burning object (HGV cargo, pool composition, etc.) can be avoided. If a car would burn at 2 MW in a naturally ventilated tunnel and *k* has a value of about 3 under certain ventilation conditions, then we would expect such a car to burn at 6 MW. However, a different car might burn at 1.3 MW in a naturally ventilated tunnel, this car could be expected to burn at about 4 MW under the same ventilation conditions, and so on.

The results from the study indicate that the HRR of a HGV will be greatly enhanced by longitudinal ventilation; there is a high probability that a HGV fire will have a HRR about five times greater with a forced ventilation velocity of 4 $m\ s^{-1}$ than with natural ventilation. Similarly there is a high probability that a HGV fire will have a HRR about ten times greater with a forced ventilation velocity of 10 $m\ s^{-1}$ than with natural ventilation[3,4].

All the results from the HGV case of this project are included as part of the CERBERUS model.

This study also predicted that forced ventilation will have an enflaming effect on small and medium pool fires at low ventilation rates, but that higher ventilation velocities will tend to reduce the HRR of the fire. On the other hand, for large pool fires, forced ventilation appears to have an enflaming effect at all ventilation rates[5,6].

The study did not show significant variation of the HRR of car fires with forced ventilation.

These results are intended to be included in future versions of CERBERUS as it is expanded to include different types of fire load.

2.2. Influence of tunnel geometry on HRR

Occasionally naturally ventilated tunnel fire experiments have been observed to have higher or lower heat release rates than expected. As these effects are not due to the enflaming or cooling properties of forced ventilation, they must be due to the geometry of the tunnel itself. Where the HRR was lower than expected this has usually been attributed to oxygen depletion due to the confining nature of the tunnel, but in those cases where the HRR was higher than expected the possible reasons for this are rarely commented on.

A research project was carried out to investigate the influence of geometry in enhancing HRR of fires in tunnels. As with the ventilation project, a coefficient ? was defined such that:

$HRR_{InTunnel}$ = ? $HRR_{OpenAir}$ [2]

where $HRR_{InTunnel}$ is the heat release rate of a fire in a tunnel and $HRR_{OpenAir}$ is the HRR of a similar fire in the open air. From a study of experimental fire data from tunnel fires and similar fires in the open air it was observed that ? can be as much as 4 under certain circumstances; that means that some tunnels can enhance the HRR of a vehicle fire by as much as four times[7].

It was found that there appears to be a simple relationship between ? and W_F/W_T (where W_F is the width of the fire object and W_T is the width of the tunnel). This relationship has been determined to be:

$$? = 24\left(\frac{W_F}{W_T}\right)^3 + 1 \; [3]$$

This relationship appears to hold for all tunnels with a rectangular aspect where oxygen depletion is not a significant factor[8]. For tunnels with concave ceilings the HRR is further enhanced by up to 10%. This information has been included in the CERBERUS model to adjust the HRR of the vehicle fire according to the size of the tunnel.

2.3. Non-linear model of fire spread

As well as understanding the factors that influence fire size in tunnels, it is also vital to consider the factors that influence fire spread from one vehicle to another. To this end a model has already been developed which predicts the critical heat release rate necessary to bring about fire spread from the fire source to another object some distance downwind of it, for a given longitudinal ventilation rate. This model, "FIRE-SPRINT A3" (an acronym for Fire Spread In Tunnels, model A, version 3), uses non-linear mathematics and the concepts of bifurcation theory. The model identifies the conditions leading to instability in the system and associates these with the conditions necessary to cause the fire to spread from one object to another. At the point of instability the system "jumps" from a lower energy state to a higher one. The lower energy state is associated with the case of a fire involving only one object out of two and the higher one is associated with the case of a fire involving two objects (vehicles, etc.). Currently, the model does not include flame impingement on the second object.

The model is described in detail elsewhere[9,10] (reference 10 describes FIRE-SPRINT A2) so an in depth description will not be presented here.

When the case of the Channel Tunnel is modelled it is shown that the critical HRR, at which fire will jump from a HGV fire to another HGV (positioned 6.5m away), is in the range 32-39 MW at 2 m s^{-1} and in the range 54-60 MW at 3 m s^{-1} (the ranges are due to uncertainties in the model inputs as discussed in reference 9). The model predicts that there would be no fire spread between these objects at ventilation velocities above 7 m s^{-1}.

The results from the FIRE-SPRINT A3 model have been included in the CERBERUS model.

3. THE COMBINED MODEL

By combining the results of these three projects into a single model the whole picture of fire size and spread in a tunnel, under specified ventilation and geometrical conditions, becomes clearer. Starting with the HRR characteristics for a HGV fire in the open air (see below) the model makes calculations to account for ventilation and tunnel size and produces a probability distribution for the peak HRR of a HGV fire in the ventilated tunnel. The model also predicts the critical HRR necessary for the fire to jump to an adjacent vehicle (a specified distance away). Finally, the model calculates the percentage probability of the peak HRR being above the critical HRR and presents all the data in an easy to understand graphical form. Typical outputs are presented and discussed below.

The model takes an open-air HGV fire as its starting point. To date, no HGV fire tests have been carried out in the open air so these data have had to be calculated by "working backwards" from the EUREKA HGV fire test in a tunnel. Applying the results of the ventilation study and the geometry study to the EUREKA HGV test a probability distribution for the HRR of a HGV in the open can be produced. This distribution is shown in figure 1.

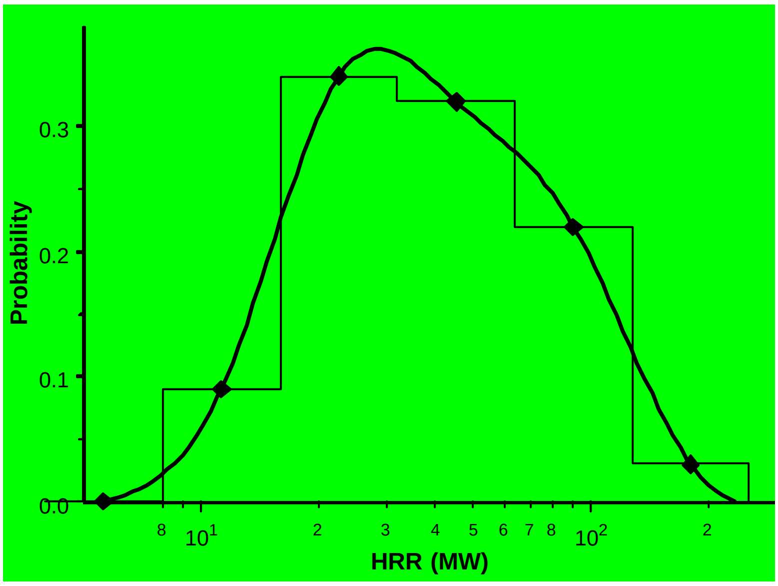

Figure 1 – Probability distribution for a HGV fire in the open air.

At its present stage of development, the ability to vary tunnel and vehicle size has not been implemented in CERBERUS. However, the model can be used to model fire size of a HGV fire in a typical single lane tunnel (dimensions based on the Channel Tunnel) and predict the probability of the fire jumping to an adjacent HGV. Figure 2 shows the scenario considered by the model.

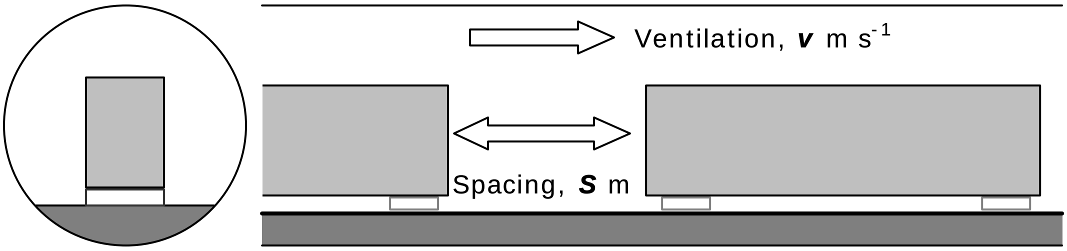

Figure 2 – The scenario modelled by CERBERUS a1

At this stage in development, the vehicles considered by the model are very simple. The model essentially considers "HGV objects" rather than true vehicles as the cab, fuel tank, wheels etc. are not taken into consideration. In the future the model will have a far more complex understanding of what a vehicle is.

The EUREKA HGV fire test, on which the "typical" HVG at the core of this model is based, was loaded with wooden framed furniture. This is a comparatively flammable cargo. In order to allow the CERBERUS user to model HGV fires with cargoes which have different properties from furniture, a cargo factor has been included in the model. This cargo factor adjusts the peak HRR of the HGV at the core of the model; a cargo factor of 10 corresponds to the HGV loaded with furniture, a cargo factor of 5 corresponds to a vehicle with half the HRR of a furniture HGV, and so on. The user can choose a cargo factor appropriate for the situation they want to consider.

4. PRELIMINARY RESULTS

To illustrate the use of the model some results are presented for a scenario involving a fire on a HGV loaded with furniture (i.e. cargo factor = 10) and its probability of spread to an adjacent HGV between 1 and 10 m away. Figure 3 shows the probability graphs for the heat release rate of the initial HGV fire subject to 2 and 4 m s^{-1} airflow velocities. The thick line at the right-hand side of each of the graphs represents the maximum HRR possible, given the amount of oxygen available; at 2ms^{-1} this is just under 250MW, at 4ms^{-1} it is just under 500MW♦.

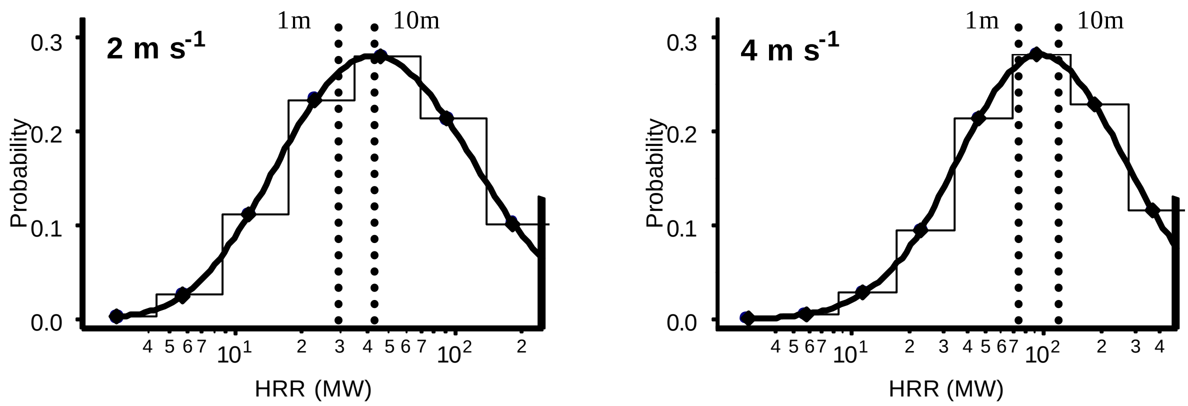

Figure 3 – Some sample results from the CERBERUS model♣.

The model calculates the probability in discrete ranges represented by the "step graphs" on the figure. Each range is twice the span of the previous one so the results are best plotted on a log scale as shown in the figure. The bold continuous line on each graph is taken to be the probability profile for calculating the probability of spread to the adjacent object.

It can be seen that the peak probabilities for the 2 and 4 m s^{-1} cases are at about 50 MW and just over 100 MW, respectively.

The critical HRR for fire spread to an adjacent HGV, either 1 m or 10 m away is indicated by the broken line on each of the graphs. For example, at 2 m s^{-1} the critical HRR is about 30 MW at 1 m separation and about 40 MW at 10 m separation. The model calculates the percentage probability of HRR above these values and so it is predicted that there is a 75% probability that the fire will spread across a 1 m gap at 2 m s^{-1} and a 66% probability that the fire will spread across a 10 m gap at 2 m s^{-1}. The results of the sample calculations are given in table 1.

♦ The probability distribution produced by the model frequently assigns non-zero probability to HRR values above the maximum HRR allowed by the ventilation. In the next refinement to the model, the calculations will be revised to compensate for this and adjust the "possible" probability values accordingly.

♣ These graphs have been drawn from the data produced by the model, they have not been generated by the model itself. The graphical output of CERBERUS is currently in development.

Velocity	Max. HRR	HRR percentile (MW)			Critical HRR (MW)			Probability of spread (%)		
		10th	50th	90th	1m	5m	10m	1m	5m	10m
2 m s^{-1}	247	18	56	169	27-33	31-37	36-43	75	72	66
4 m s^{-1}	495	39	119	338	75-90	83-101	97-115	66	61	58

Table 1 – The results from the example case

5. USE OF THE MODEL WITH CFD AND OTHER MODELS

CFD and other model users are urged to consider the results of this model before running any simulations of fires in tunnels. In practical terms, fire is a non-deterministic process and two seemingly identical fires may behave differently under ostensibly identical conditions. The probabilistic results of this study show the spread of possible fire behaviour under given conditions. When carrying out CFD or other simulations of tunnel fires, the operators are encouraged to run at least three simulations for each scenario they are modelling, basing their HRR inputs on, for example, the 10th, 50th and 90th percentiles from the probability distributions produced by CERBERUS. In this way their simulations will demonstrate a span of possible fire scenarios, not merely the average one.

6. FUTURE DIRECTIONS

The preliminary version of CERBERUS will be available to the public as a Java applet on our web pages shortly after the end of the current project (due to end in July). See ***www.civ.hw.ac.uk/research/fire*** for details. The development of CERBERUS will continue over the next few years and it is hoped that the model will eventually be able to model fire size and spread along queues of a variety of vehicles and fuel pools in tunnels of a variety of shapes and sizes. It is also intended to develop a version of CERBERUS which is designed to predict the fire size and spread of fire on trains in tunnels. In the short term it is intended to develop a sub-model of fire spread by flame impingement.

7. ACKNOWLEDGEMENTS

This project is funded by the Engineering & Physical Sciences Research Council under grant GR/R46502.

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AN ANALYSIS OF THERMAL ENVIRONMENT FOR ROAD TUNNEL IN THE INCIDENCE OF FIRE

Yoshikazu Ota, Ota Engineering
Kenji Horiuchi, Chiyoda Engineering Consultants

ABSTRACT

In recent years road tunnel fires have erupted in many locations around the world, which calls for the necessity to adopt more fire-effective and economical tunnel construction practices, having systematically analyzed the entire system of the tunnel. In this study, for probing into the basic characteristics pertaining on the thermal environments to tunnel structures, it is aimed at developing some fundamental literature on fire proofing measures of tunnels by setting up standard conditions and then focusing mainly thermal environmental analysis of flow field and concrete surface by numerical simulations, thereby clarifying the thermal distribution of each type of tunnel structure.

In this report, we discussed about relationship between thermal conditions and heat release rate of 30MW, 50MW, 100MW with time progress for two different cross section with rectangular and circular. As a result of this study, thermal environment in the tunnel space to be more cleared. It was clarified that, assuming the same fire scale, circular tunnels are advantageous (in terms of thermal environment) compared to rectangular tunnels.

In addition, airflow rate for preventing of the back layer of smoke flow also was clarified.

Key words: (Road Tunnel, Tunnel Cross Section Shape, Heat Release Rate, Air Temperature, Concrete Surface Temperature)

1 INTRODUCTION

In recent years road tunnel fires have erupted in many locations around the world, which calls for the necessity to adopt more fire-effective and economical tunnel construction practices, having systematically analyzed the entire system of the tunnel. In this study, for probing into the basic characteristics pertaining to the thermal environments to tunnel structures, it is aimed at developing some fundamental literature on fire proofing measures of tunnels by setting up standard conditions and then focusing mainly thermal environmental analysis of flow field and concrete surface by numerical simulations, thereby clarifying the thermal distribution of each type of tunnel structure. It was clarified that, assuming the same fire scale, circular tunnels are advantageous (in terms of thermal environment) compared to rectangular tunnels.

In this study, for probing into the basic characteristics pertaining to the thermal effects on tunnel structures, it is aimed at developing to the mitigation of fire protection systems for concrete structure, ventilation systems and other safe systems which will be exposed in the thermal environment.

The thermal environmental analysis is implemented by Computational Fluid Dynamics (CFD). The results of CFD, always we compared with suitable references to thermal environment.

2 BASIC CONDITIONS FOR FLUID DYNAMICS SIMULATION

2.1. Heat release rate for calculation

Heat output in the incidence of fire depends on the scale of fire. Here we assume a heat output of 30 MW due to burning of a Heavy Goods Vehicle (HGV), and the maximum

temperature inside the tunnel to reach 1000 Celsius (PIARC Report 1999).[1)]
Figure1 presents most probable development of total released energy and heat release rate for HGV introduced from EUREKA Report[2)], in the case of HGV fire, the maximum heat release rate exceeded 100 MW with the time duration 10 - 20 minutes. This heat release rate seems to be maximum value for HGV fire without dangerous goods transportation.

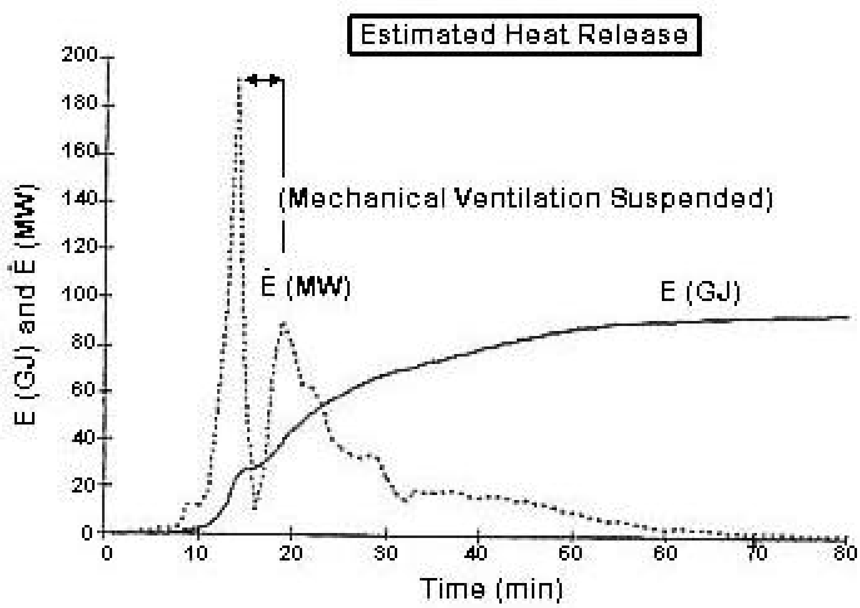


Figure 1 Most probable development of total released energy and heat release rate for HGV[2)]

Based on these 30MW to 100MW of HGV heat release rate, from PIARC and EUREKA REPORT, and also 50MW fire could be assumed in real situation for fire of HGV.
In this report, we discussed about relationship between thermal conditions and heat release rate of 30MW, 50MW, 100MW with time progress for two different cross section with rectangular and circular sections.
The thermal output curve is arranged as shown in Figure 2 below.

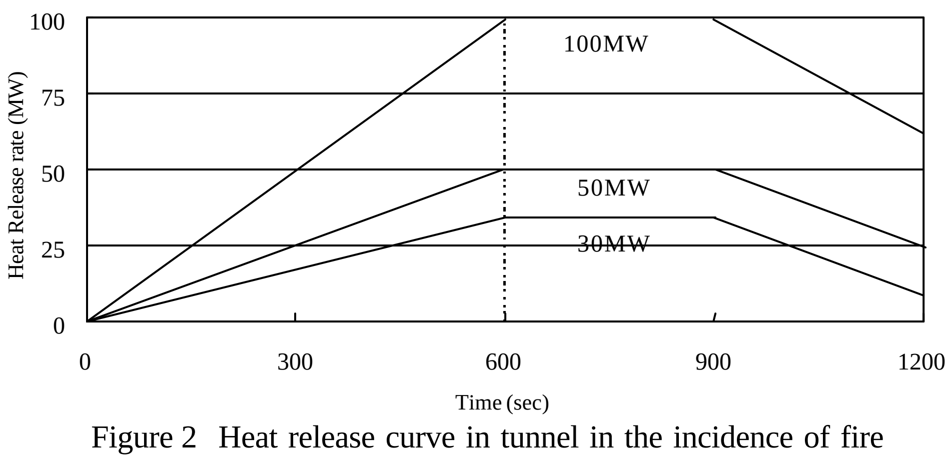


Figure 2 Heat release curve in tunnel in the incidence of fire

2.2. Conditions and location of heat output for tunnels

For the heat output source, a heavy goods vehicle has been assumed, where it is set to that meshes in an area of vehicle width of 2.2m and length of 6m receive the effect of this heat output. Figure 3 shows the basic configuration of heat output source of vehicles in road tunnels.

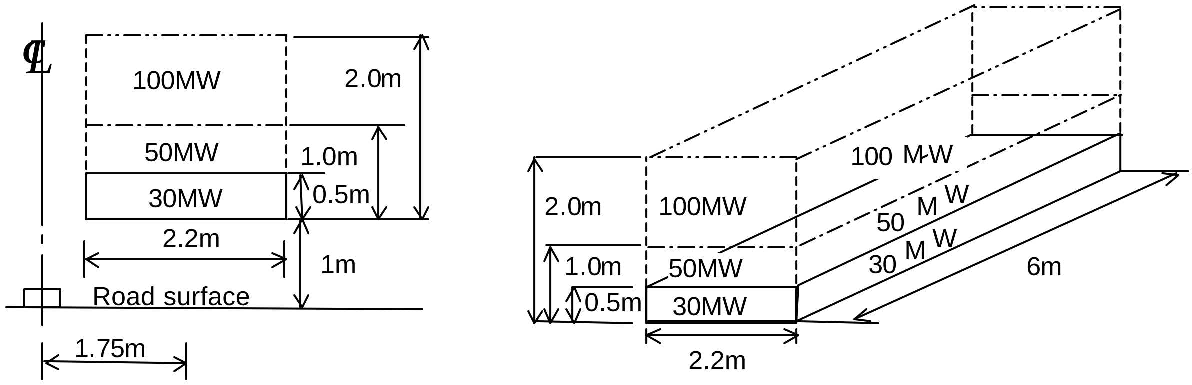
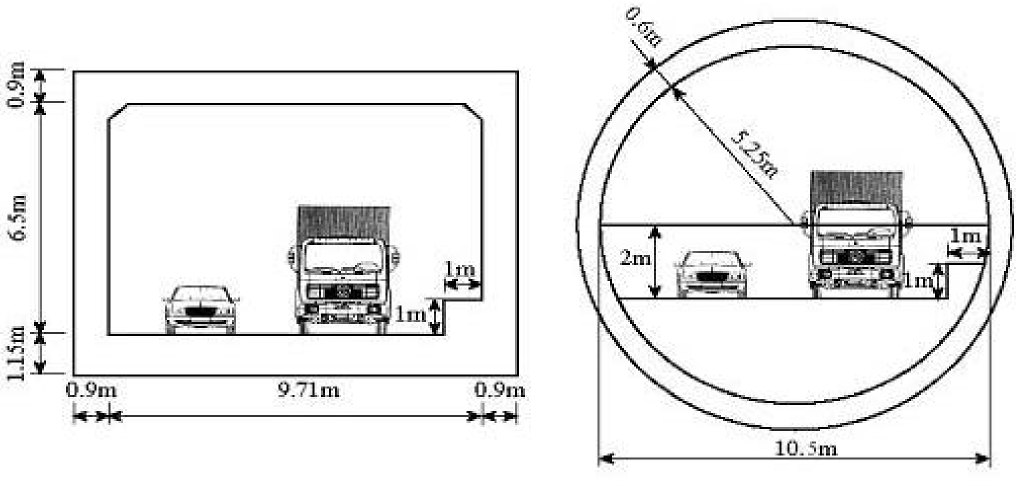


Figure 3 Basic configuration of heat output source of road tunnels

Basically, if the thermal capacity of burning goods is constant, heat release rate should be determined by the contact area with air (oxygen). Therefore for the purpose of simplification for comparing with each heat release rate, the basic configuration of heat output source was fixed at increase of the height of burning goods. (Bigger heat output source mount on smaller output source.)

2.3. Standard Cross-section

From the topographical, geological conditions of the tunnels, and point of view from flow and thermal distribution field, rectangular and circular section have a different character, therefore, circular and rectangular cross-sections are employed in the present analysis. Figure 4 presents these standard cross-sections.
In road tunnels, kinematics gauge of both crosssections is similar for each direction. The number of lanes are generally assumed to be two, with uni-directional traffic. Therefore in actual roads, this becomes two tubes.



Rectangular section Circular section

Figure 4 Standard cross-section of road tunnels

2.4. Basic Equations of Fluid Dynamics

The basic equations of fluid dynamics (Continuity equation, Navier-Stokes equation and Enery equation) have been adopted for forecasting air flow and temperature through a numerical analysis. Further, the ?-e model has been used to make turbulent flow realistic here.

2.5. Heat Transmission to Structure

Here these computations are assumed to be a problem of heat conductivity between fluid and solid portions. Solid portion is assumed to be of equal sides, that heat transfer within the solid is governed by the following equation:

$$\frac{\partial(re)}{\partial t} = \frac{\partial}{\partial x_i}\left(k\frac{\partial T}{\partial x_i}\right)$$

?	:	Density	T	:	Temperature
e	:	Internal energy	k	:	Thermal conductivity coefficient
t	:	Elapse time	x_i	:	Cartesian coordinate

Further, heat transfer between fluid and solid portions, it assumed that continuity in this process is a key to the solution.
The effects of heat radiation to the thermal environments in the tunnel structure was not take into account to the CFD simulation, due to the simplify and shorten of calculation time.
The effects of heat radiation are acting to the increment of the air and structural temperature.
Therefore, for the evaluation and discussion in the actual conditions, the appropriate margins for safety design should be take into account form this predicted results of thermal environments.

2.6. Various Computational Conditions

For computations in this respect, the following coefficients pertaining to air inside the tunnel and concrete surface of tunnel have been used as in Table 1:

Table 1 Tunnel condition and coefficients of computational model

Item		Confirmed value
Tunnel length		Tunnel length 450m within fire source
Air	Density	28.96 kg/m^3 (mol weight)
	Molecular viscosity	1.81 x 10^{-5} kg/m·s
	Specific Heat	1006 J/kg·K
	Conductivity	0.02637 W/m·K
Concrete	Density	2300 kg/m^3
	Specific heat	840 J/kg·K
	Conductivity	1.6 W/m·K
Heat transfer coefficient		automatically set value by ventilation condition
Heat release rate		30MW

2.7. Mesh Condition for Computations for Tunnels

Considering total number of meshes for computations and computational difficulty, concerning the cross-section, 320-360 meshes for fluid portion and 360 - 430 meshes for solid portion have been adopted. Further, 100-140 cross-sections at 1 - 5m intervals have been selected in the longitudinal direction of road. Thus, the total number of meshes amounted to 80,000 - 100,000.

2.8. Mesh Condition and Dispersion

In this analysis, modeling is achieved through a virtual mesh configuration, and adopting a finite volume method, the governing differential equation of preservation of mass, movement, and energy of fluid and solid bodies is used to determine the dispersion.

2.9. Ventilation Conditions

If we assume a fire in a tunnel due to a burning vehicle that produces a heat output of 30 MW, from existing literature [1), 2)] we can judge that a wind velocity of 2.5 m/s may be appropriate to control smoke, that we set the wind velocity in tunnel upstream of fire source to be 2.5 m/s. In an actual fire, there are vehicles in the upstream of fire source causing aerodynamic resistance and turbulence flow. However, this problem is one that should be tackled as a ventilation system issue, therefore, will not be considered here. This argument thus leads to setting a resulting wind velocity of 2.5 m/s.
In the case of 50MW, 100MW fire, critical wind velocity for prevention for smoke of back layering to be found in the process of calculation, then the longitudinal wind condition to be fixed.
On the point of view of egress environment, the inhalation of fume and smoke are one of the major factors of the serious damage to the human body.
If in the case of back layer spread to entire section of tunnel space at upstream side from fire source, the air flow velocity should be increased. However, in the case of the depth of back layer from ceiling to downwards to carriage way is still shallow at the 2.5m/s wind velocity, in other words, the clearance of visibility space still sufficient for evacuation, the ventilated air velocity did not revise in calculation.

3 DETERIORATION OF STRENGTH IN CONCRETE

It is a well known fact that the strength of concrete will be reducted in the case of temperature increased at certain level.
Generally, if in case of concrete temperature increase up to 200°C, the basic performance of concrete assumed at 100%. However, Dr. E. Richter mentioned fallowing issues to concrete performance under the thermal condition, [3)] "as lasting plastic deformations in the reinforcement are avoided through temperatures 300°C, it is assured that only a short period is required to repair the tunnel after the fire."
Based on these opinion, in the case of predicted results will be exceed 300°C. The appropriate fire protection mitigations should be adopted to the structure.

4 COMPUTATIONAL RESULTS AND DISCUSSION

4.1. Circular Cross Section

Figure 5 presents air temperature distribution in the case of 100MW fire as a example. The back layering near the ceiling part has been occurred. However, the thermal environment for evacuation is still ensured to the equivalent height of tunnel passengers under the 2.5m/s of ventilated air velocity.

The peak air temperature at closest point of concrete surface exceeds easily by 1500°C?

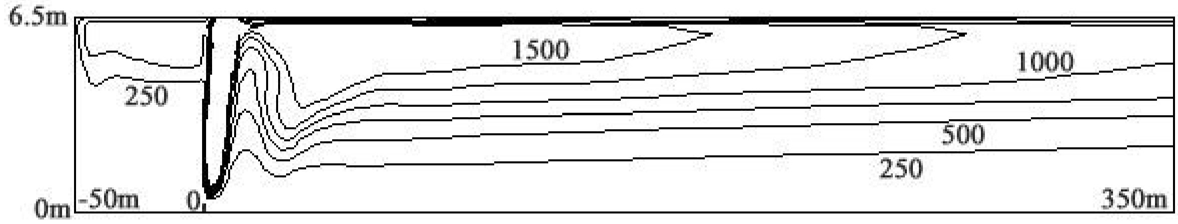


Figure 5 Example of air temperature distribution of circular cross section in a traffic space (Central section of fire source, HRR=100MW, elapse time : 900sec)

Figure 6 presents the temperature distribution in the concrete tunnel lining in the case of 30MW, 50MW and 100MW fire. If ventilated wind velocity to be created 2.5m/s for these heat release rate, then in circular tunnel cross-sections the area where temperature exceeds 200°C is small, and concrete structure is not susceptible to great damage.
In the case of 50MW fire within circular section, the temperature distribution in the concrete surface of ceiling part at above of fire source and side wall exceed 300°C. It seems to be not serious damage to concrete linings, such as collapsed structures, leakage of waters, etc.
In the case of 100MW fire within the circular cross section, some parts of ceiling above fire source will be reached to 670°C. Under this thermal condition, it becomes very serious collapse will occur in the concrete lining. If in the case of 100MW fire to be adopted to design criteria, it may be necessary to mitigation measures for fire protection systems for concrete structure.

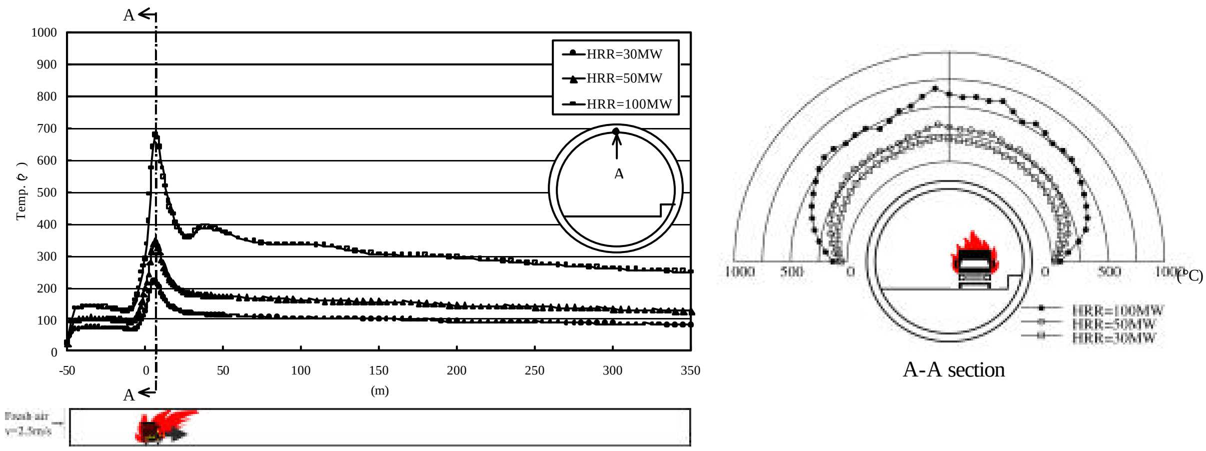


Figure 6 Temperature distribution in the concrete tunnel lining in the case of 30MW, 50MW, 100MW fire with circular cross-section

4.2. Rectangular Cross-section

Figure 7 presents air temperature distribution in the case of 100MW fire, the depth of back layering near the ceiling part is deeper than circular section within the air velocity 2.5m/s. However, minimum height is still ensured for the evacuation at the upstream side from fire point.
The peak air temperature at closest point of concrete surface exceed easily by 1500°C.

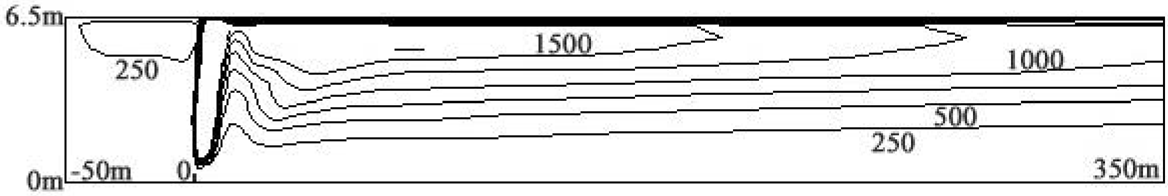


Figure 7 Example of air temperature distribution in a traffic space of rectangular cross section (Central section of fire source, HRR=100MW, elapse time : 900sec)

Regarding to the comparison with Figure 5and Figure 7. The temperature distribution at cut section of circular section is higher than rectangular tunnel. However, the temperature variation to lateral direction in circular section is bigger than rectangular section. The thermal distribution to lateral direction in rectangular section is more uniformly than circular section. On the other hand, decrement of thermal distribution to lateral direction in the circular section is bigger than rectangular section.

Figures 8 presents the distribution of concrete surface temperature in the case of 30MW – 100MW fire from CFD simulation results. In the case of 30MW fire, it may be judged that approximately an area of 200m^2 exceeds the permissible temperature of concrete. In the case of rectangular cross-sectional tunnels, the area that exceeds 200°C is much larger than that of circular section counterparts.

In the case of 50MW fire within the rectangular section, this case will be more serious thermal condition than circular cross section.

In the case of 100MW fire within rectangular cross section, the maximum temperature at concrete surface of entire part will exceed 700°C. It means tunnel structure will be collapsed, this phenomena is more than serious than circular section

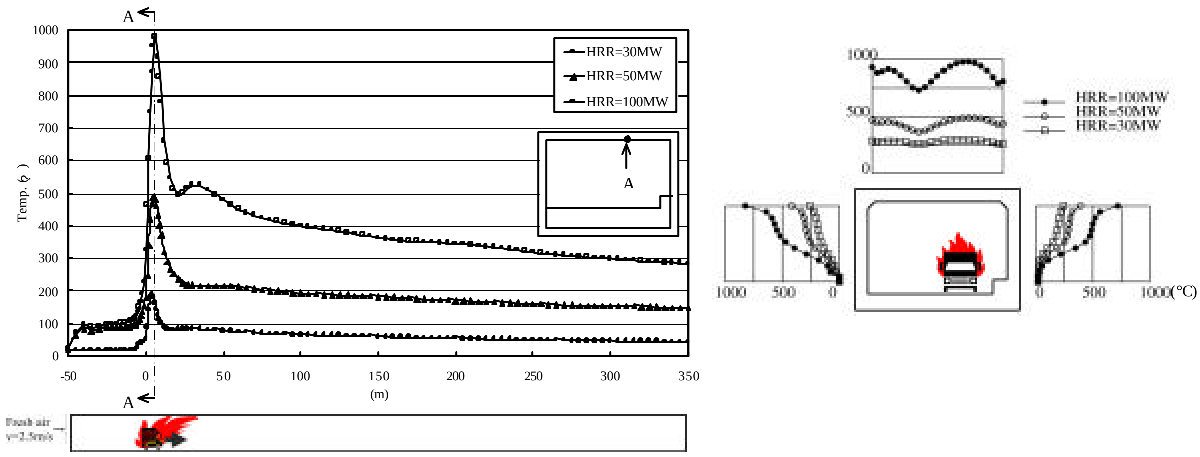


Figure 8 Temperature distribution in the concrete tunnel lining in the case of 30MW, 50MW, 100MW fire within rectangular cross section

5 Conclusions

Present day situation reveals that all over the world many experts have engaged in researches, analyses, and surveys for deepening the understanding of various phenomena governing traffic tunnel fires occurring in several cities around the world. Still at a fundamental stage of this study, based on the initial conditions of fire, in this article it has been attempted to clarify the relationship among cross-sectional shape of tunnel and reduction of strength in concrete due to heat of fire.

In the case of 100MW fire, the maximum air temperature at closest part of ceiling will be exceeded 1500°C within circular cross section. In the case of rectangular cross section, the maximum temperature is higher than circular section due to the differncy of shape of cross section, mass of air volume and thermal air flow field.

In the case of 30MW fire, surface temperatures at concrete ceilings of circular and rectangular tunnel sections were found at 230°C and 315°C respectively. This phenomenon is assumed to be caused due to the lateral air flows in the circular tunnel that function largely. In other words, temperature increases in circular sections even close to the road surface, however, the maximum temperature at ceiling area is much lower than that of rectangular tunnels.

In the case of road tunnels, when circular and rectangular tunnel cross-sections are compared against each other, the area that exceeds 200°C of rectangular section is wider than the case of circular section tunnel. This indicates that even though both sections are subject to same scale of fire, the degree of damage in the rectangular cross-section tunnel is much larger.

In the case of ventilation duct are located at ceiling within rectangular, circular or hose shoe cross section, the thermal environment will be appeared to similar conditions with rectangular cross section.

In the case of 50MW, 100MW fire, the circular cross section is still better thermal environment than rectangular cross section. However, both type of cross section will be occurred to very serious damage near the fire source, therefore, the fire protection mitigation must be necessary.

In spite of the similar heat release condition, the reasons for the differency of thermal environment between circular cross section and rectangular cross section are as follows.

(1) The distance from fire source to ceiling within rectangular cross section is shorter than circular section.
(2) The flow field of longitudinal air rate by mechanical ventilation and thermal flow field from fire source within circular cross section are bigger than rectangular cross section.

Due to these two major differences between rectangular and circular cross section, the value of maximum temperature at concrete surface are controlled.

However, due to the computational conditions, the effects of heat radiation from fire source are not taking into account to this calculation. Therefore in the actual situation, the temperature distribution in the concrete members will be slightly bigger than these predicted results.

In the case of mitigation design for fire protection systems, it is better to leave a margin for the heat radiation effects.

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AUTOMATIC TRACKING AND MONITORING INCLUDING IMMEDIATE FIRE DETECTION FOR DANGEROUS GOODS IN TUNNELS

Raimund Pammer
EFKON AG, Graz, Austria

ABSTRACT
Transport of dangerous goods across tunnels is at present a complicated paper based process. The proposed method involves smart card storage media, transponders to read the smart card from a roadside unit to track vehicles as they travel on their route, sensors to detect potential fires in vehicles within seconds and mobile control devices to verify proper function of the on-board equipment. The procedure is simplified and can be considered a safety improvement as the speed of transport increases, and, hence, the number of required vehicles on the road and their presence in dangerous locations is reduced.

1. INTRODUCTION

Catastrophes that have happened in tunnels in the recent past have directed attention of politics to address the problem, and this has lead to an open attitude of infrastructure operators to look for possibilities to re-engineer their current operating procedures.

The particular focus in this article is on transport of hazardous goods, though in principle of course all vehicles could be tracked using the same procedure without any hold-up in dangerous locations.

A study is currently going on in a major inner-city tunnel in Austria, to test the advantages of automatic tracking of hazardous goods inside tunnels.

The current procedure requires trucks with hazardous loads, to stop at tunnel entrances and wait for an accompanying vehicle. The type of good, container, planned route, the potential risks and the allowed treatments in case of accidents and fires must be registered manually with the authority.

It goes without saying that the process is time consuming and unpopular among freight forwarders. In addition, it keeps vehicles on the street for a long time and is therefore a safety risk component on its own.

2. INFORMATION AND COMMUNICATION SYSTEM

In the study, all information on hazardous freight is stored on a contact less smart card (contact cards suffer from slot-related problems in rugged environments) and the card is inserted in an On-Board Unit (the "OBU"), which transmits all data to the roadside reader when interrogated.

The OBU is glued to the inside of the windshield and requires line of sight to the roadside units. The communication is performed employing a novel technology of infrared light communication, which works under all weather conditions including direct sunlight, snow and fog. The OBU consumes very low standby power, which enables operation of the device on a single battery for years. This technology has been invented as one of the results of the Austrian Space Program (Austromir) and has been published elsewhere.

Fig. 1: On-Board Unit with and without Smart Card

The interrogation may take place at particular spots like tunnel entry, tunnel ventilation segment change, tunnel exit, change of legal district responsibility, entry into city, border crossing point, arrival at destination etc. Inside the tunnel and in other suitable locations, the vehicle is tracked by video cameras, and registration with checkpoints is matched with the pictures in the backend system.

Fig. 2: Checkpoint for Hazardous Goods Transport (Study)

In case of an emergency, it is exactly known in what section which material is present and what else is inside the tunnel at any given moment.

The smart card can be programmed using a desktop or a hand-held device, and activation takes place after the authority has issued a digital certificate. The authority still has to verify that sufficient resources are nearby in case of a disaster. The programmed smart card plus OBU can also be handed out at border checkpoints in case of foreign vehicles.

It is also possible to check the validity of the registration via a hand-held device from up to 100m away without stopping the vehicle.

Fig. 3: Mobile Checking from Roadside

The system is also understood as a complimentary solution to other programmes based on GPS/GSM, which would not work inside tunnels or where very exact location is required.

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3. FIRE AND SMOKE DETECTION

Additional safety can be achieved if fire and smoldering-fire reliably can be detected in an early state. The main problem is caused by the fact that cars are moving objects, even the burning one in some cases. To detect a fire, sensors available today's needs time in the scale of minutes. Within a research project, Efkon has developed a novel Fire and Smoke Detection System, which is able to detect hazardous situations within 5 to 10 seconds and vehicle-speeds up to 35 m/s. The sensors are connected in form of a corresponding sensor network, which is able to share all the information and correlate the data with the moving vehicle. This system is still a prototype.

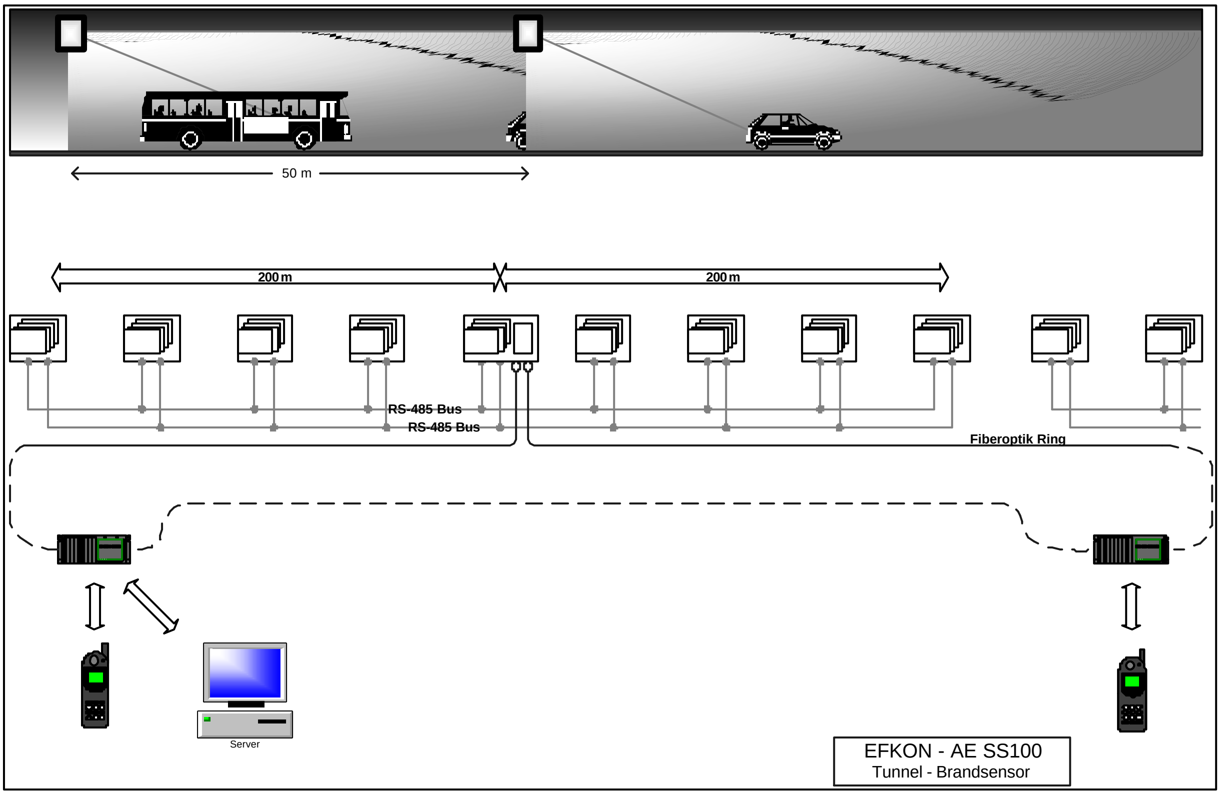


Fig. 4: Fire and Smoke Detection System

4. CONCLUSIONS

The study has shown that vehicles can reliably be detected and tracked in discrete locations using infrared light communication and that real-time information about hazardous goods in tunnels can be an efficient alternative to the currently used procedures. The expected improvement in safety would probably come for a low cost or even for no cost to the overall economy as vehicle numbers are reduced and personnel can be reduced while still achieving higher overall safety.

5. ACKNOWLEDGEMENT

We thankfully mention the readiness of ASFINAG (Austrian Highways Agency) to allow us to perform such testing in real life situation.

The study is a joint project of PKE Engineering (former Philips Projects Austria) and EFKON AG.

EARLY DETECTION SAVES LIFE : HI-TECH SYSTEMS FOR FIRE DETECTION

Hubert Schinkinger
WAGNER Alarm- und Sicherungssysteme GmbH, D
E-mail: info@wagner.de

ABSTRACT

Life is saved as soon as a traffic light changes to "red".

The objective is to achieve the earliest possible detection of a fire in a traffic tunnel in order to prevent further traffic access into the danger zone and to avoid vehicles from blocking rescue and escape routes.

The advantage of the optical detection principle of intelligent air sampling smoke detection systems is the speed at which reliable detection of a fire can be achieved, gaining decisive seconds for the implementation of counter measures which will result in saving life. Even before a driver or passenger has realized that a fire danger exists, reliable detection and respective alarm procedures can take place. Most important of all, only a real fire scenario will result in an alarm! The proposed detection system is immune to the deceptive phenomena common to traffic tunnel environments.

Tests lasting several months have been carried out in the 10 kilometre long Plabutsch Tunnel, proving impressively the advantages of air sampling smoke detection:

The systems high reliability and detection integrity is based on the analysis of the particles seen by the detection system when plotted against typical fire pattern algorithms stored individually in each and every detection systems CPU.

Traffic lights in future will change to "red" at the earliest possible stage of fire development, allowing the fight against smoke and fire to be implemented without any delay.
With the solution presented here today, the Plabutsch Tunnel is exemplary, and can be regarded as being the safest traffic tunnel in Europe.

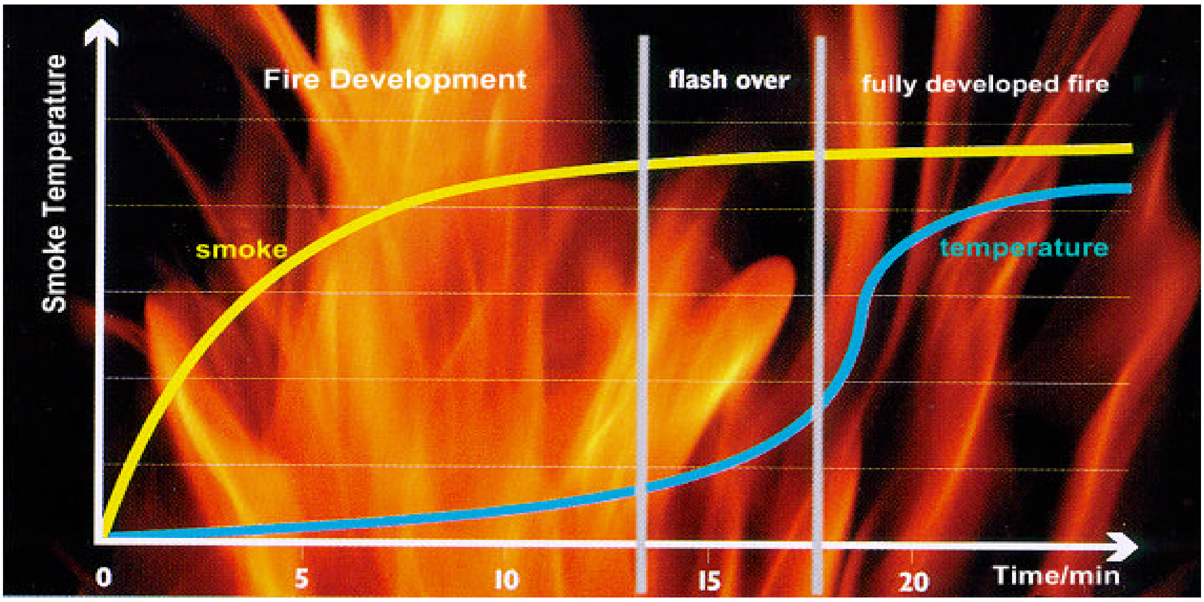
Key words: *Fire protection*
Smoke detection
Air sampling smoke detection system
Fire detection
Tunnel safety

1. Life is saved as soon as a traffic light changes to "red".

The primary objective in the event of a tunnel fire is to allow all persons fast and safe rescue from the tunnel, and escape from the deadly fumes that present the most immediate threat to life. Achieving this will make the task of fire fighters and rescue workers so much easier. The less people and vehicles in the tunnel, the better!
That is why the earliest possible detection of a fire, and the immediate restriction of further traffic flow into the tunnel is so important. In addition, it is important to prevent vehicles that have already entered the tunnel from continuing their journey deeper into the tunnel, and getting closer to the source of the fire. An intelligent traffic signalling system can be used to achieve this. The Fire Detection System assumes responsibility for the all important activation of the intelligent traffic signalling system, and provides the triggering impulse.

2. Conventional Detection Methodologies reach their limitations

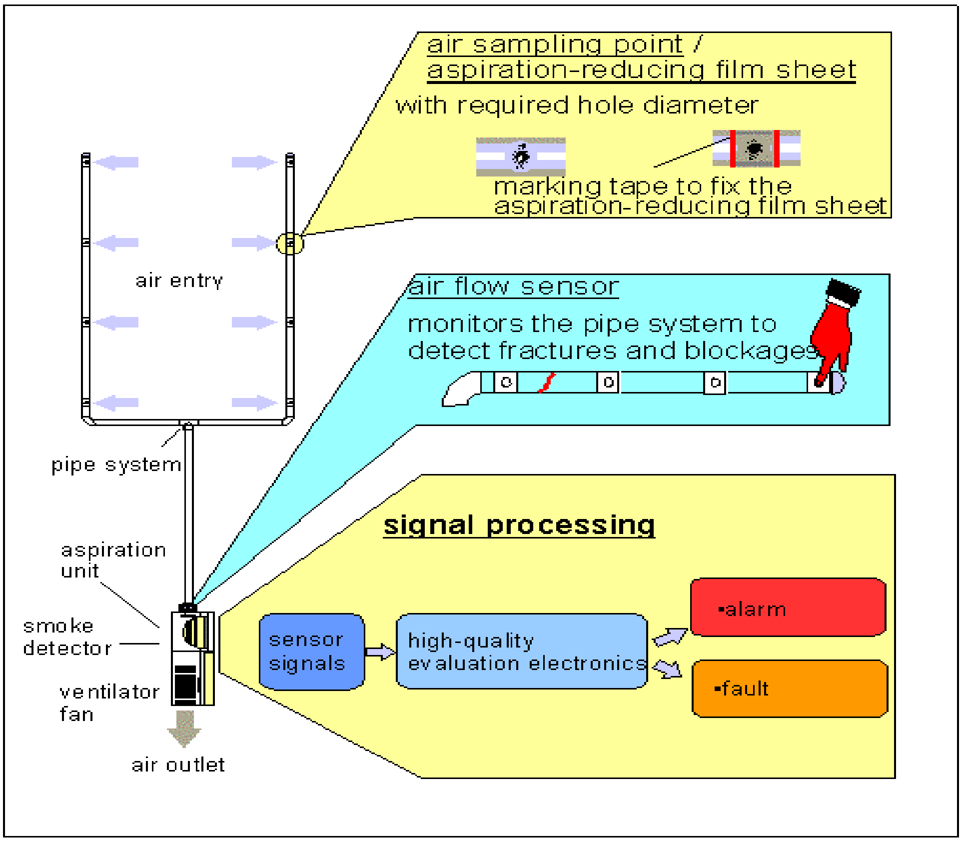
In order to achieve early detection of a fire, optical smoke detection devices are often chosen because visible smoke particles form the first detectable signs of a fire. Conventional type smoke detectors are stretched to the limits of their capabilities when confronted with the aggressive nature of the tunnel environment. Temperature fluctuations between –20°C and +35°C, humidity, rain, fog, and snow which is transported by the traffic into the tunnel, high dust concentrations caused by braking and tyre friction, must not impair or influence the reliable performance of the tunnels fire detection system. This is the reason for the common use of linear thermal detection systems in road tunnels to date. Such systems may well detect the fire at some stage, but the effective measurement of a fire in terms of heat development only becomes possible at a much later stage in comparison with that of the smoke particle production. (Picture 1). Valuable time, needed for safe rescue is lost.
To prevent such a loss of time in the future, a very special and innovative aspirating smoke detection system has been developed especially to match the extreme and harsh environmental conditions prevalent in a traffic tunnel.



Picture 1: Fire Development Chart

3. Air Sampling Smoke Detection System – Function principle

The function of an air sampling smoke detection (ASD) system is easily explained. The system comprises of an air sampling pipe network and a detection unit that incorporates air flow monitoring circuitry, a ventilator fan and an optical smoke detection sensor (Picture 2).

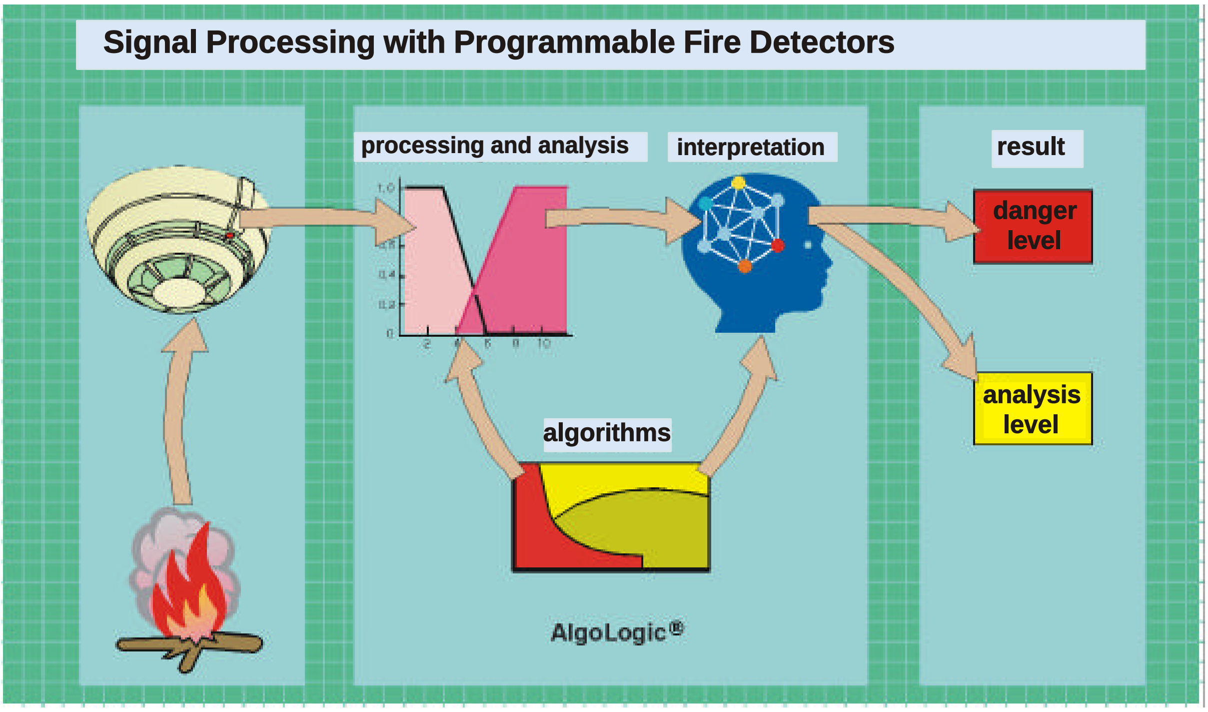


Picture 2: Function principle of an ASD - System

With the aid of the ventilator fan, air samples are continually taken from the tunnel section in question and passed through specially designed holes sited at equal distances along the length of the of the air sampling pipe network, back to the detection unit. Different hole diameters ensure a constant and equal distribution of air samples taken throughout the pipe network and tunnel section. Specially pre fabricated air flow reducing clips allow each hole to be sized exactly, which is vital for the correct function and integrity of the air flow monitoring system. Blockage or rupture of the pipe network can be detected and reported, helping to maintain the reliability of the detection system at all times.
Air samples once inside the detection unit, are analysed for smoke particle content. Response characteristics can be adjusted to meet the requirements of ambient conditions. A fire can be detected at its incipient stage due to the ability of the detection unit to recognise even the smallest concentration of smoke particles, irrespective of their size or colour.
For a number of years now, the wide and growing variety of successful ASD - system smoke detection applications such as recycling plants, diesel locomotives, industrial production facilities, and horse stables to name only a few, have lent proof of the reliability and impressive superiority of intelligent ASD systems in the field of fire detection.

4. Air Sampling Smoke Detection System for Traffic Tunnels

The ASD system developed especially for tunnels incorporates a 3 – stage filter system which is designed to remove the airborn dust particles that contaminate the tunnel atmosphere, before the air is passed from the air sampling pipe network into the detection unit. Smoke particles, however, are allowed to pass through the filter without obstruction.
Vehicle exhaust emissions that would normally lead to unwanted false alarms are effectively screened out by the intelligent evaluation based on algorithms.
Actual detection values measured within the detection unit are compared with a large number of complex, real fire development characteristics which are stored as algorithms within the detectors CPU. In this way, absolute detection stability and real alarm reliability is achieved. (Picture 3).

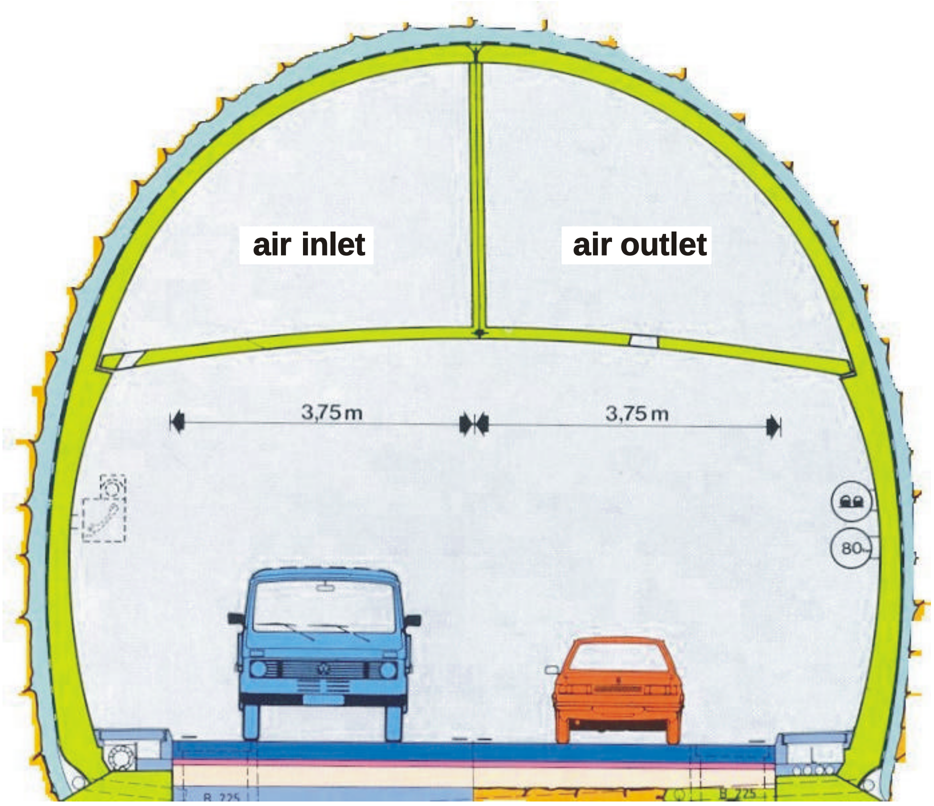


Picture 3: Principle of intelligent evaluation based on Algorithms

5. Test Installation in the Plabutsch Tunnel

An intensive and long term study of all aspects of tunnel fires, involving tunnel safety experts and fire engineers has culminated in the development of an air sampling smoke detection system, especially for this application.
As a testing ground for this development project, the Plabutsch tunnel, frequented daily by more than 20,000 vehicles, and renowned for being the busiest tunnel in Austria, was selected for installation.
The Plabutsch tunnel was built to relieve the traffic density around the city of Graz in Austria between 1983 and 1987. Stretching for 9.755 meters, the tunnel is Austrias second longest road traffic tunnel in use today.
The Plabutsch tunnel (Picture 4) is ventilated by a 100% full length air flow duct which is divided into five sections of equal length.

The fresh air duct above the tunnel ceiling supplies the tunnel with fresh air through diffusors of 20 x 50 cm in size, mounted in the tunnel ceiling at intervals of 6 meters.



Picture 4: Cross section of the Plabutsch tunnel

Exhaust gas extraction vents of 50 x 100 cm in size, are sited at intervals of 12 meters along the axis of the air return duct. In the event of a fire, heat resistant motors open the vents for each section of the tunnel allowing the total cross section of the duct to facilitate forced extraction of the smoke and gases. The air sampling detection pipe network was mounted at the centre of the tunnel ceiling above the road along the tunnels axis. A total of 12 air sampling holes were introduced along the pipe network. The detection unit was installed in an adjacent technical room, permitting unimpeded access for maintenance purposes.

6. Fire tests in the Plabutsch Tunnel

After a three month test period without any system faults or false alarms, several different qualified fire tests were carried out in the tunnel together with the tunnel operator and the authority having jurisdiction over fire safety in road traffic tunnels. It only required 3 standard type PUR mats to cause the ASD system to register the first of three possible stages of fire alarm. Shortly after lighting 8 similar mats, the third and highest level of detection was achieved. A linear, thermal system installed in the tunnel showed no reaction to the tests at all.

7. Conclusion

The conclusion of the 3 month long tests in the 10km Plabutsch tunnel have made the advantages of using air sampling smoke detection systems in the tunnel very clear. Intelligent ASD systems with their Algorithm based analysis and processing detect fire fast and reliably. The specially developed tunnel ASD system from Wagner, opens a new chapter in the history of tunnel fire safety for all its users.
Traffic signals can now go to „red“ in time, the fight against the fire and the deadly fumes exhumed by it can begin much earlier.
These will remain the decisive factors in saving life.

FIRE FIGHTING SYSTEM FOR TUNNELS – A REPORT ABOUT THE PRACTICAL EXPERIENCE WITH OUR WATER MIST TUNNEL SYSTEM

Georg Reichsthaler
AQUASYS Technik GmbH
Industriezeile 56, Postfach 100
A-4040 Linz, Austria

ABSTRACT

Aquasys Technik GmbH, from Linz, Austria, has developed and designed a water-mist system for efficient fire fighting in tunnels. The main target for this research and development project was to optimise the specific properties and advantages of water mist as a fire suppression agent, which we dready successfully utilised in other applications, to the very specific requirements of tunnels to significantly improve safety and property protection in case of a fire there.

The tunnel fires of Mont Blanc, Tauern and Gotthard obviously demonstrated the main problem of fighting a fire in a tunnel: the fire developed to a size where the extreme temperatures within the tunnel hindered the fire brigade from access to the scene.

From these experiences the objective of a water mist system in tunnels were derived together with a number of experts: Quick response to the outbreak of a fire by fighting it already in it´s emerging phase in order to prevent temperature from rising to a dangerous dimension to protect persons and tunnel structure and to limit the development of smoke by prohibiting the fire to spread. Additionally this helps the fire brigade to enter the tunnel to extinguish the source of the fire. The only way to comply with this objective is to install the water mist system directly within the tunnel.

Due to our philosophy of empirical evidence, we decided to demonstrate the specific properties of water mist which in no way are comparable with the properties of sprinklers, in full scale tests. For that reason Aquasys contracted the erection of a 200 m tunnel in the size of a two lane motorway. In this tunnel an intermediate ceiling, a smoke exhaust system and the Aquaysys water mist system were installed.

In the course of the year 2001 we performed a number of full scale fire tests with a fully loaded truck (HGV) mock-up in this test tunnel After having further optimised the water mist system due to the large experience gained from those optimisation the official full scale test programme was conducted by two notified bodies, the IBS (Institut für Brandschutztechnik und Sicherheitsforschung GmbH) Austria and the VdS GmbH (former: Verband der Schadenversicherer) Germany. The test programme comprised three tests at different longitudinal wind speeds (2 m/s, 5 m/s, 6,5 m/s) whith the water mist system being activated three minutes after detection by an approved detection system and one test where the water mist system was activated after the complete HGV was on full fire. Thewhole test programme was successfully passed!

Details will be given on the lay out and performance of the system at those test series.

Key words: water mist, tunnel fire, full scale tests, tunnel protection

1. WATER MIST IN TRAFFIC TUNNELS

1.1. Basics of Water Mist

Water mist as ejected from specific designed nozzles consists of tiny water droplets properly distributed at the scene of the fire. These fine dispersed water droplets provide an immense water surface in the area of the fire which results in an improved heat transmission from the fire to the water. As a consequence the water mist is evaporated with high efficiency due to the heat release of the fire. The two main effects of this optimised evaporation, which are responsible for the efficiency of fire suppression by use of water mist are: the expansion of the vapour on the one hand and the energy demand of the evaporation process on the other hand.

When evaporated water expands its volume by the factor 1.675, this leads to an oxygen depletion in the immediate area of the fire and subsequent suppression of the fire. Beside this physical fact water also needs energy input for the evaporation process. This energy demand can be covered by the thermal energy of the fire, which leads to a high efficient cooling of the environment around the fire. It is the simultaneous presence of both effects which causes the high efficiency of water mist for fire suppression.

1.2. Safety in Traffic tunnels

In times where traffic increases every year the potential danger to each passenger is rising significantly, especially in confined spaces as tunnels are. An accident in a tunnel leads to a stand still of traffic in the tunnel, which results to an accumulation of persons at the area of danger. If fire is involved at such an accident a life threatening situation for all passengers emerges.

The tunnel fires of Mont Blanc ,Tauern and Gotthard obviously demonstrated the main problem of fighting a fire in a tunnel: the fire developed to a size where the extreme temperatures within the tunnel hindered the fire brigade from access to the scene.

From these experiences the objective of a water mist system in tunnels were derived together with a number of experts: Quick response to the outbreak of a fire by fighting it already in it’s emerging phase in order to prevent temperature from rising to a dangerous dimension to protect persons and tunnel structure and to limit the development of smoke by prohibiting the fire to spread. Additionally this helps the fire brigade to enter the tunnel to extinguish the source of the fire

The only way to comply with this objective is to install the water mist system directly within the tunnel.

Such a water mist system can easily be activated by a proper tunnel fire detection as available on the market and provides following advantages:

As a consequence the impact to persons and to the tunnel construction due to a fire accident will be appreciably reduced and the break of operation of the tunnel due to subsequent damages of such accident will be minimised.

1.3. Configuration of the Water Mist System in the Tunnel

The Aquasys water mist system is installed inside the tunnel and consists of:

- pumping units at each portal,
- a main line through the total length of the tunnel,
- nozzle lines installed under the ceiling of the tunnel and a
- control unit, which also provides the interface to the detection system.

2. TEST PROGRAMME OF THE AQUASYS FIRE TEST SERIES

2.1. Test Arrangement

Due to our philosophy of empirical evidence, we decided to demonstrate the specific properties of water mist which in no way are comparable with the properties of sprinklers, in full scale tests. For that reason Aquasys contracted the erection of a two lane motor way tunnel, meaning approximately 10 m with, about 4,80 m height of the intermediate ceiling and 200 m long. Additional to the water mist system this tunnel is also equipped with a smoke exhaust system to simulate conditions as applicable in a real operational tunnel.

In this tunnel a full scale HGV mock-up was placed, entirely loaded with timber pallets and 12,5 % shredded plastics.

For monitoring the conditions in the tunnel during a full scale HGV fire an array of 120 temperature sensors distributed in the tunnel and a few of them in the exhaust ducts and inside the concrete. Additionally two different types of fire detection systems were installed to simulate the real time fire alarm.

Last but not least five mobile ventilation units were placed in the tunnel to provide wind speeds up to 8 m/s in the tunnel during the various tests.

2.2. Test Procedure

In the course of the year 2001 we performed a number of full scale fire tests with a fully loaded truck (HGV) mock-up in this test tunnel After having further optimised the water mist system due to the large experience gained from those optimisation the official full scale test programme was conducted by two notified bodies, the IBS (Institut für Brandschutztechnik und Sicherheitsforschung GmbH) Austria and the VdS GmbH (former: Verband der Schadenversicherer) Germany.

The tests started with the ignition of the mock-up by using a small pool fire within the load and the development of the fire until the detection system provided the fire alarm. After a delay (intervention time) of another three minutes the water mist system was activated and subsequently operated for 33 minutes, as it was assumed that within this time span the fire brigade of a real tunnel should be able to reach the scene.

The certification tests according to the above test procedure were conducted at different wind speeds of approximately 2 m/s, 5 m/s and 6,5 m/s.

Additional to above described test series, the notified testing institutes also required a full scale fire test with delaying the activation of the water mist system not before steady state conditions, which is the worst case with temperatures in the tunnel up to 800 °C.

2.3. Test results

The result of the full scale fire test programme in the tunnel was, that the Aquasys water mist system successfully passed all criteria as required by the notified testing institutes.

These criteria were:

- max. 250°C in a distance of 5 m from the burning HGV to prove that spread of the fire can be successfully prevented (actually the temperatures as measured at this distance were in the range of 50°C!!).
- max. 50°C in a distance of 20 m from the fire to prove that the scene can be accessed by the fire brigade to finally extinguish the fire.
- less than 100°C at 10 mm within the concrete structure of the ceiling to prevent the concrete from spalling (the actual temperature increase of this probe was about 4-5°C at the most).

3. WATER MIST IN RAIL TUNNELS

Beside the just presented empirical evidence from the test programme for Traffic Tunnel Application, also rail tunnels can be protected by a Water Mist System.

Back in 1996 a truck on a freight shuttle train in the 50km long Channel Tunnel between France and Great Britain caught fire. The fire lasted 7 hours and destroyed ten trucks, half of the shuttle train and damaged the channel tunnel in a way that the repair took six months and the resultant loss of income was about 300 Millions Euro.

As a consequence Eurotunnel undertook an extensive research programme to improve asset protection in the event of a fire in the tunnel. This included wind tunnel tests in France, and tests with real fires inside a purpose-built wind tunnel in Northern England. Those tests clearly showed the technical superiority of the water mist technology.

As a result Eurotunnel decided to equip its fleet of freight shuttle trains with an on–board–fire–fighting–system from Aquasys which is installed directly on the HGV-carrier- wagons for a quick and efficient response in case of a truck fire.

HOW WE ACT IN THE HELSINKI RESCUE DEPARTMENT IN THE CASE OF UNDERGROUND METRO FIRES

Marko Järvinen
Regional Rescue Chief
B.Sc. Fire Master
City of Helsinki Rescue Department

ABSTRACT

Helsinki, the capital of Finland has a metro transport system. It is all together 26 km long including tunnels about 10 km. The tunnel system is so called twin tube but has openings to next tunnel every 150 – 200 metres which makes smoke ventilation very complicate to operate during underground fire. Tunnels and metro stations are situated very deep underground. The system has been built mainly in the 80´s and 90´s so there is a lot of technical safety equipment to help City of Helsinki Rescue Department manage in large operations. Progressive computer-guided assistance for fire officer gives him a real time information about what is happening in the tunnel.

Although a lot of money and time has been invested to the safety of metro it is possible that the worst can happen. Also the human behaviour can either cause the accident or make the situation worse. That is why the Helsinki Rescue Department has to prepare to the accidents in metro.

Operationally speaking it is essential that all rescue forces are well trained and equipped with suitable tools. Leading many rescue units in a rapid accident effectively is a very challenging task for fire officers. They must be familiar with underground surroundings and the importance of smoke ventilation. Planning beforehand all standard operational procedures and testing those in reality are the key of success.

Keywords: Metro, underground fire, smoke ventilation, standard operational procedures, technical safety equipment

1. GENERAL INFORMATION ABOUT THE METRO OF HELSINKI

2. TECHNICAL SAFETY EQUIPMENT

2.1 Metro stations
2.2 Tunnels
2.3 Smoke ventilation
2.4 Communication systems
2.5 Water mist

3. STANDARD OPERATIONAL PROCEDURES IN THE CASE OF METRO FIRE

3.1 City of Helsinki Rescue Department
3.2 Smoke ventilation
3.3 Special rescue equipment
3.4 Emergency medical service

1. GENERAL INFORMATION ABOUT THE METRO OF HELSINKI

The Helsinki metro transport system is 26 km long. Tunnel sections are about 10 kilometres long build in hard rock and going quite deep, the deepest point is over 30 metres underground. Tunnels are so called twin tubes but the openings and exit ways between those tunnels are open every 150-200 metres so for example smoke can fill both tunnels easily. That is so because earlier we thought that it is better for passengers to have a short exit way to next tunnel in the case of emergency. Tunnels are quite wide. You can walk beside the metro car easily. In the narrowest point is 0,7 metres free space but generally over 1,5 metres.

The Helsinki metro system was mainly planned in the 70´s and built in the 80´s and 90´s. The traffic started 1982 so it is a quite young system. In the oldest parts of metro tunnels there were no official regulations about safety. All has been built after discussion between Communal Traffic Company and the Rescue Department. In the last ten years there has been a lot of improvements in the metro and its safety systems.

Metro trains are quite large. Nowadays the traffic company is using combination with four cars so the capacity is about 800 passengers. The maximum capacity with six cars is 1200 passengers. The metro trains are running with three minutes interval in rush hours but in the next August it will be changed to 2,5 minutes. Last year there were about 53 million passengers using the Helsinki metro.

There have been only few real fires in the Helsinki metro during the recent years. There are about 30 alarms yearly in the metro. Most of them caused by maintenance staff. Ambulances are visiting metro stations daily.

2. TECHNICAL SAFETY EQUIPMENTS

2.1 Metro stations

Every metro station has automatic fire alarm system connected to the Rescue Departments alarm centre. Smoke detectors or heat detectors are situated in platforms and all places where passengers can go. Also all technical rooms are equipped with automatic alarm system. Sprinkler system is in all exit ways in stations. Traffic control centre has cameras which allows visual detecting. All underground stations have guards with radios so they can do a lot in case of fire, too. They are trained by the Rescue Department.

2.2 Tunnels

In tunnels there are nowadays no fire detecting system but it is under construction and will be ready until July this year. The system will be based on new cable technology and will be connected to computer aided smoke ventilation system so that firemen can easily see from the computer monitor in every metro station what is the current wind speed and direction in the tunnel and where is the fire. That has been the most difficult thing to detect for the rescue personnel who is trying to use smoke ventilation right because of several tunnel openings going to the surface and air temperature difference specially in wintertime between the tunnel and open air.

2.3 Smoke ventilation

The smoke ventilation system is based on all information we can get mentioned before. After detecting the situation it is possible to use smoke fans situated in metro stations and in every shaft (at least one between two metro stations). It is also possible to use smoke doors to shut down the running tunnels. Every underground metro station is equipped with four smoke doors.

The purpose of smoke ventilation is on the other hand to save the passengers and on the other to improve possibilities to firemen to do their job.

2.4 Communication systems

The communication systems have always been the weakest point when emergency personnel has operated in underground circumstances if they don´t have special systems with them.

All underground tunnels and stations are equipped with so called leaky feeders giving rescue personnel two channels to their radios. The radio system is the same as metro trains and guards are using. Metro has given those radios to the Rescue Department so the only use for these radios is in metro not anywhere else.

Now they are building a new digital radio system to the metro. It is based on TETRA technology. The Helsinki Rescue Department starts using that system 1.4.2002. That system is going to be a new authority radio system to whole Finland during this year and few next years.

To be on the safe side there is also so a called field phone system and ordinary phones planned to use by firemen if there are some problems with the radio systems.

2.5 Water mist

In the tunnel there is situated 110 mm water pipe line with 6 bar pressure for the rescue personnel. It is insulated (non-flammable and coated with plate) and warmed by electricity because of our winter time. Hydrants are situated in every 100 metres.

3. STANDARD OPERATIONAL PROCEDURES IN THE CASE OF METRO FIRE

3.1 City of Helsinki Rescue Department

The Rescue Department has a decentralised unit system. It has facilities and bases in various districts of Helsinki. The operative section of Helsinki Rescue Department is responsible for daily fire, rescue and medical stand-by duties. Operational staff is about 400 men in addition there are also 200 volunteer firemen divided in 15 volunteer fire brigades. In Helsinki there is eight rescue stations. Each rescue station has two basic units and at least the capabilities required for all first-aid measures, i.e. a rescue unit capable of independent extinguishing and rescue duties and medical and damage control, and an ambulance unit for medical rescue duties.

If we have the information of fire or smoke in underground section of the metro we will alarm immediately so called second grade. That means:

2 fire officers
4 fire engines
2 heavy rescue tenders
1 tender with 10 000 litres water
1 heavy control unit
1 emergency medical services
1 medical supervisor
5 ambulances

Altogether that means about 50 men. When it is clear that it is a question of a big accident the system will automatically alarm more units on scene. All underground metro stations are situated very near to the rescue stations so the driving time to the nearest station is only 1-3 minutes.

Main forces goes to that metro station where the fire is but in the same time at least two units divides up to the next stations too (Figure 1). That is because we are afraid of the rapid smoke movement to the next metro stations.

STANDARD OPERATIONAL PROCEDURE

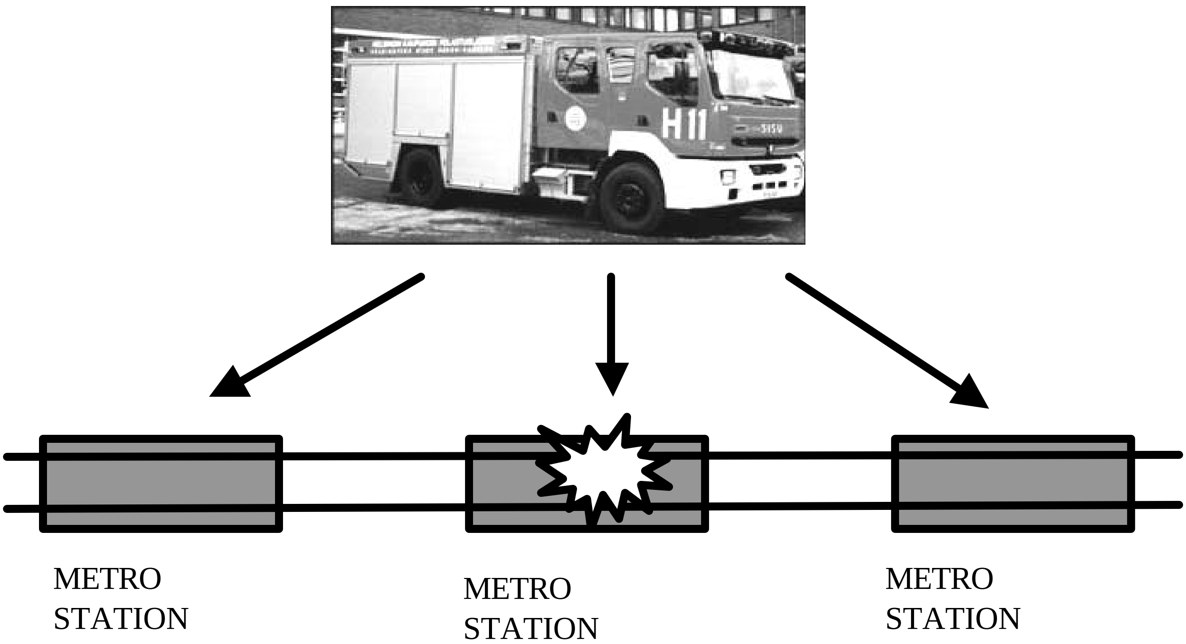


Figure 1

Having gathered further information the rescue leader perhaps have to make a new grouping of rescue forces depending on the real situation so that we have enough strength in the right place. In the same time he has to create capable leading organisation on the scene (Figure 2).That is very demanding task in the most urgent period of the rescue operation. In the same time he must order more units and men to scene (3. Grade, 4. Grade, 5.Grade) and be aware of the possible collapse of the tunnel if the fire is threatening and lasts too long.

STANDARD COMMAND SYSTEM IN
COMMAND AREA IN THE CASE OF METRO FIRE

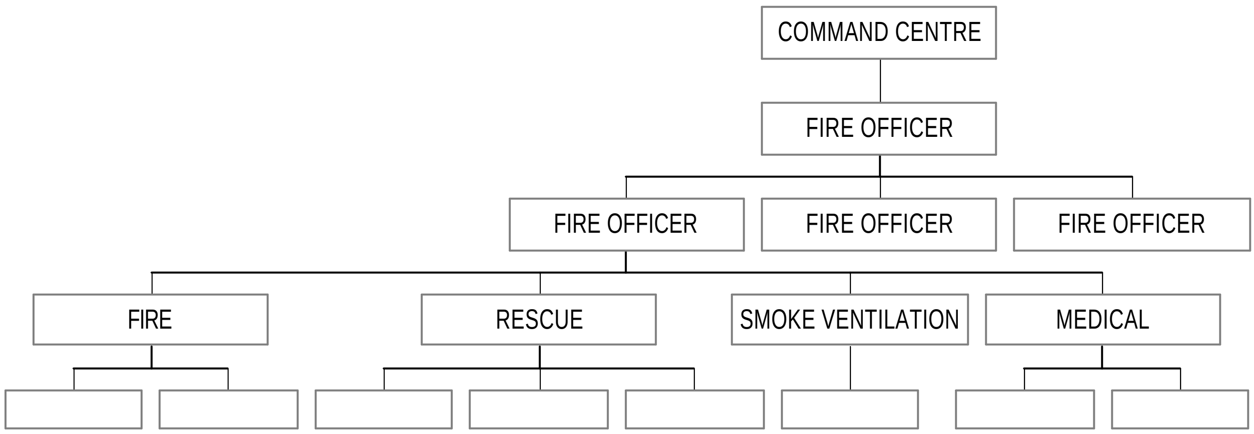


Figure 2

3.2 Smoke ventilation

One of the most important things during the rescue operation is how to handle the smoke removal so that passengers can come out from the tunnel and metro stations. Without successful smoke ventilation it is almost impossible for firemen to enter in the tunnel. The whole idea is to create wind speed in the tunnel to 2 m/s and then enter downwind to the fire.

It is essential to know what is the normal wind speed and direction before you try to begin control the smoke. The normal wind in the tunnel can be up to 3 m/s after the metro trains has stopped. The influence of wind starts after one minute after the trains have stopped. The normal wind speed varies a lot depending of the season. In the winter time nearly all trellises and doors are shut down because of the cold air so the influence is smaller. We tried to find out the relationship between the weather on the ground and tunnel but did not manage to analyse the correlation.

Our solution was to build a system in the tunnels and metro stations where in the case of emergency the rescue leader can have the real time information about the situation underground. The system is based on wind detectors which are situated in the tunnels and stations. All information can be seen from computer screen in every metro station. The view is simple: tunnel map where coloured arrows shows the speed and direction of wind.

- light blue arrow = no wind or less than 0,5 m/s
- blue arrow = you can fight against the current wind, 0,5 – 1,5 m/s
- red arrow = you cannot fight against the wind, over 1,5 m/s

In the same map is also shown all smoke fans, smoke doors and water pipe lines etc. Every metro station has especial room for the Rescue Department where all safety information is gathered.

With that system we can have reliable information for decision-making very quickly. Also a very good point is that by this system we can place our own units easier and make faster decisions about our tactics. We call this system Computer Guided Assistance for rescue leader.

The system is planned so that if in the case of fire heat damages some gables or wind sensors it does not break the whole system.
Now when we know the wind direction the only thing is to find out where the passengers are and where are they going and what are they doing. Where are injured people and how many are they ? That must be known very rapidly. Our principle is that we do not start smoke ventilation before we have enough information about the whole situation going on in the tunnel.

3.3 Special rescue equipment

Because of the metro our rescue units have special equipment with them all the time. Also in metro stations there is stored some more necessary equipment. We are prepared for long distance smoke diving with pressured air breathing apparatus (2 x 6,8 litres, 300 bar), and we have the possibility to use guidance rope (700m) so that firemen can not get lost. Because of the metro train is using 700 V electricity system it is very important to ground it as soon as possible. That is the first task when firemen are entering the rails. We have also special jack for lifting the metro train. The reliable radio system for metro tunnels and other communication systems makes modern leadership possible to rescue leaders and fire officers. It also helps firemen occupational safety in a very demanding circumstances.

However the best equipment for firemen is training in metro environment before the fire or accident. Our training is based in several forms:

- individual training of special rescue equipment
- unit training and familiarise to stations and tunnels including smoke ventilation
- large scale training with real units and men and passengers three times per year
- theoretical lessons about metro and the tactics of rescue operations

3.4 Emergency medical service

All firemen in the Helsinki Rescue Department has the education and practical knowledge of taking care injured people. Firemen are working in 24 hour shifts. From that they are 12 hours in rescue units and 12 hours in ambulances. That makes our operations easier to handle because we can flexibly use all multiskill firemen in right place when needed. For example if there is need for more ambulances we can use rescue units instead because our rescue units are equipped with the same medical instruments as ambulances only stretchers are missing.

Fire in the underground part of metro is always very severe situation. On the other hand of course for the passengers but also for firemen. Even if the Municipal Traffic Company and the Rescue Department are working together to increase the safety in metro all the time it is still possible that something unexpected can happen. It is not enough if all basic safety systems are working well (exit ways and signs, safety lighting etc.) because with the passengers there are always disable and old persons or children who needs extra help to get out. Also the human behaviour in the case of fire is very often very surprising in safety meaning. That is why rescue operations must be planned and trained often. In the operational situation firemen do seldom mistakes, all the mistakes have been done before if the preparation of difficult situation has been underestimated.

AIR QUALITY MONITORING IN TRAFFIC TUNNEL AND AT STREET LEVEL

Traugott Kilgus, Harald Rosenberger and Gabriele Schmid
MLU – Monitoring für Leben und Umwelt
Babenbergergasse 12
2340 Mödling
e-mail: traugott.kilgus@mlu.at, harald.rosenberger@mlu.at

ABSTRACT

Several monitoring principles are explained.

The principle of the DOAS technique (Differential Optical Absorption Spectroscopy) is shown by an example of measuring nitrogen dioxide (NO_2) and is compared with conventional techniques.

Also point measurements of nitrogen dioxid/nitric oxid (NO_2/NO), carbon monoxide (CO), ozone (O_3) and Benzene, Toluene and Xylene are shown, and also the TEOM (tapered element oscillating microbalance) Series to measure particulate mass concentrations. The instrument incorporates the patented tapered element oscillating microbalance; a true microweighing technology that provides true mass measurements. Emissions of soot and PAH (polycyclic aromatic hydrocarbons) are also important in traffic, the methods of monitoring these compounds are also discussed here.

Keywords:
measurement systems, traffic emission, particulate matter, particulate matter,
DOAS (Differential Optical Absorption Spectroscopy)-technique,
TEOM (tapered element oscillating microbalance)

1. INTRODUCTION

The atmosphere is a mixture of gaseous, liquid and solid substances. The concentrations of the various gaseous compounds and other species can change very quickly, also, other influences like weather conditions, traffic situation etc. have direct influence in these variations. Several studies have shown, that there is a direct relation between peak concentration and human health.
Therefore we concentrate on direct online continous monitoring methods with a time resolution in the range of minutes to less than one hour. The individual compound concentration may also be used as a signal for controlling purposes.

2. MONITORING SYSTEMS

2.1. Measuring Gaseous compounds with continous Methods

2.1.1. Fence-line Monitoring with OPSIS DOAS Principle

This system is based on a light path between an emitter and a receiver. Changes in the air quality between these two points can be detected even over long distances of several hundred meters. This makes DOAS an ideal fence-line monitor, since a light path will act as a tripwire to detect fugitive emissions. A DOAS system will simultaneously monitor several user-defined compounds. Typical examples are nitrogen dioxide (NO_2), nitric oxide (NO), ammonia (NH_3), sulphur dioxide (SO_2), formaldehyde, benzene, toluene, phenol and other hydrocarbons. It is therefore possible to specify a system to monitor the emissions for instance in a traffic tunnel, along traffic road, an industrial estate or a manufacturing complex. Because DOAS will monitor the entire length of a boundary, and because it monitors several compounds simultaneously, it is more efficient and cost-effective than a number of point monitors for individual compounds. Continuously generated data is stored by the system's analyser. This allows information to be presented as averages for any user-defined interval – minutes, hours or days – either in real time or retrospectively.

2.1.1.1. The OPSIS DOAS Technique

A basic OPSIS DOAS system includes an analyser connected by a fibre optic cable to a light path created by a light emitter and a receiver. Several light paths may be run from a single analyser. The system may be permanently installed or operated from a mobile facility such as a specially equipped vehicle. In either case the analyser will accept data from other devices producing a 4–20 mA or a digital output. This allows information from meteorological sensors (wind strength and direction, temperature etc.) to be presented together with air quality data to give a more detailed picture of environmental events.

2.1.1.2. Tests and Approvals

OPSIS DOAS has been tested and approved by a number of internationally recognized institutes and authorities. The system meets the requirements of the U.S. EPA and the German authorities.

2.1.1.3. Comparison of a light path and a point measurement of NO and NO2

A light path based system (DOAS, differential optical absorbtions spectroscopy) and a point based system of NO/NO2 detection based on chemiluminescence detection were compared in a traffic tunnel. A tunnel is an excellent setting for comparative measurement, because the measurement space is well defined and demarcated. Within a limited path, the air in the tunnel is also relatively homogeneous with regard to contents of exhaust gases. However, due to the different measurement principle light path and pointwise system can lead to different readouts.
Both instruments show virtually identical mean period values. At higher concentrations of NO and also of NO2 the DOAS instrument shows slightly lower values than the chemiluminescence instrument. This fact can be explained for NO with the high sensitivity chemiluminescence instrument to interference from certain hydrocarbons and for NO2 by interferences from substances such as HNO2, HNO3, R-NO3, R-CN etc. Slb-analys, Stockholm (1994).
The disadvantage of a sampling point monitor is the dirtification and necessary cleaning of the sampling system and tubings on a short interval regulary basis. DOAS has no mooving parts and measures NO_2 directly.

2.2. Measurement of Particulte Matter

2.2.1. Total Suspended particulate Matter (TSP)

The TEOM Series 1400a Ambient Particulate Monitor is the choice of air pollution monitoring networks worldwide to measure particulate mass concentrations continuously.
The instrument incorporates the patented *tapered element oscillating microbalanc*e, a true microweighing technology that provides true mass measurements. Using a choice of sample inlets, the hardware can easily be configured to measure PM-10 (Particulate Matter, 10 microns) , PM-2.5, PM-1 or TSP concentrations. Because of the high resolution of the instrument, one-minute-mean values are possible. An other advantage is, that no radiation source is needed.
The exchangeable filter in the Series 1400a monitor can also be used to determine heavy metal concentrations using atomic absorption (AA) and inductively coupled plasma (ICP). The Series 1400a monitor incorporates an inertial balance that directly measures the mass collected on an exchangeable filter cartridge by monitoring the corresponding frequency changes of a tapered element. The sample flow passes through the filter, where particulate matter collects, and then continues through the hollow tapered element on its way to an active volumetric flow control system and vacuum pump.
The TEOM mass transducer does not require recalibration because it is specially designed and constructed from non-fatiguing materials. Its mass calibration may be verified, however, using an optional Mass Calibration Verification Kit that contains a filter of known mass. active volumetric flow control is maintained by mass flow controllers whose set points are constantly adjusted in accordance with the measured ambient temperature and pressure.

2.2.2. Speciation Methods

2.2.2.1. Ambient Particulate Nitrate Monitor

The Series 8400N monitor generates 10 minute averages of the ambient particulate nitrate concentration. The instrument consists of a weather-protection inlet and transport tubing, pulse generator, microprocessor-based control system, user interface, nitrogen oxides detector, sample pump, and gas cylinder. Built-in software and hardware automatically calibrate and verify zero and span. Bidirectional RS-232 communication provides the capability for remote data interchange and internal data storage.
A stream of ambient air containing particulate matter enters the sample inlet line beneath a rain cap mounted above the roof of the air quality monitoring station. A sheath flow surrounds the sample line, and then enters the sample processing section of the pulse generator after being filtered. The sheath air flow is designed to keep the sample stream and inside of the instrument as close as possible to the ambient air temperature.
A PM2.5 sharp cut cyclone removes the larger particles from the sample stream. A bypass flow, which shortens the residence time of the sample stream in the sampling section, passes through a critical orifice. An activated charcoal denuder removes acidic gases that would otherwise interfere with the measurement of the ambient particulate nitrate concentration.
The Series 8400N uses a flash volatilization technique to measure the concentration of particulate nitrate contained in PM2.5 .
To achieve high collection efficiencies even for very small secondary aerosols, a humidifier moistens the sample stream and causes the hygroscopic nitrate particles to grow. The remaining part of the sample stream forms a jet as it passes through a critical orifice.
Particles collect on an impactor/flashing strip during the sample collection phase (eight minutes by default). The sample and bypass flows then combine and exit from the instrument on their way to an external pump.
Flash volatilization of the collected particulate matter in a nitrogen atmosphere occurs at approximately 350°C through the resistive heating of the metal impactor/flashing strip, which creates a pulse of oxides of nitrogen that is quantified by the chemiluminescent reaction with excess ozone.
The Series 8400N computes a new data point every 10 minutes, with a resolution of the reported values of ±0.2 $\mu g/m^3$. Cowen K. et. al (2001)

2.2.2.2. Ambient Particulate Sulfate Monitor

The Series 8400S monitor generates 10 minute averages of the ambient particulate sulfate concentration. The instrument has the same general comparison as the 8400N-Series but for sulfur detecton.
The Series 8400S uses a flash volatilization technique to measure the concentration of total particulate sulfur (which is assumed to be sulfate) contained in PM2.5 .
Flash volatilization of the collected particulate matter in an air atmosphere (the Series 8400N works in a nitrogen atmosphere) occurs at over 600°C through the resistive heating of the metal impactor/flashing strip, which creates a pulse of sulfur dioxide that is quantified in the sulfur detector.
A constant flow of ambient air keeps the pulse generator at ambient temperature. The Series 8400S computes a new data point also every 10 minutes, with a resolution of the reported values of ±0.2 $\mu g/m^3$. Cowen K. et. al (2001)

2.2.2.3. Ambient Carbon particulate Monitor

The Ambient Carbon particulate Monitor provides time resolved particulate carbon information.
Series 5400 is an automatic speciation analyzer of suspended particulate matter. It measures the elemental and organic carbon contained in suspended particulate matter at averaging times as short as one hour. Its thermal CO_2 analysis technique is similar to that used in many analytical laboratories to measure carbon particulate concentration. Results from the instrument can be used to compare organic and elemental carbon particulate concentrations (in µg/m³) with mass-based measurements such as PM2.5 , PM10 or PM1 (in µg/m³).
Ambient air passes through a PM2.5 , PM10, or PM1 size-selective inlet before entering the instrument. The Series 5400 contains two cartridges located in temperature-regulated ovens to collect the sampled particulate matter. While one cartridge is being used for particle collection, the instrument performs its thermal CO_2 analysis on the previously collected particulate matter contained in the other collector.
The Series 5400 differentiates between organic and elemental carbon particulate matter by oxidizing collected samples at an intermediate temperature and at a high final burn temperature.
When operated at a two-hour cycle, the Series 5400 can perform up to three sample oxidations at intermediate temperatures prior to the final burn.
With zero and span gas sources attached, the Series 5400 automatically audits and calibrates the CO_2 sensor at user-defined intervals. Sample oxidation during the analysis phase regenerates the Series 5400's exchangeable collection cartridges. The Series 5400 is constructed to be operated automatically and unattended for months at a time between maintenance routines. (ETV Summary for Series 5400 Monitor).

2.3. (PAHs)

No continous monitoring method approved at this time, The US-EPA method is described in Manning J. A. (1999).

CONCLUSIONS

Due to recent works and studies, the effect of peak concentrations of particulata matter and gaseous compounds becomes more and more important to human health. Therefore we need modern instrumentation with high time resolution and accuracy to improve the situation at the „hot spots“ e. g. tunnels and highly frequented streets.

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EVALUATION OF VEHICULAR POLLUTANT EMISSIONS INSIDE TUNNELS

Pasquale Grassia, Mariano Migliaccio, Andrea Unich
Department of Mechanical Engineering, University of Naples
Via Claudio 21 - 80125 Napoli, Italy
E-mail unich@unina.it
Giuseppe Police
Istituto Motori, National Research Council
Via Marconi 8 - 80125 Napoli, Italy

ABSTRACT

Ventilation systems for tunnels have to be sized taking into account pollutant emissions inside them, which depend on vehicular traffic and can reach very high levels especially in urban tunnels. This paper describes a procedure to estimate pollutant emissions in order to calculate the ventilation flow rate necessary to have an acceptable air quality in tunnels. The prediction is based on legislation limits set by European Union on vehicular pollutant emissions. Limits are different for each type of vehicle (passenger cars, heavy duty vehicles, motorcycles) according to the year of registration. Statistical data on circulating vehicles were used to consider the distribution of vehicles typology, age and annual mileage. The effect of different traffic conditions on emissions was considered. An example was performed in order to evaluate ventilation air flow rate in a urban tunnel.

Key words: pollutant emission, tunnel ventilation, emission limits, urban tunnel, driving cycle.

1. INTRODUCTION

Vehicular pollutant emissions subject to limits are carbon monoxide (CO), unburnt hydrocarbons (HC), and nitrogen oxides (NOx) both for spark ignition and compression ignition engines, while particulate matter (PM) is limited only on compression ignition engines. Other noxious substances are present in exhaust gases but not subject to limits. Some of them (i.e. benzene and sulphur) are present in fuels and their amount is limited by legislation on fuel composition [1]. Carbon monoxide is a product of combustion in presence of rich fuel-air ratio and is toxic for concentrations higher than 0.3%, which can cause death in 30 minutes. Hydrocarbons and nitrogen oxides contribute to photochemical smog, while some hydrocarbons can have carcinogenic effects. Particulate matter is composed by a carbon matrix on which high molecular weight hydrocarbons are adsorbed. These particles have a diameter of few microns so they have a long residence time in atmosphere and can be inhaled. In order to estimate vehicular emissions, it is necessary to know the driving cycle (speed vs. time), the different typology of vehicles, their age and maintenance, anyway this evaluation is particularly difficult, in spite of the presence of many models. An approach to the problem is based on measurements performed on engine test bed in steady state conditions; from driving cycle it is possible to calculate the forces acting on the vehicle and consequently the instantaneous values of engine speed and torque. Considering the phenomenon as quasi-stationary, the results of test points are interpolated in order to evaluate fuel consumption and emissions. The accuracy of this kind of models is satisfactory for fuel consumption and HC emissions, while CO, NOx, and PM are strongly underestimated due to the effect of transients on such emissions. This methodology requires a large amount of experimental data for each engine. A different and simpler approach is to refer to emission limits set by EU legislation [2]. Considering the limits imposed in different periods to passenger cars, heavy duty vehicles, motorcycles and knowing the number of vehicles for each category it is possible to estimate the pollutant emissions for a certain driving cycle. These data can be used to size ventilation system of a tunnel, particularly in urban areas where traffic conditions are highly variable and in general congested.

2. EMISSION REGULATIONS

Emission test for passenger cars is performed on a chassis dynamometer. At present the driving cycle is composed by a Urban Driving Cycle (UDC) with a length of 4.052 km, average speed of 18.7 km h^{-1}, max speed of 50 km h^{-1} and an Extra Urban Driving Cycle (EUDC), length 6.755 km, average speed 60.8 km h^{-1}, max speed 120 km h^{-1}, figure 1 [3].

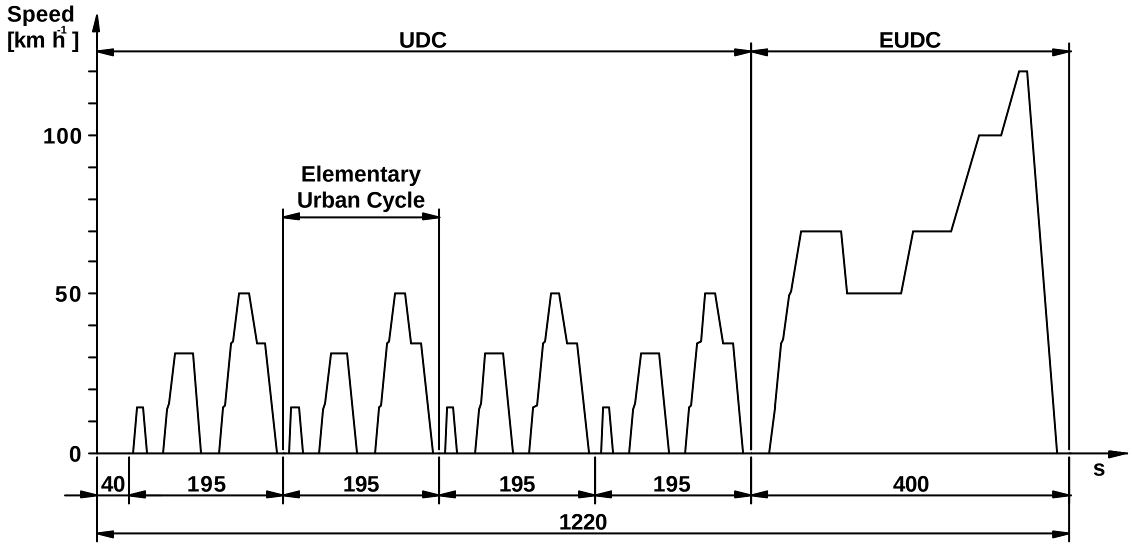

Figure 1: Urban Driving Cycle and Extra Urban Driving Cycle

The whole cycle UDC + EUDC has a length of 10.807 km and an average speed of 33 km h^{-1}. UDC is composed by an elementary module repeated four times. Exhaust gas is diluted with ambient air to prevent water condensation and to freeze chemical equilibrium. The flow of air-exhaust gas mixture is controlled by a positive displacement pump and remains constant during the test, figure 2. Measuring gas concentrations in the bags and the mass flow rate across the pump is possible to calculate the mass of pollutants emitted during the test.

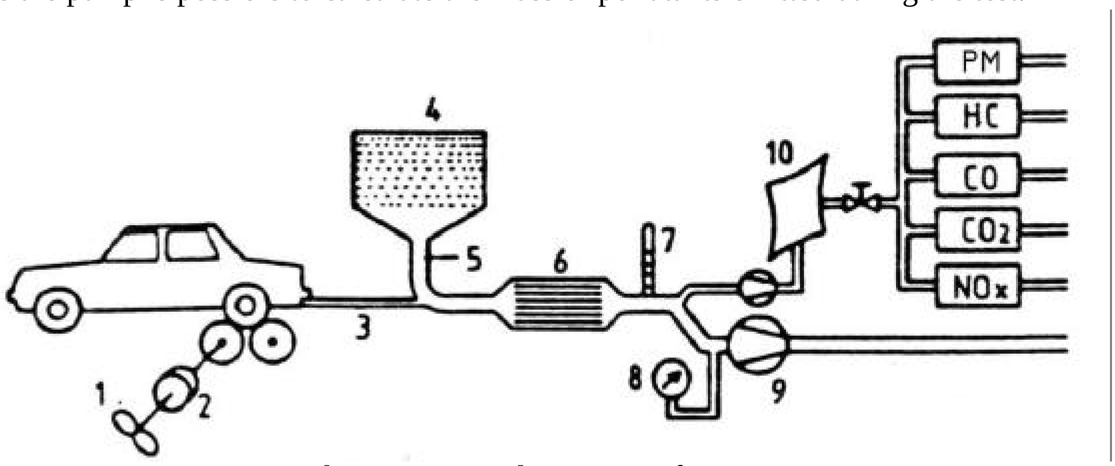

Figure 2: exhaust gas sampling system for passenger cars

1: dynamometer	5: dilution air	9: positive displacement pump
2: flywheels	6: heat exchanger	10: sampling bag
3: exhaust gas	7: gas temperature	
4: air filter	8: gas pressure	

Emission limits for passenger cars in force from 1984 (ECE 15-04) are reported in table 1. These limits are referred to the UDC driving cycle and are different according to vehicle reference mass, their values being expressed in g per test.

Table 1: ECE 15-04 limits, g per test

Reference mass [kg]	CO	HC + NOx
< 1020	58.0	19.0
1021 – 1250	67.0	20.5
1251 – 1470	76.0	22.0
1471 – 1700	86.0	23.5
1701 – 1930	93.0	25.0
1931 – 2150	101.0	26.5
> 2150	110.0	28.0

In 1988 new limits were imposed (ECE 83), table 2. In this case, limits expressed in g per test, vary according to engine displacement, being stricter for larger engines. The driving cycle was the UDC, while different limits were set for diesel engines in which particulate matter was taken into account.

Table 2: ECE 83 limits, g per test

	Cubic capacity CC [cm^3]	CO	HC+NOx	PM
Gasoline	CC > 2000	25.0	6.5	-
	1400 < CC < 2000	30.0	8.0	-
	CC < 1400	45.0	15.0	-
Diesel	CC > 2000	30.0	8.0	1.1
	1400 < CC < 2000	30.0	8.0	1.1
	CC < 1400	45.0	15.0	1.1

In 1993 the 91/441/EEC regulation was enforced. In this case limits are the same for all type of cars. The driving cycle is UDC + EUDC, while limits are expressed in g km^{-1}. In 1996 new limits were set (94/12/EEC), while test procedure remained unmodified, table 3.

Table 3: 91/441/EEC and 94/12/EEC limits, g km^{-1}

Directive	91/441/EEC			94/12/EEC		
	CO	HC+NOx	PM	CO	HC+NOx	PM
Gasoline	2.72	0.97	-	2.2	0.50	-
Diesel	2.72	0.97	0.14	1.0	0.70	0.14

Motorcycles and mopeds are tested on a chassis dynamometer, similarly to passenger cars. The driving cycle for motorcycles is the UDC, while mopeds have a different driving cycle. Table 4 shows limits for motorcycles and mopeds [4].

Table 4: motorcycles and mopeds limits, g km^{-1}

<table>
<tr><th></th><th>Year</th><th colspan="2">Directive</th><th>CO</th><th>HC + NOx</th></tr>
<tr><td rowspan="2">Mopeds</td><td>1992 - 1998</td><td colspan="2">ECE 47</td><td>8</td><td>5</td></tr>
<tr><td>from 1999</td><td colspan="2">97/24/EEC</td><td>6</td><td>3</td></tr>
<tr><td rowspan="2">Motorcycles</td><td rowspan="2">from 1999</td><td rowspan="2">97/24/EEC</td><td>2 stroke</td><td>8</td><td>4.1</td></tr>
<tr><td>4 stroke</td><td>13</td><td>3.3</td></tr>
</table>

Emissions from heavy duty vehicles are measured according to ECE R49 13 mode test [3]. Test is performed on the engine test bed in 13 steady-state operating conditions. Each point has its weight factor. The test sequence is the following: idle; intermediate speed increasing load (10, 25, 50, 75, 100%); idle; rated speed decreasing load (100, 75, 50, 25, 10%); idle. Measuring pollutant concentrations and exhaust mass flow rate it is possible to obtain pollutant mass flow rate. This value is multiplied by its weight factor in each mode and divided by engine power in order to be expressed as g $(kWh)^{-1}$. Table 5 shows heavy duty emission limits.

Table 5: limits for heavy duty vehicles, g $(kWh)^{-1}$

Directive	Year	CO	HC	NOx	PM
ECE 49	1984 - 1988	14.0	3.5	18.0	-
ECE 49.01	1989 - 1992	11.2	2.4	14.4	-
Euro I	1993 - 1996	4.5	1.1	8.0	0.36
Euro II	1997 - 2000	4.0	1.1	7.0	0.15

3. CONSIDERATIONS ON CIRCULATING VEHICLES

In order to obtain emissions estimate from legislation limits it is necessary to process some data. Emission limits set by ECE 15-04 has to be referred to a frequency distribution of vehicle mass, which can be evaluated from data on circulating vehicles [5]. A 30 % increase of emissions due to engine wear and incorrect set-up was considered, according to the technology used in that period. Particulate emissions for diesel cars were evaluated to be 50% higher than ECE 83 limits. In a similar way ECE 83 limits were elaborated considering the frequency distribution of engine displacement on circulating vehicles. The increase in emissions for used vehicles was evaluated in 20%. For 91/441/EEC emissions for circulating vehicles were considered 10% higher than limits, while for 94/12/EEC the increase was evaluated in 5%. An increase of 40% from ECE 47 limits was considered for mopeds due to incorrect set up and engine tampering, while an increase of 20% was estimated for 97/24/EEC limits. Emissions from motorcycles registered before 1999 were evaluated 50% higher than 97/24/EEC limits, while for motorcycles registered from 1999 emissions were estimated 20% higher than 97/24/EEC limits. The result of such calculations is the emission in g km^{-1} for each registration period, table 6.

Table 6: estimated emissions from circulating passenger cars, motorcycles, mopeds, $g\ km^{-1}$

Directive	Year	CO	HC + NOx	PM
ECE 15-04	1984 - 1987	26.5	6.8	0.61
ECE 83	1988 - 1992	13.3	4.3	0.41
91/441/EEC	1993 - 1996	3.5	1.4	0.20
94/12/EEC gasoline	1996 - 2000	2.3	0.53	-
94/12/EEC diesel	1996 - 2000	1.1	0.74	0.14
Motorcycle	before 1999	18.0	5.3	-
97/24/EEC Motorcycle	1999 - 2000	14.4	4.2	-
ECE 47	1992 - 1998	11.2	7.0	-
97/24/EEC Moped	1999 - 2000	7.2	3.6	-

For heavy duty vehicles it is necessary to convert limits from $g\ (kWh)^{-1}$ to $g\ km^{-1}$, estimating in 45 kW the power required by an average heavy duty vehicle at the speed of 19 $km\ h^{-1}$. Table 7 reports limits for heavy duty vehicles. For used vehicles an increase of 20% for emissions was considered. PM emissions for vehicles registered according to ECE 49 and ECE 49.01 directive were considered 60 and 90 higher than Euro I limits.

Table 7: estimated emissions from circulating heavy duty vehicles, $g\ km^{-1}$

Year	CO	HC + NOx	PM
1984 - 1988	39.8	61.1	1.94
1989 - 1992	31.8	47.8	1.63
1993 - 1996	12.8	25.9	1.02
1997 - 2000	11.4	23.0	0.43

The driving cycle has a strong effect on emissions, so the hypothesis on vehicle speed profile are very important. In particular for a stop-and-go cycle composed by the first part of the elementary module of UDC, figure 3, with an average speed of 6 $km\ h^{-1}$ many test on different vehicles proved a strong increase in emissions [6].

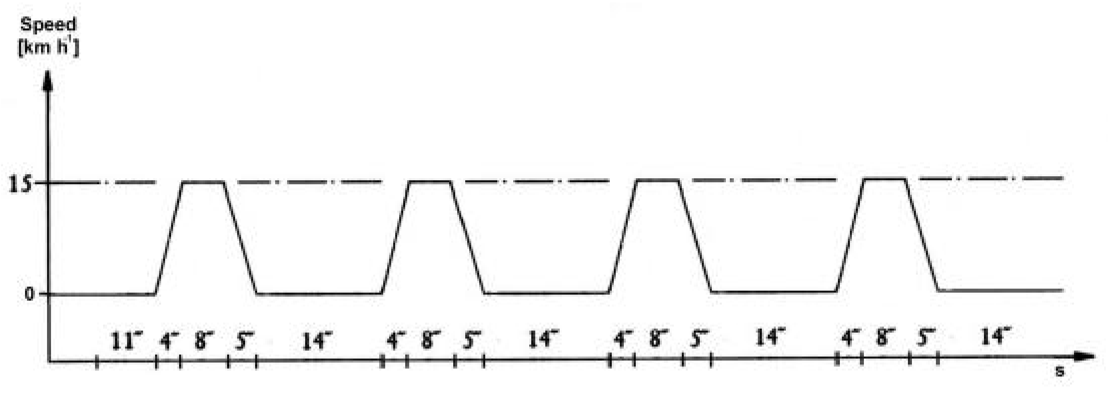

Figure 3: stop and go driving cycle

As a consequence, three traffic conditions were considered:

- regular traffic, average speed 33 km h^{-1}
- congested traffic, average speed 19 km h^{-1}
- very congested traffic, average speed 6 km h^{-1}

The effect of very congested traffic was taken into account multiplying by 2 estimated emissions reported in table 6 and 7. In congested traffic values from table 6 and 7 have been considered for passenger cars until 1992, motorcycles, mopeds and heavy duty vehicles, being limits referred to an average speed of 19 km h^{-1}. For passenger cars built from 1993 the values have been multiplied by 1.2 being average speed lower than the regulation driving cycle. For standard traffic values in table 6 and 7 have been multiplied by 0.8 for vehicles registered before 1993, motorcycle, mopeds and heavy-duty engines. At the end of year 2000 there were in Italy 32.5 million passenger cars, 3.5 million heavy duty vehicles, 3 million motorcycles and 5 million mopeds. On the base of statistical data on circulating vehicles [5] it was possible to subdivide vehicles according to the registration period and, for passenger cars, separating gasoline and diesel engines. These values were corrected taking into account the different annual mileage of each category. Table 8 shows the final result.

Table 8: composition of circulating vehicles taking into account annual mileage

Year	Type of vehicle	%
1984 - 1987	Passenger car gasoline	10.9
1984 - 1987	Passenger car diesel	3.6
1984 – 1988	Heavy duty	6.7
1988 – 1992	Passenger car gasoline	17.5
1988 – 1992	Passenger car diesel	2.3
1989 – 1992	Heavy duty	4.8
1993 - 1996	Passenger car gasoline	13.2
1993 - 1996	Passenger car diesel	2.4
1993 - 1996	Heavy duty	4.8
1997 - 2000	Passenger car gasoline	13.9
1997 - 2000	Passenger car diesel	7.1
1997 - 2000	Heavy duty	4.8
before 1999	Motorcycle	2.5
1999 - 2000	Motorcycle	0.5
1992 - 1998	Moped	4.0
1999 - 2000	Moped	1.0

4. ESTIMATE OF POLLUTANT EMISSIONS

The mass flow rate of each pollutant per unit of tunnel length and per lane is obtained dividing P100 (the pollutant flow rate emitted by 100 vehicles distributed as in table 8) by L100 (the length of a convoy of 100 vehicles running on a lane). For each pollutant P100 can be computed as follow:

$$P100\left[kg\ h^{-1}\right] = \sum \frac{n \cdot m \cdot f \cdot s}{10^3}$$

where:

n = percentage of vehicles for each category (from table 8)
m = mass of pollutant emitted in g km^{-1} (from tables 6 and 7)
f = factor taking into account traffic conditions
s = average speed of vehicles, km h^{-1}

L100 can be calculated from the average length of vehicles and the distance between them. An average length of 5 m for cars, 10 m for heavy duty vehicles and 2 m for motorcycles and mopeds was considered, while the distance between two consecutive vehicles was evaluated as 5 m at 6 km h^{-1}, 16 m at 19 km h^{-1} and 28 m at 33 km h^{-1}. As a consequence, taking into account percentage of vehicles for each category, the values of L100 at different speed are:

1.08 km at 6 km h^{-1}
2.18 km at 19 km h^{-1}
3.38 km at 33 km h^{-1}

The pollutant mass flow rate for each lane expressed in kg h^{-1} km^{-1} is:

$$P = \frac{P100}{L100}$$

The values of P for different traffic conditions are reported in table 9.

Table 9: pollutant mass flow rate per lane, kg h^{-1} km^{-1}

Average speed [km h^{-1}]	CO	HC + NOx	PM
6	15.3	12.6	0.36
19	11.5	10.0	0.30
33	10.4	9.0	0.27

These results show that the worst condition corresponds to the very congested traffic. In order to calculate the amount of air necessary to obtain a defined concentration of a pollutant, it is possible to write the following mass balance:

$$m_i + m_p = m_o$$

where:
m_i = mass flow rate of pollutant entering in the tunnel, kg h^{-1}
m_p = mass flow rate of pollutant emitted by vehicles inside the tunnel, kg h^{-1}
m_o = mass flow rate of pollutant out of the tunnel, kg h^{-1}

and being:

$$m_p = P \cdot l_t \cdot n_l$$

where:
l_t = length of tunnel, km
n_l = number of lanes

The presence of pollutant in the inlet air is neglected, so $m_p = m_o$ In the hypothesis of a perfect mixing between air and pollutant inside the tunnel:

$$m_p = m_a \cdot c \cdot k$$

where:
m_a = dilution air mass flow rate
c = concentration of the pollutant by volume
k = ratio between pollutant molecular weight and air molecular weight

Considering a limit concentration of 50 ppm for CO in the tunnel the ventilation mass flow rate per unit of tunnel length and per lane is reported in table 10.

Table 10: ventilation mass flow rate, kg h^{-1} km^{-1}

Average speed [km h^{-1}]	Ventilation mass flow rate
6	$317 \cdot 10^3$
19	$238 \cdot 10^3$
33	$215 \cdot 10^3$

5. CONCLUSIONS

An estimate of vehicular pollutant emissions in a tunnel was proposed. On the base of legislation limits and statistical data on circulating vehicles it was possible to predict emissions. The effect of different traffic conditions typical of urban tunnels was considered. A numerical example was performed in order to evaluate ventilation air flow rate in a tunnel.

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PHASED CONSTRUCTION AND SAFETY IN MALA KAPELA TUNNEL

Darko Šaric
Civil Engineering Institute of Croatia
Croatia, 10.000 Zagreb, J. Rakuše 1
e-mail: dsaric@zg.igh.hr

Goran Legac
Croatian Motorways, Ltd
Croatia, 10.000 Zagreb, Voncinina 2
e-mail: goran_legac@inet.hr

ABSTRACT:

Mala Kapela tunnel is a major structure designed to overcome the so called Mountain sill on the part of E-59 motorway between Zagreb and Dubrovnik, i.e. on the Pyhrn corridor towards Southeastern Europe and Mediterranean.

The report outlines the design solution and operation of 5,76 km long Mala Kapela twin tube tunnel during its phased construction. The fact that the traffic movement will take place on two separate double - tracked traffic lanes for each direction has been taken into consideration in tunnel design. Phased construction that would bring tunnel to its function has been explored considering that this tunnel, due to its construction time, is critical to opening to traffic of the Zagreb – Split section. Thereby, safety aspects of the traffic movement and tunnel users must not be endangered.

While choosing the twin tube tunnel design and ventilation system the current regulations and practices in EU countries as well as recommendations of expert institutions were followed. The relevant Croatian regulations for design and construction of tunnels have been used as a source criteria.

Key words: Twin tube tunnel, phased construction, traffic flow, safety aspects, ventilation

1. INTRODUCTION

Zagreb-Split Motorway that is its Bosiljevo-Sveti Rok section, is part of the international road corridor Austria-Maribor-Zagreb-Karlovac-Bosiljevo-Split-Dubrovnik which has been classified as European road E-59 (Pyhrn corridor). Zagreb - Split Motorway links Adriatic littoral area with Croatian inland and is of vital significance for socio-economic and tourist development.

The motorway is currently under construction and it shall be opened to traffic in 2005. From financial and technical aspect the most important structure within Bosiljevo-Sveti Rok section is Mala Kapela tunnel whose construction cost is estimated at about 5% of the total investment cost for the entire Bosiljevo – Split Motorway route.

2. GENERAL TECHNICAL DATA

2.1. Cross and longitudinal section

The tunnel is designed as a twin tube tunnel with the 25 m axial distance. The cross section has been chosen according to the lane width required for the design speed V=100 km/h.. The tunnel cross section has clear opening of 56,17 m2 and permits placement of all necessary equipment and devices. The traffic lanes and marginal strips width is chosen in accordance with Croatian regulations. The total width is 7,70 m (with two traffic lanes of 3,50 m and two

marginal strips of 0,35 m). Inspection sidewalks are foreseen at both sides in the minimum width of 90 cm and are raised 15 cm above the carriageway.
Under sidewalks there are installation ducts for service cables and tunnel equipment.
The tunnel entrance and exit are in circular arches which are connected with the straight line by means of transition curves. The left tunnel tube is 5.761,76 m long and the right tunnel tube is 5.760 m long. The chosen longitudinal gradients are 1,20 % and 1,50 % towards portals which are optimum considering drainage, the costs of construction, electromechanical devices, transport and maintenance.
The tunnel lining shall be made of MB 30 concrete in the minimum thickness of 30 cm. Between the tunnel lining and primary support there shall be a waterproofing layer of PVC foil protected with geotextile.
The pavement structure consists of three asphalt layers with Splittmastixasphalt SMA 11s with PmB as a wearing course.

2.2. Drainage

The tunnel drainage system is foreseen by the longitudinal sewers with the 50 cm diameter. The carriageway surface fluid is drained through the system of hollow curb unit and siphon overflow with immersed partition in the longitudinal sewerage.
The carriageway drainage is dimensioned according to the volume of incident fluid afflux of the initial 200 l/s at the tunnel length of 200 m and the implementation of the drainage system prevents fire from spreading through sewerage. At the tunnel sides and in the pavement sub-base longitudinal perforated pipes with the 150 mm diameter are foreseen. At the tunnel sides manholes spaced at 110 m shall be placed for side longitudinal drains.
Manholes are also foreseen in the longitudinal sewerage at the approximate distance of 55 m.

2.3. Ventilation

The chosen ventilation system for Mala Kapela tunnel is reversible longitudinal ventilation. This choice has been made on the basis of cost-efficiency and safety-technical analysis for the normal operation conditions and for the case of fire accidents.
Since Mala Kapela tunnel has been designed as a twin tube tunnel with each tube providing for one-way traffic, the longitudinal system has numerous advantages keeping the safety of passengers in case of fire. Economic justifiability of the longitudinal ventilation system is evident not only in the initial investment in equipment and construction works but also in the costs of operation cause in one-way two-lane traffic, the traffic flow in one direction helps the ventilation of the tunnel tube in longitudinal direction making use of the so called "piston effect".

The possibilities for passenger evacuation in case of fire are good since in case of fire in one-way traffic vehicles are permitted to leave the area of accident and the vehicles coming into are alarmed in time to stop. Since we are talking here about two tubes connected by transversal passages for vehicles and passengers the other tube shall be used as the emergency escape to the safe and open area in front of the portal as well as the access for firemen and rescue team to the place of accident i.e. fire.

2.4. Safety Facilities Inside the Tunnel

Designed facilities related to the safety of tunnel users are: lay-bys for vehicles, cross passages for vehicles, cross passages for pedestrians, recesses for emergency call boxes, hose valve stations and recesses for control and surveillance devices.

Lay-bys for vehicles are placed at the right side of carriageway and are used for temporary stopping. The dimensions of the lay-bys are 3.0 m x 40 m. They are spaced at about every 840 m and they also comprise the recesses for emergency call boxes and recesses for uninterruptible power supply.

Opposite of lay-by there is a cross passage for vehicles which can be used for redirection of traffic due to works or congestion, as well as emergency passage in case of accident and fire and for the access of rescue team (fig. 1).

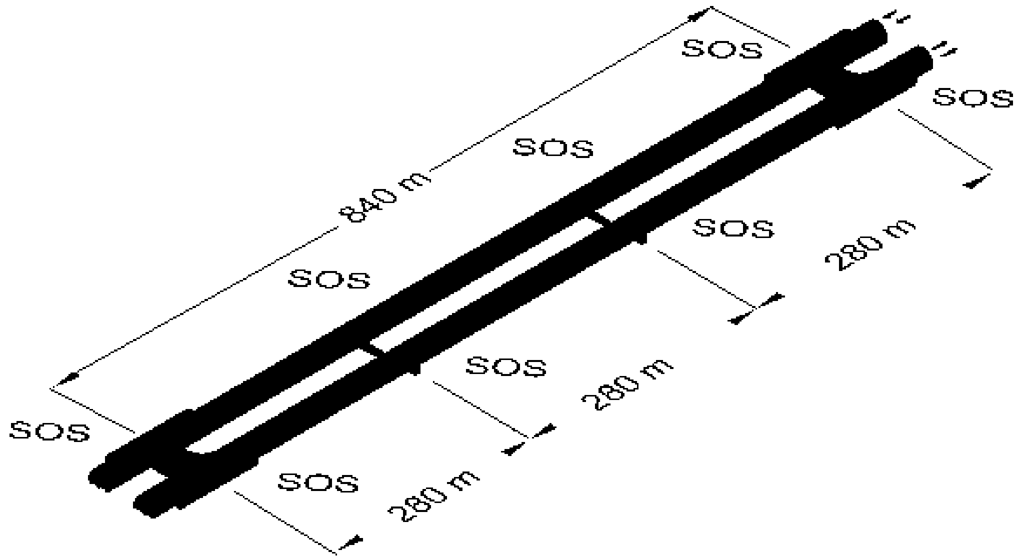

Figure 1. Layout of safety facilities inside the tunnel

Cross passages are blocked with fire fighting walls comprising fire fighting sliding doors that, when open, allow vehicles to pass from one tube to another (fig. 3). Clear opening is 4,50 m high while the carriageway width is 5 m. Doors are designed so they can be opened only by authorised officials. Fire fighting wall is also equipped with the pedestrian exit. The door can be opened on both sides which is signalled in the traffic control centre.

The chosen solution comprises the placement of vehicles lay-bys opposite of emergency escapes opposite of vehicle lay-bys considering that transformer stations are placed in the passage and this will allow for their maintenance and repair without interfering with the traffic going on in the tubes.

SOS recesses with phone device are spaced at 280 m, and are equipped with telephone device comprising the hand-operated fire alarm and two hand-operated fire extinguishers.

Opposite of SOS recesses there is a pedestrian emergency escape permitting evacuation of the endangered tunnel users from one tube into the other i.e. into the safe area over the adequate period of time.

While determining the distance between the pedestrian cross passages the type of ventilation and the length of the evacuation path was considered. In case of fire the movement of evacuating people can be decreased to 1m/s due to the smoke and heath. While calculating the evacuation time we shall also add the time for detection of fire as well as the time required to alarm tunnel users and to allow them to get out of the vehicles. The evacuation time should normally comprise 10 minutes which can be obtained by constructing pedestrian emergency escapes spaced at 280 m. Pedestrian escapes are equipped with fire-fighting door the opening of which shall be signalled in the in the traffic control centre. The door can be opened on both sides and the light in the passage shall automatically be switched on and off as the door opens and closes.

The fire-preventing hydrant distribution is also foreseen in the tunnel. It is supplied from the water tank of 100 m^3 which ensures enough water for one hour of fire-fighting. The volume of water used shall be 1200 l/min and the pressure at least 6 bars to 12 bars at the most with the automatic monitoring of changes i.e. decrease of the water level in the water tank. Hydrants shall be placed on the walls and spaced at 100m, put in cubicles and equipped with 120 m of hose.

2.5. Safety Systems

Electric power supply for the tunnel shall be provided within two transformer stations (one transformer station on each portal) and six additional transformer stations inside the tunnel. Safety systems comprise uninterruptible power supply (UPS) devices placed in the emergency recesses. Systems supplied from uninterruptible power supply are secondary and alarm lights, alarm lights of passages, lightening for all SOS signs, supply for changeable signs, phones, public-address system, TV surveillance, radio-communication device, operation of fire alarm, remote control and sign work for all systems installed in the tunnel.

The public-address system providing all necessary information and instructions for tunnel users shall be placed in the tunnel as well as TV and radio system.

Lightening of the tunnel access areas covers the approach area at both tunnel portals in the approximate length of 180 m. The disposition of lights and the possibility of adjusting ensures economical and safe operation of the lightening system with the optimum parameters.

Within the ventilation system there are also devices for measuring CO concentration as well as visibility and air flow direction and velocity.

Automatic fire detectors with sensor cable for surveillance of the main tunnel tubes are foreseen while the surveillance of other areas shall be carried out by spot-type detector. Hand-operated fire alarms shall be also placed in SOS recesses. The emergency call system is also placed in SOS recesses.

Changeable traffic signs are foreseen for traffic regulation.

The remote operating system whose function is to operate traffic and to survey tunnel operation shall be placed in the traffic control centre 5 km form the south portal which is also the location of the fire fighting unit.

3. PHASED CONSTRUCTION

Traffic forecast based on preliminary analyses anticipates the traffic load of about 12.000 vehicles a day in the year 2014. 16 % of that load is made by heavy traffic (lorries and buses). During the summer period however the traffic load increase is 70 to 80 % with regard to the average annual daily traffic. Various possibilities of the tunnel phased construction were explored while searching for the optimum choice from financial and traffic aspect. The explored alternatives comprised several constructional and engineering solutions combining various types of ventilation system (transverse, semi-transverse and longitudinal).

The choice of the design solution is based on the fact that the first construction phase calls for the least possible volume of additional works at the final construction stage of the twin tube tunnel with one-way traffic without endangering the safety of tunnel users.

Among various considered possibilities, one solution in particular was accepted as economically justified and acceptable from technological and safety aspect. In the first construction phase both tubes would be simultaneously excavated and supported as a whole final cross section (fig. 2). All cross passages and pedestrian emergency escape shall be built in the first phase. Upon completion of all necessary works the right tunnel tube would be opened to traffic whereas the left tunnel tube would be used in case of incidents in the right tube by means of cross passages i.e. as an access to fire brigades and rescue teams with all the necessary equipment and vehicles.
During the first construction phase the right tunnel tube should keep the longitudinal ventilation system in order to decrease the construction costs and comply as much as possible with the final tunnel solution.

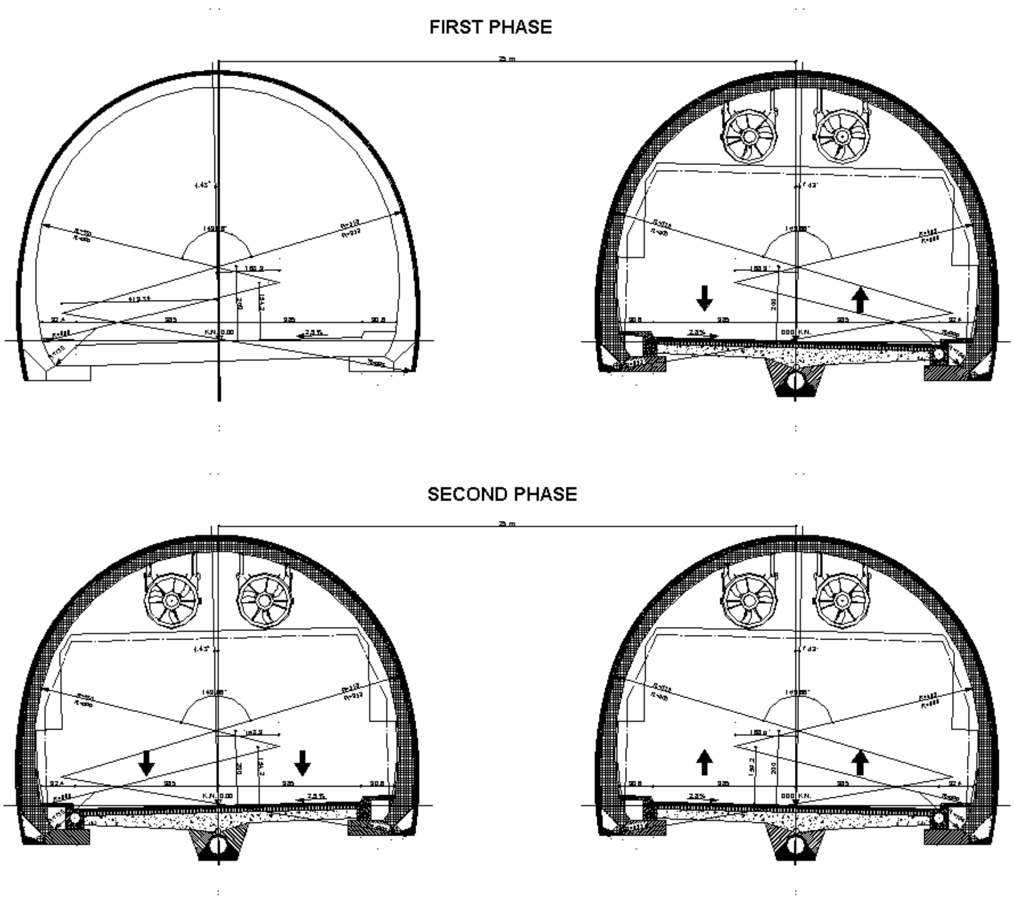

Figure 2. Outline of the phased construction

Considering the required minimum construction time and the use of standard mechanisation and equipment we are anticipating less technological delay than in case of one tunnel tube.

Since the excavation will take place simultaneously in both tubes the left tube could be used for the job site needs as well.

The subsequent construction of the second tunnel tube by means of blasting has also been considered provided that the right tunnel tube has been constructed and opened to traffic. Based on previous design experience in similar ground conditions we estimate that the subsequent excavation of the second tunnel tube would take place in two stages with the limited advance length depending on excavation phase by blasting. Assuming that the greater part of the tunnel is in favourable soil conditions where restrictions are not necessary, the stated excavation restrictions requiring several work phases will surely make the cost of the second excavation phase greater. Variable construction costs which are mostly the same and are not affected by the choice of construction of one or two tubes, in simultaneous excavation of both tubes affect the greater volume of work which subsequently means significant decrease of the excavation unit price. The decrease of the excavation unit price is related to the maximum usability of equipment and mechanisation in the course of simultaneous excavation with two work faces on both sides of the tunnel.

4. CONCLUSION

The studied phased construction of Mala Kapela Tunnel is proposed as the optimum solution with regard to the overall construction costs of the twin tube tunnel and safety for the tunnel users in case of incidents. A disadvantage of this solution is greater initial investment for the first construction phase and an advantage is maximum compliance with the final solution. The second disadvantage is greater costs of operation in the two-way traffic during the first phase than in the case of one-way traffic which is due to the lack of the “piston effect”.

However there are no additional works in relation to the final solution that would considerably increase the costs of construction e.g. the construction of the ceiling for the duct in the semi-transverse or transverse ventilation system.

Considering the two-way traffic in the first phase the priority is to ensure the tunnel users’ safety and to permit timely evacuation in case of fire incidents.

In case of tunnel with longitudinal ventilation system such as this one the procedure in case of fire is the following: upon fire detection the ventilation system allows smoke to stick to the tunnel ceiling thus permitting safe evacuation of passengers. The second stage is fire fighting which is carried out after the users have been evacuated from the place of incident.
The proposed phased construction with longitudinal ventilation system and the arrangement of evacuation passages ensures safe and timely evacuation of tunnel users and access to rescue teams and fire brigade to the place of incident.

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POSITIVE PRESSURE VENTILATION: AN EMERGENCY VENTILATION TECHNIQUE FOR HIGHWAY, RAIL, AND SUBWAY TUNNEL FIRES

Juergen Bader, B-I-G Brandschutz-Innovationen, Germany
Leroy B. Coffman III, Tempest Technology Corporation, U.S.A.

ABSTRACT

Positive Pressure Ventilation (PPV) is the use of high-powered blowers to remove the hostile interior environment of an enclosed structure and replace it with fresh, ambient air. Its purpose is to increase safety for fire fighters and rescue personnel, enhance the speed of fire fighting and rescue operations, and lessen property damage caused by smoke, heat, and fire. Over the past four years, PPV has been proven effective for ventilation of highway tunnels, railway tunnels, and subway tunnels. The techniques of PPV are applied with the use of a large diameter (1200-1800mm), truck-mounted blower called a Mobile Ventilation Unit (MVU). Because the MVU is located outside of the tunnel during ventilation operations, it is not subjected to the extreme conditions that exist inside a tunnel during a fire. If a fixed system happens to fail due to prolonged exposure to extreme heat, the MVU is still capable of providing effective ventilation for fire fighters access and rescue.

INTRODUCTION

Positive Pressure Ventilation, or PPV as it is commonly known, is a fire fighting technique that uses air as a tool to control the hostile environment inside an enclosed structure. Small electric and gasoline-powered blowers are used to replace a hostile interior environment with fresh, ambient air. The most common blowers range in size from 460mm to 690mm in diameter and deliver from 11,900 m^3/hr to 40,600 m^3/hr airflow.

PPV was first developed in the United States in the 1960's and was used on a limited basis by progressive fire departments. In the early 1990's, information about the use and applications of PPV became widely available and research was conducted to study the benefits it offered to fire fighters. Today, PPV is an accepted fire fighting technique and is used by fire departments and fire brigades around the world.

Since PPV works on the principle that air flows from high pressure to low pressure, a specially designed fan is used to increase the air pressure inside an enclosed structure. This is achieved by placing the fan on the outside of the structure, blowing inward, so that the cone shaped air pattern created by the fan "seals" an entrance opening and forces air into the structure (*Figure 1*). Once this seal is achieved, the air pressure increases equally at all points inside the structure.

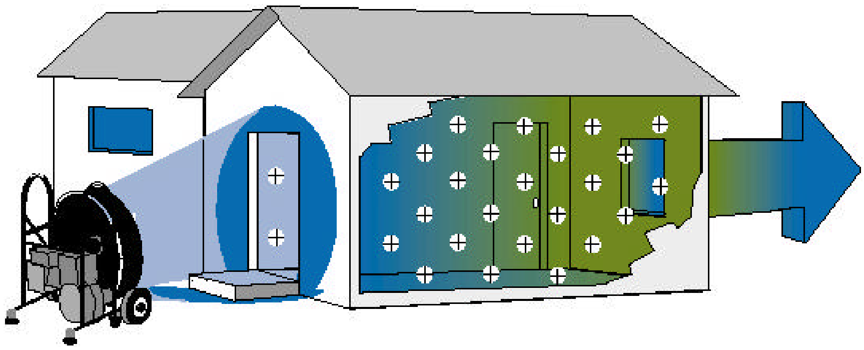

Figure 1. PPV Cone Simulation

To remove the contaminants, an exhaust opening is created near the source of the fire. The exhaust opening releases the air pressure and all of the contaminants are drawn towards this point of low pressure. The smoke, heat, and gases are replaced with fresh, ambient air. Because the positive pressure is equal at all points inside the structure, contaminants are drawn from the ceiling, floor, hallway, attic, and basement.

PPV benefits fire-fighting personnel by creating a safer environment inside an enclosed burning structure. The removal of smoke makes it easier for them to find victims and the location of the fire. The removal of heat allows them to move freely within the structure. Removal of hot gases reduces the possibility of flashover. Ultimately, PPV benefits victims by increasing their chances of survival.

PPV AND LARGE STRUCTURES

Large structures such as high-rise, industrial buildings, and tunnels present unique challenges to fire and rescue personnel. The structures' large size and multiple chambers can make locating a fire and applying water a difficult task. Search and rescue personnel attempting to locate victims are at greater risk because of the time required to get into and out of a large structure.

The physics of PPV can be applied effectively to very large structures using the same techniques and principles applied to smaller structures. The process of sealing an entrance opening and creating an exhaust opening are the same; the fans are simply larger. Mobile ventilation units ranging in size from 1200mm to 1800mm in diameter, which produce from 135,000 m^3/hr to 272,000 m^3/hr air output, are now available and used for larger structures.

PPV AND TUNNEL FIRE FIGHTING

Of all large structure fires, tunnel fires can present the greatest challenges. Heat and smoke can quickly develop to a level that reduces survivability and hampers fire fighting operations. Getting close enough to apply water to a fire can be difficult as the temperature inside the tunnel exceeds that which personal protective equipment can withstand. Finding the location of a fire can be impossible as smoke fills the tunnel from ceiling to floor to completely obscure visibility.

As with other structures, PPV can be effectively applied to ventilate a tunnel during a fire. To achieve an entrance opening seal (as in *Figure 1*), the mobile ventilation unit is placed 20 to 30 meters away from the tunnel portal and elevated so that the fan is located approximately in the center of the tunnel diameter (*Figure 2*). As the air cone expands to match the inside diameter of the tunnel bore, the tunnel becomes sealed. Once the entrance is sealed, the tunnel becomes positively pressurized. As mentioned earlier, the flow is from high pressure to low pressure, which means the smoke, heat, and gases are forced to the opposite, unpressurised end of the tunnel.

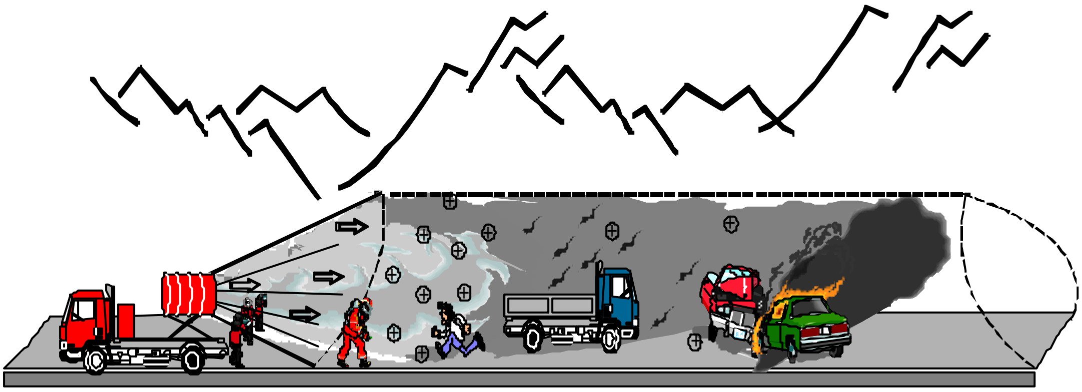

Figure 2, PPV Blower Placement for Tunnel Fire Fighting.

Once ventilation has started, fire and rescue personnel can walk directly to the location of the fire with clear visibility and greatly reduced temperatures (*Figure 3*). The fire can be extinguished quickly and survivors can be rescued. If a situation arises that forces fire and rescue personnel to evacuate the tunnel, they have a clear path of fresh air to follow to safety.

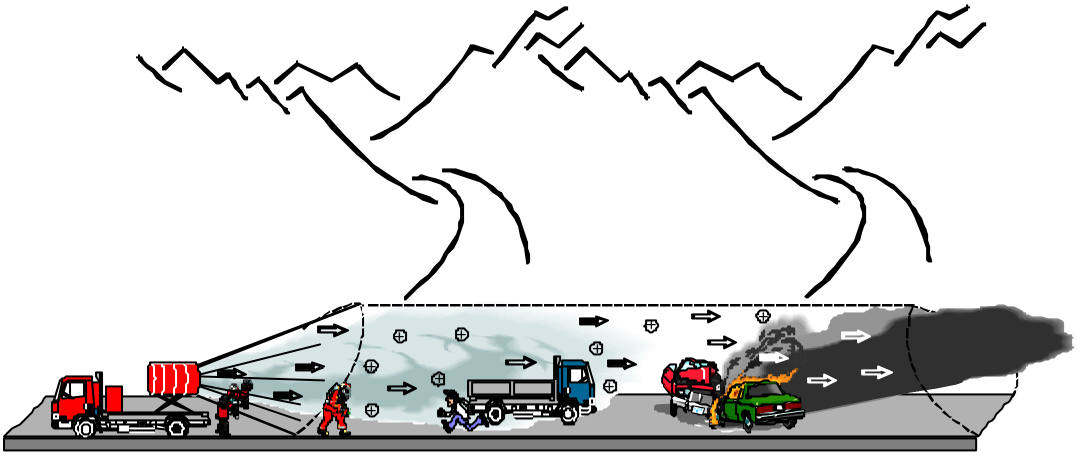

Figure 3, PPV Ventilation During Tunnel Fire

Victims capable of self-rescue can be helped with the application of PPV. The environment inside a tunnel will begin to improve the instant that PPV is applied. Regardless of their location or direction of travel, heat will be reduced, harmful gases will be ventilated, and chances of survival will improve dramatically.

DETERMINING THE DIRECTION OF TUNNEL VENTILATION

Once the decision to use PPV has been made, the direction of ventilation must be determined. In order to have a choice of ventilation directions, response agencies on each end of the tunnel must have access to equipment for PPV or there must be a way to place an MVU at either end of the tunnel. The following issues must be considered:

1. **The approximate location of the fire within the tunnel.**

PPV is most effective when the contaminants travel the shortest possible distance to the exhaust opening. If a fire is located near a tunnel portal, ventilation should be initiated from the opposite end of the tunnel.

2. **The slope of the tunnel.**

Hot smoke in a tunnel with a steep slope will flow towards the higher elevation due to buoyancy. When possible, it is important for fire and rescue personnel to use this to their advantage. In cases where the direction of ventilation must go downhill, against the natural flow of smoke, PPV has the ability to overcome the buoyancy by changing the air pressure within the tunnel.

3. **Wind direction and velocity.**

Strong headwinds can have a negative impact on the effectiveness of PPV. Conversely, a strong tailwind can have a positive impact. It is best to use the wind to an advantage if possible. In the event of a strong cross wind at the entrance opening, the direction of the fan duct must be turned into the wind to compensate for the cross wind.

PPV AS A SUPPLEMENTAL VENTILATION SYSTEM

PPV is not intended to replace jet fans or fixed ventilation systems. It is recommended as an alternative or supplement to current technologies. PPV can be applied in the following situations:

1. **When a tunnel does not have a fixed ventilation system in place.**

There are many tunnels with no emergency ventilation system installed. The technology was either not available at the time that the tunnel was built or it was deemed unnecessary by the people who designed it. When the agencies responsible for protecting these tunnels have access to an MVU, they greatly enhance their ability to manage an incident.

2. **When the fixed ventilation system in a tunnel is not operational.**

Fixed emergency ventilation systems, including jet fans, are designed to withstand the extreme conditions that exist inside a tunnel during a fire. However, there are limitations to the length of time that they will continue to function in the environment. In the event that a fixed system fails due to prolonged exposure to extreme heat, an MVU is capable of providing PPV to the tunnel. The length of time that PPV can be applied is unlimited, as long as the MVU has enough fuel.

3. **To supplement and enhance a fixed ventilation system.**

In some cases, a tunnel emergency ventilation system designed to control exhaust from vehicles may not be effective for controlling heat and smoke from a fire. In these cases, an MVU can be an effective supplement to this system (See Test Data, Example 2, below).

INTRODUCTION OF WATER MIST FOR COOLING

Introducing water to the air stream of a PPV fan unit can enhance the reduction of heat inside a tunnel. By installing a high-pressure misting ring in the middle of the air stream, water mist can be carried in the air to improve cooling. Breaking the water down to a very small droplet size increases the surface area, improving the heat absorption properties of a given amount of water. Water flow averaging only about 275 liters per minute can absorb 20,000 kJ/sec.

TEST DATA, EXAMPLE 1 (Ref. 1)

Habsburgtunnel, Switzerland (1)

Date:	May 14th, 1996
Place:	Habsburgtunnel N3, Effingen-Birrfeld, Switzerland
Length of the tunnel:	1.550 m, approx. 1 mile
Entrance size:	56.435 square meters
MVU Used:	48" (1.25m) MVU with 37.5 m^3/sec. output = ≅ 136.000 m^3/h
Weather:	Partly clouded, temperature 20° Celsius Wind from Southwest. Natural airflow inside the tunnel from the South to the North
Special Problem:	Inside the tunnel the alley warp interconnecting both tubes is not sealed off.
Test No. 1:	Placement of the 48" size MVU on the North entrance. Sealing the portal with the cone of air. After 6 minutes there was an airflow of 2,1 m/s (7 feet per sec.) continuously inside the tube. The elevation from South to North is 40 m.
Test No. 2:	Placement of the 48"-MVU on the south portal for air movement in the opposite direction. After 6 minutes there was an airflow of 2,3 m/sec. /7,6 feet per sec.) continuously.
Total airflow:	Test 1: 406.332 m^3/h (239.018 cfm) Test 2: 467.282 m^3/h /274.870 cfm)

Test Data, Example 1, Conclusion:

This test showed that one 48" (1.25m) MVU is capable of producing an airflow of at least 2.1m/sec in a tunnel over 1.5km in length. This airflow was achieved against a slope of 2.6% with the tunnel that connects both tubes open. The total airflow was 3 times more than the ventilator's performance.

TEST DATA, EXAMPLE 2 (Ref. 2)

Live Fire Training inside the A 8 High-Way-Tunnel Sachseln (CH) 14. May 1997

General situation
With the opening of the A 8 High-Way section Sarnen south - Ewil and the tunnel Sachseln with a length of 5,2 km all rescue services and in particular the fire services will be confronted with new and unpredictable situations. In order to familiarize the members of the Sarnen fire department (voluntary fire services) with the peculiarities of a fire in a road tunnel it was decided to conduct training under live fire conditions.

Objective and purpose of the training
Demonstrating the possibility of a solution to the problem by means of mobile equipment in cases where the capacity of the fixed ventilation system is insufficient or when a full system failure occurs.

Scenario
Frontal collision between a car and a small bus at km 72.200 (approx. 2000 m distant from northern portal). Both of the vehicles instantly burst in flames. No rescue required.

Observations
During phase I, with the fixed ventilation system used for smoke control, visibility was obscured by smoke arising from the fire to such an extent that:

- Approach to the site by vehicles is considered heavily impeded, and if at all possible only at sacrifice of time and by using breathing equipment.
- There appears to be no chance to rescue other persons from vehicles that may also be involved in the collision

During the exercise phase II with the MVU positioned in front of the entrance of the tunnel the following was observed:

- Within a few minutes from starting the MVU, the "effect" was noticed at the site (2000 m distant from MVU location).
- The MVU created an air movement at a velocity of 1.94 m/sec. in the south direction.
- The approach road for vehicles was clear from smoke
- Visibility at the site was fairly good. The fire fighters were able to advance under almost "normal" conditions

Test Data, Example 2, Conclusion:

The test demonstrated the positive impact that PPV can have on fire fighters' ability to locate and extinguish a tunnel fire. With a fire located 2 km from the portal of a tunnel 5.2 km in length, one 48" (1.25 m) MVU was able to effectively control the environment inside a tunnel. Smoke, heat, and gases were instantly ventilated, allowing fire and rescue personnel to approach the fire and apply water in a short period of time. Without the benefits of PPV, it took the fire fighters much longer to find and extinguish the fire and visibility was obscured for over 30 minutes.

PLACEMENT OF A MVU (Ref. 3)

An expert from Paul MicLea's study MVU-CFD Simulation Report shows a computational grid of the airflow area outside of the tunnel which emphasize the position of a Mobile Ventilation Unit.

The discretization of the physical domain was performed using the ICEM-CFD grid generation software [6], which provided hexahedral control volumes. A typical grid is shown in Figure 4.

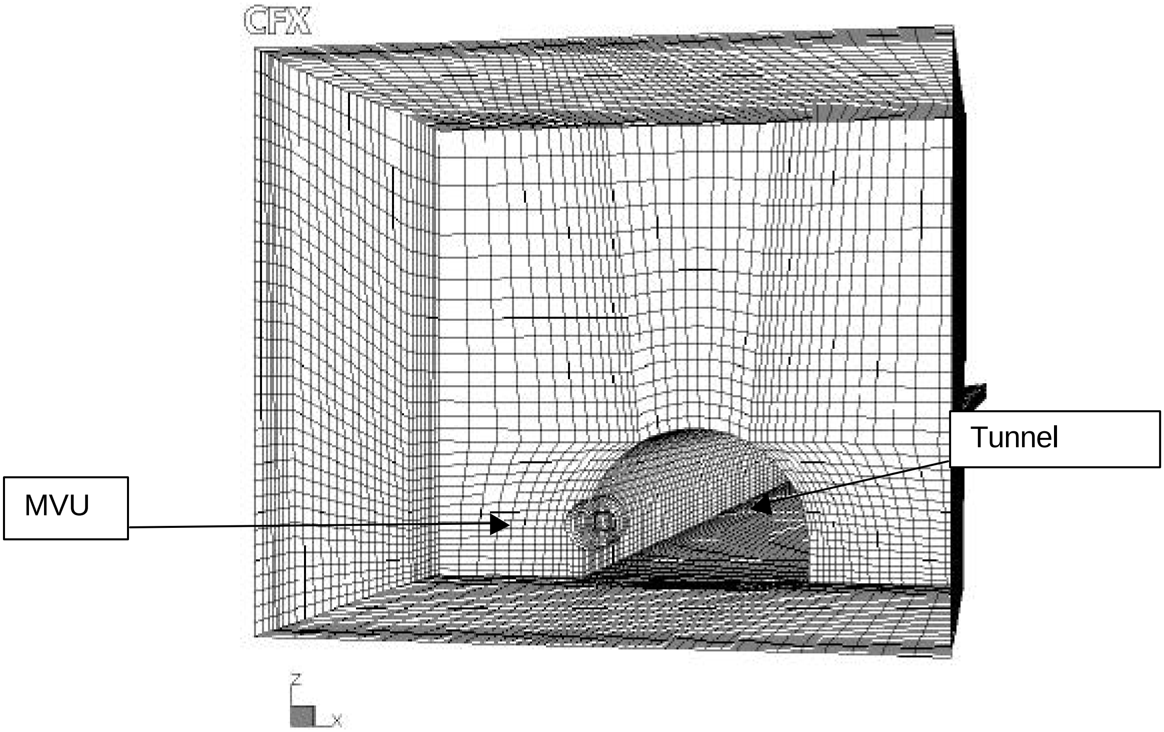

Figure 4. Typical computational grid.

The computational domain included the tunnel plus a rectangular area "outside" the tunnel, within which the MVU is located. The open boundaries of the outside area were set far enough such that their effect on the MVU flow would be minimized. The typical outside area is approximately 36 m (120 feet) wide (x-dimension) by 23 m (75 feet) high (z-dimension) by 20 m (66 feet) long (y-dimension) (Figure 3) using a right-handed Cartesian coordinate system. The far field faces of the outside area were modeled as openings with a linear pressure profile, which decreases with increasing height (z), in order to accurately account for the hydrostatic pressure distribution at these boundaries. Similar pressure boundary conditions were specified at the tunnel exit face. The MVU discharge face was modeled as an inflow boundary with specified mass flow rate. Walls were modeled as no slip boundaries with estimated roughness values of 0.25 cm (0.1 inch). The number of nodes within the computational domain depends on the tunnel length. The total number of nodes ranged from about 110,000 for the short tunnel cases to approximately 380,000 for the longest tunnel.

CONCLUSIONS

1. PPV is a proven ventilation technique that offers clear benefits for fire and rescue personnel when fighting tunnel fires. The main challenges that tunnel fires present are poor visibility and extreme heat. The nature of tunnel construction makes it difficult to overcome both of these. The application of PPV can quickly and effectively reduce heat,
2. improve, visibility, and create a safer environment for fire and rescue personnel. There are also clear benefits to victims.

3. The MVU is an effective tool for applying PPV during tunnel fire fighting operations. Because the MVU is located outside of the tunnel during a fire, it is not subjected to the extreme conditions that exist within the tunnel. Additionally, it is possible to calculate the size and quantity of mobile ventilation units required for specific tunnel to ensure that adequate ventilation is achieved.

4. Further research and testing are required to develop operational and tactical guidelines for fire and rescue personnel to follow. As with any fire fighting tool, training and coordination of personnel are important for safe and effective operations.

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USE OF MOBILE TUNNEL VENTILATION DEVICES TO ASSIST EMERGENCY SERVICES DURING FIRES IN UNDERGROUND ROAD SYSTEMS

Stefan Hofbauer, Hubert Heissl
Rosenbauer International AG, Paschinger Str. 96, A-4060 Leonding, Austria

ABSTRACT

Constantly rising volumes of traffic mean that the risk of accidents on open roads and in tunnels is also steadily on the increase. The danger of vehicles catching fire in underground road systems is exacerbated by the fact that the smoke and toxic gases emitted soon reach dangerous levels. This often prevents emergency services from reaching the scene of the accident fast enough to rescue people and fight the fire, and also hampers them during clean-up operations. Mobile ventilation devices can be of considerable assistance to the emergency services by affecting the natural air currents in the desired way or boosting the capacity of the stationary ventilation systems in place.

Having evaluated the operational conditions required, mobile tunnel fans were designed and their efficiency validated using CFD calculations. In many field tests, some under emergency conditions, the results of the theoretical considerations were examined and the handling checked. It was therefore proved that if these ventilation devices are taken into consideration in operation procedures, they can be a great help to the emergency services and enable them to reach the scene of the accident much faster.

Key words: tunnel safety, fire, positive pressure ventilation, PPV, fan, mobile

1 CURRENT SITUATION

The volume of traffic in Europe has risen dramatically over the past few decades and in view of the current situation with globalisation, EU enlargement to the east and the expiry of existing transit agreements, it would appear that it will continue to rise, above all national and transnational freight traffic. Although the EU Commission is committed to stepping up rail transport, the majority of passenger and freight traffic will also go by road in the future.

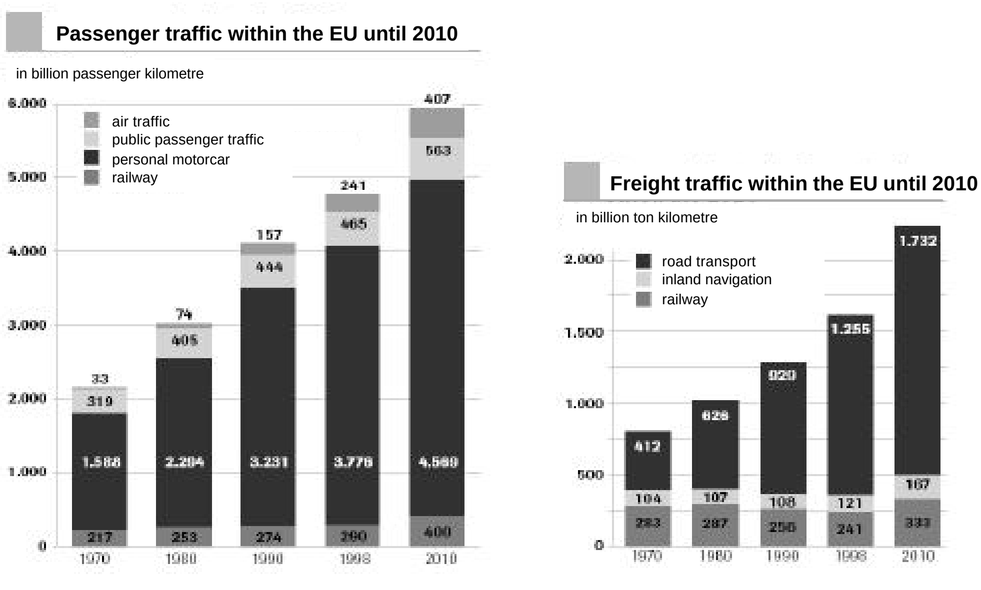

Fig. 1: Traffic volume in Europe [VDA 2001]

At the same time the percentage of underground traffic routes is growing. In Alpine regions, such as Austria, Switzerland and Italy, tunnels are often the only possible or at least the shortest link, while in less mountainous countries, such as Germany, they are usually built for reasons of noise abatement (city bypasses). Of the 250km of road tunnels in Austria, around 190km are in the main road network (motorways and dual carriageways). As the main network is approx. 2000km in length, the tunnels represent roughly ten per cent of the total [OEAMTC]. The percentage is equally high in Switzerland where there are 170 tunnel kilometres out of a total of 1640 motorway kilometres. Switzerland is currently planning on building a further 218 motorway kilometres, 110 of which will be underground, thus raising the tunnel share to 15 per cent over the next few years [ASTRA 2000]. Table 1 and Fig. 1 show the Austrian motorway and dual carriageway tunnels broken down into groups in lengths of under 1km, 1 to 5km, 5 to 10km and over 10km.

Table 1: Tunnels in Austria

Lenght [km]	One-way traffic		Two-way traffic		Total		
	Number	Total lenght [km]	Number	Total lenght [km]	Number	Total lenght [km]	
< 1 km	4	2	99	68	103	70	37%
1 to 5 km	8	17	16	32	24	49	26%
5 to 10 km	8	55	0	0	8	55	29%
> 10 km	1	14	0	0	1	14	8%
	21	**88**	**115**	**101**	**136**	**188**	

By far the largest number of tunnels is to be found in the group under 1km long. Even if the kilometres of the individual groups are added together, almost two thirds are still in tunnels less than 5km long. The majority of these sections are two bore, i.e. each with one-way traffic. The groups longer than 5km represent the typical Alpine tunnels. They are generally single bore, but some of them will be upgraded to two bores for reasons of safety and capacity.

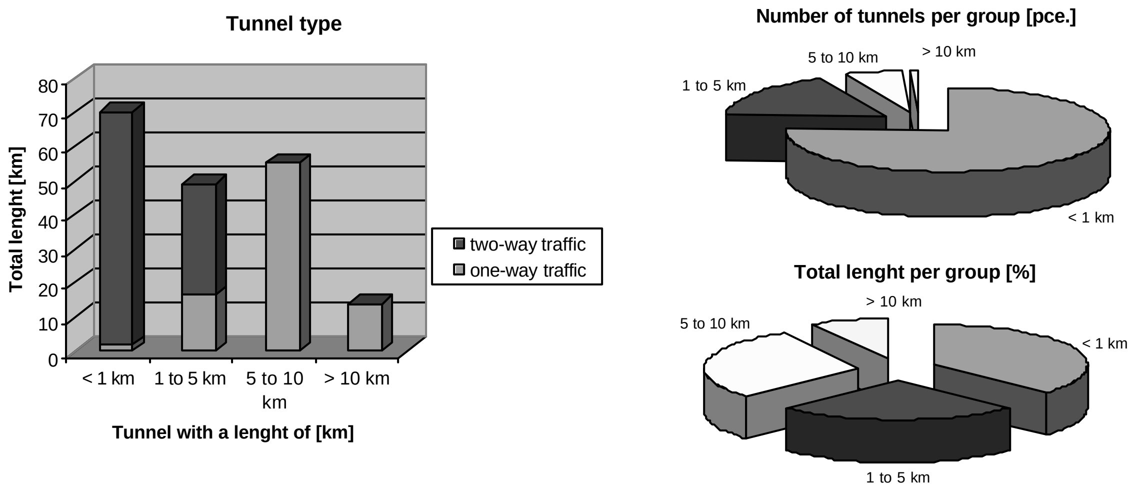

Fig. 2: Tunnels in Austria

If the tunnels in the federal and provincial roads are included in these figures, the focus is still on shorter tunnels to an even greater extent.

In the tunnels various types of stationary ventilation systems are used [Pucher 1999].

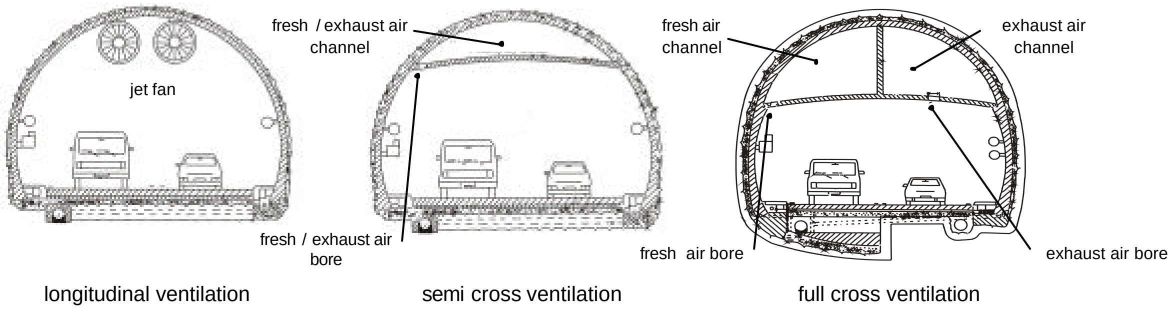

Fig. 3: Ventilation designs

Longitudinal ventilation: primarily used in tunnels up to 3km long. The air is replaced by axial flow in the tunnel that is either caused by the thrust from the vehicles (one-way traffic) or assisted by high volume fans.

Semi-cross ventilation
Extract air: the supply air is sucked in through the tunnel mouths, and the extract air removed through a separate duct and blown outside.
Fresh air: fresh air is blown into the tunnel through a duct, and the extract air dissipates through the tunnel mouths.

Full cross ventilation: fresh air and extract air are moved in and out of the tunnel through separate ducts. This ventilation design does not therefore require axial flow in the tunnel.

2 FIRES IN UNDERGROUND TRAFFIC SYSTEMS

Road accidents in tunnels are particularly critical situations. In statistical terms, the probability of having an accident in underground sections is less than on the open road. If however the risk is examined as the product of accident probability x accident consequences, it soon becomes clear why safety in tunnels has become such an issue [Knoflacher]. When a vehicle in a tunnel catches fire and cannot be kept under control, the consequences can prove catastrophic, as many examples in the past have shown. In addition to the injuries sustained by the people involved, there is the damage to the tunnel itself and the costs of closure.

The greatest problem in the case of fires in tunnels is definitely the enormous heat and smoke that develops and often cannot be expelled properly. If a fire gets out of hand, the only way people can save their lives is to try and escape. An additional danger lies in the fact that the smoke initially forms layers, i.e. the fumes rise up to the roof and the fresh air remains near the ground. The people are lulled into a false sense of security while the toxic gases spread above their heads. After a few minutes, however, the layers start to mix and the people are trapped in the middle of asphyxiating smoke.

Smoke and heat are also what prevent the emergency services from reaching the scene of an accident quickly. Conventional compressed air devices (twin packs) are designed for 30 to 45 minutes maximum. If the services have to proceed on foot, it does not give them much time to rescue the people and fight the fire. Fire brigades at the tunnel mouth are therefore equipped with breathing apparatus that permits longer periods in action. In addition, the smoke obstructs vision, reducing the speed of advance and making it virtually impossible to find the injured (without heat image cameras). Finally, heat that cannot be dissipated also prevents services from reaching the scene of the accident or spending longer time in the tunnel [Vries 2002].

These scenarios show how important smoke-free escape and access routes are in the case of tunnel fires. Extraction dampers that suck out high concentrations of fumes are definitely useful both for protecting the people affected and also for assisting the emergency services on the spot [Lucas 2001]. In Austria for example planning specifications RVS 9.261 require such extraction dampers for ventilation systems in tunnels with cross ventilation, and they are currently being retrofitted in a number of road tunnels [BMVIT 2001], [BMVIT 2002], [OEAMTC], [OESAG]. As discussed above using Austria as an example, the majority of underground traffic systems are shorter than 5km, and have simple axial flow systems at the most. It is not therefore to be expected that these tunnels will be equipped with full cross ventilation and extraction dampers in the foreseeable future. The next section shows that the positive pressure ventilation (PPV) principle represents a sensible option, especially in such cases.

3 PRINCIPLE OF POSITIVE PRESSURE VENTILATION – USE IN TUNNELS

Fire brigades have successfully been applying the principle of PPV for fighting fires in enclosed spaces for many years. It is based on the fact that air in higher pressure environments escapes to areas of lower pressure. The pressure is built up by fans sited in front of the door ensuring that the air cone completely covers the opening. At the same time air outlets are made through which the smoke and heat can escape. This creates a flow, and the fire fighters can work with the "wind" in their backs.

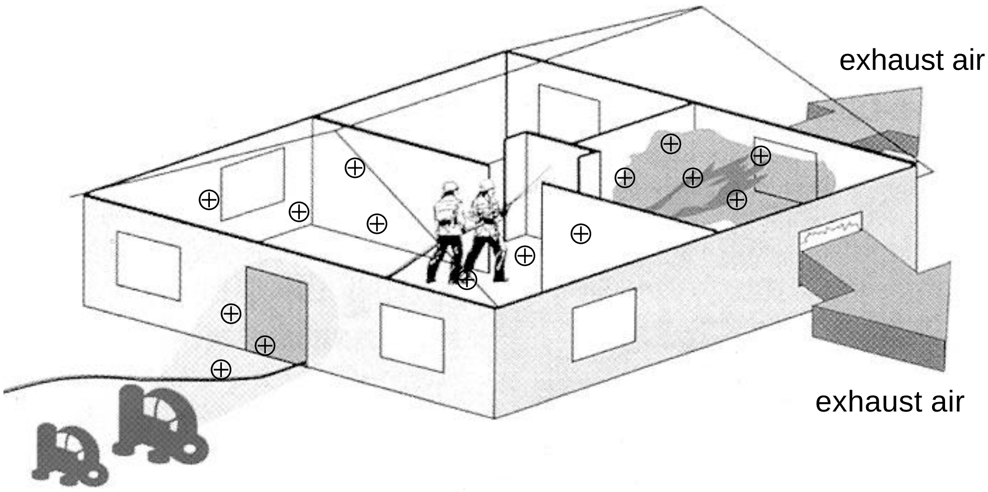

Fig. 4: Principle of positive pressure ventilation

Traffic tunnels are enclosed spaces with openings at the mouths and, in the case of cross ventilation, also at the fresh and extract air dampers. The positive pressure fans are placed in front of the tunnel mouth, ensuring that the air stream seals the opening completely. This enables the pressure to build up inside the tunnel. The air can either escape through the mouth at the other end or through the extract bore.

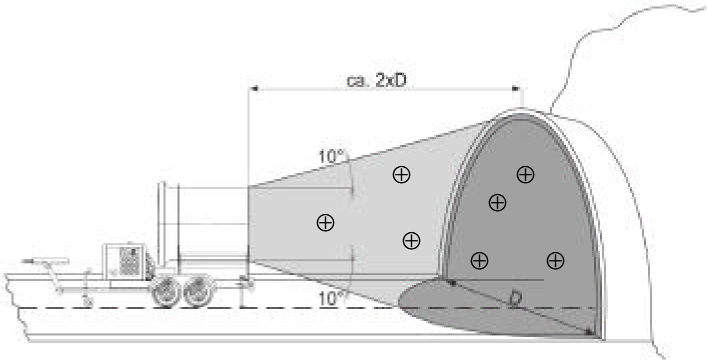

Fig. 5: Location of a mobile positive pressure fan

3.1 One-way traffic tunnel without stationary ventilation or with longitudinal ventilation

As mentioned above, the majority of Austrian motorway tunnels are under 1km in length. These tunnels are almost all operated with one-way traffic, and are generally equipped with longitudinal ventilation systems. In the group up to 5km there are also many tunnels with one-way traffic and longitudinal ventilation. When the stationary ventilation systems are not adequately dimensioned for larger fires or there are not any stationary systems in place, axial flow can be generated, existing natural currents increased or even reversed with the help of positive pressure fans. This keeps the area in front of the accident smoke-free where the people involved and those following are located, and from where the emergency services arrive.

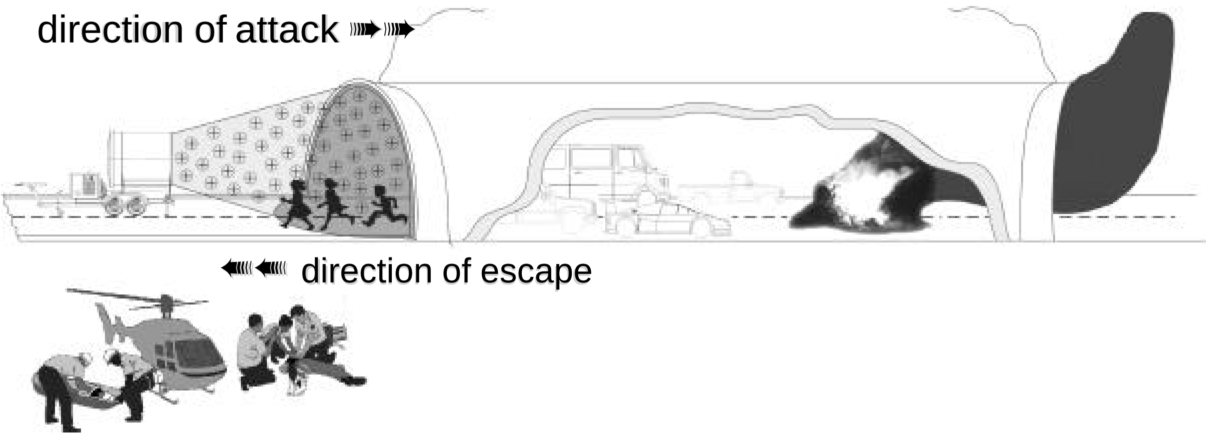

Fig. 6: Tunnel with one-way traffic

3.2 Two-way tunnel without stationary ventilation or with longitudinal ventilation

If a tunnel is operated with two-way traffic, great care has to be taken when generating axial flow. Those responsible have to ensure that nobody is behind the accident, as they would be put at risk from the gases and heat set in motion. Only once they have established that the area is clear can the positive pressure fans be used to assist the firefighting and clean-up work.

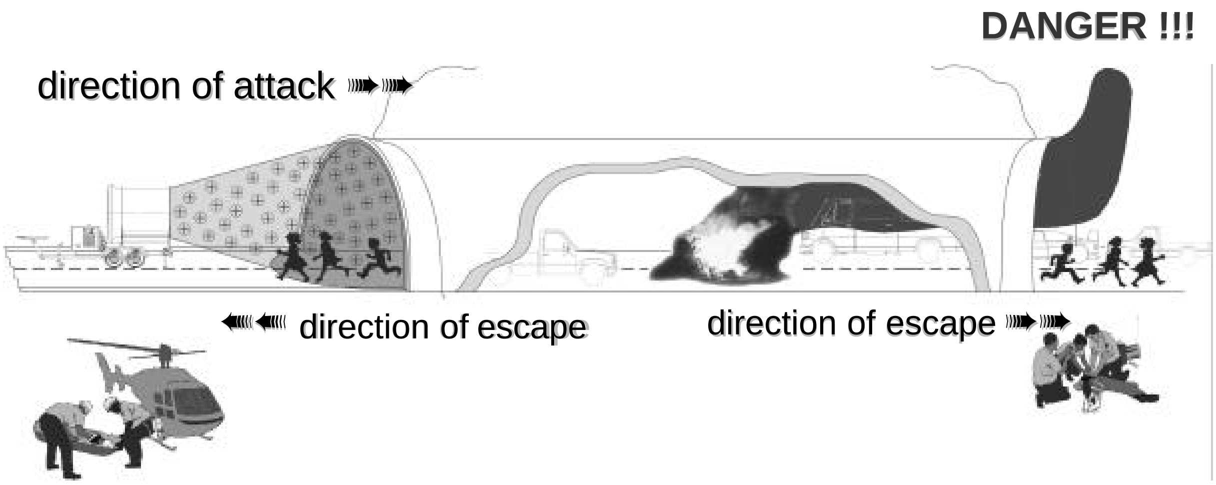

Fig. 7: Tunnel with two-way traffic

3.3 Tunnel with cross ventilation

In tunnels with cross ventilation the smoke primarily has to be extracted at the scene of the accident. To achieve this, the axial flow in the tunnel has to be less than 1.5m/s. Mobile fans can be used in such cases to halt natural axial currents. Natural axial flow can for example occur due to weather conditions or the chimney effect. In addition, mobile positive pressure fans can be used at both tunnel mouths to boost the stationary ventilation system's extraction capacity.

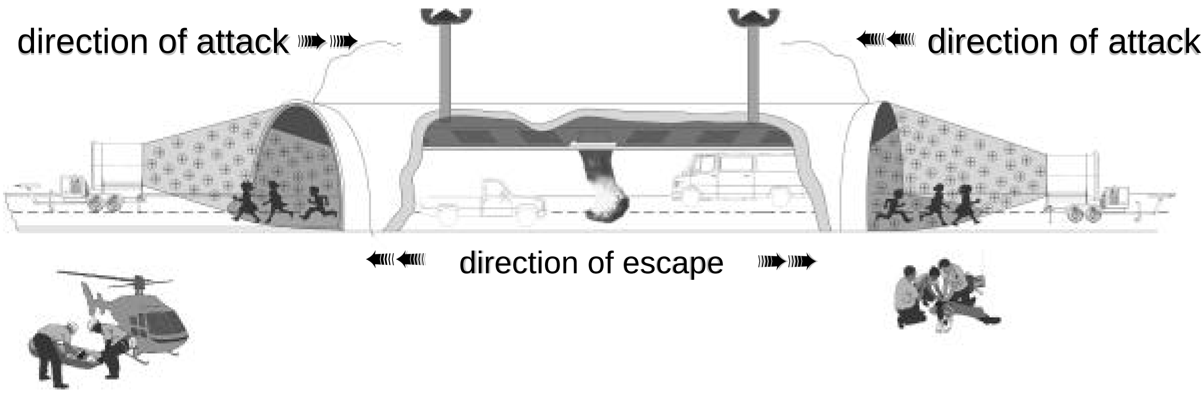

Fig. 8: Tunnel with two-way traffic and cross ventilation

4 MOBILE TUNNEL FANS: THEORETICAL DESIGN AND PRACTICAL TESTS

The aim of using positive pressure fans is to build up, stop or reverse axial flow in the tunnel. To obtain a detailed picture of the flow characteristics, computational fluid dynamics (CFD) simulations were carried out in cooperation with the Institute of Internal Combustion Engines and Thermodynamics at Graz Technical University. The spread of heat and fumes in a fire in a tunnel without a stationary ventilation system was examined, as well as the effect of PPV on the flow characteristics in the tunnel.

An extract of the calculation results is shown below:

Tunnel			
Tunnel length	1,500m	Cross section	50m²
Fire			
Capacity	20MW (lorry)	Distance from fan	1,000m
Initial conditions			
Natural flow	1m/s	No stationary ventilation	
Fan			
Thrust	2,500N	Velocity	37m/s

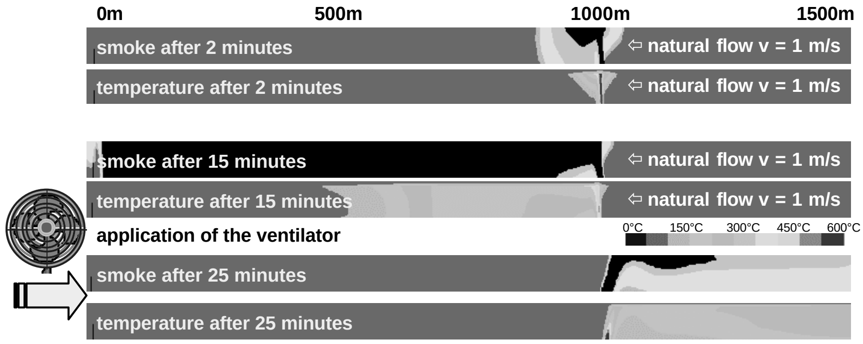

Fig. 9: CFD simulation of a tunnel fire [Pischinger 2000]

Due to the natural currents, the entire tunnel was filled with smoke from the mouth to the scene of the accident after 15 minutes. The fan was then started. After another ten minutes the natural flow was successfully reversed and both the smoke and the heat expelled through the mouth at the other end of the tunnel.

These simulations served as the basis for the fan design. In addition, various factors had to be observed, such as maximum fan diameter to ensure that the fan could be transported and would comply with the highway code. The fan also has to be manoeuvrable to enable it to be positioned in front of the tunnel mouth without obstructing entry and exit to any great extent. Finally, the fan also has to be fundable, i.e. all the components, such as drive (internal combustion motor), blower, and power transmission have to be utilised to the full in terms of efficiency, weight, space requirements and cost-benefit ratio. Extensive practical trials proved the theoretical findings and the capability of the fans even in hot fire tests [Sturm 2001], [Knittel 2000], [Oberhollenzer 2001].

Table 2 and Fig. 10 show examples of firefighting exercises where mobile fans were used to support the emergency services.

Table 2: Practical testing of the tunnel fans

Ventilator	Total thrust [N]	Country	Tunnel	Lenght [m]	Stationary ventilation konzept	Stationary ventilation in use JES / NO	Natural flow	Ventilation with / toward natural flow	Flow velocity with ventilator
TL2500	2500	Österreich	Selzthal	1000	none	NO	0,5	toward	4
2 * TL2500	5000	Österreich	BöcksteinTauerntunnel	9400	none	NO	0	-	1
TL 1000	1000	Italien	Ultental	1700	none	NO	1	toward	1,5
TL2500	2500	Italien	Franzensfeste	750	longitudinal	NO	0,5	with	3,75
TL 2500	2500	Österreich	Ambergtunnel	3000	cross	NO	0,5	with	3

Fig. 10: Firefighting exercise in Southern Tyrol [Oberhollenzer 2001]

During all the exercises the fire brigade approach route was kept smoke free, which greatly facilitated the emergency services' work. In addition, it is extremely reassuring for the people involved when the escape route remains "open".

5 ONE-DIMENSIONAL CALCULATION FOR ESTIMATING FAN EFFICIENCY

When simulating emergency situations in particular, it is vital to be able to predict the effect of a tunnel fan in advance. In addition to the extensive CFD simulations, a program was therefore developed together with the Institute of Internal Combustion Engines and Thermodynamics for quickly estimating the flow characteristics. It is based on a one-dimensional consideration of the stationary flow, taking the following into account

- power input (fan thrust),
- force due to the pressure differentials at the mouths (weather),
- buoyant forces due to the difference in temperature inside and outside the tunnel (if there is a slope in the tunnel),
- forces due to buoyancy in the event of a fire,
- wall friction and resistance forces due to vehicles in the tunnel [Pischinger 2002].

The program is very easy to use thanks to simple parameter input, and the extremely short calculation times enable online evaluation of the results. Fig. 11 shows the dialog box for the parameters and Fig. 12 the results of the relevant calculations.

In the diagram the flow velocities are shown in relation to the pressure difference between the two tunnel mouths. The broken line corresponds to the natural currents from the prevailing weather conditions and the grey highlighted area up to the continuous line shows the extent to which the natural flow can be affected by the use of fans. For example, if there is no natural flow in the tunnel, the fan can achieve a maximum wind velocity of nearly 5m/s. If the weather conditions cause air turbulence in the tunnel of 3.75m/s, the fan can reverse the flow maintaining the strength, but moving it in the opposite direction.

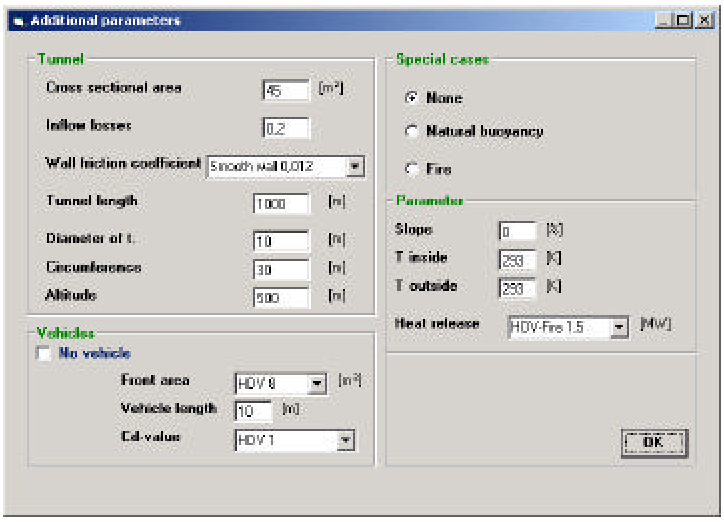

Fig. 11: Dialog box

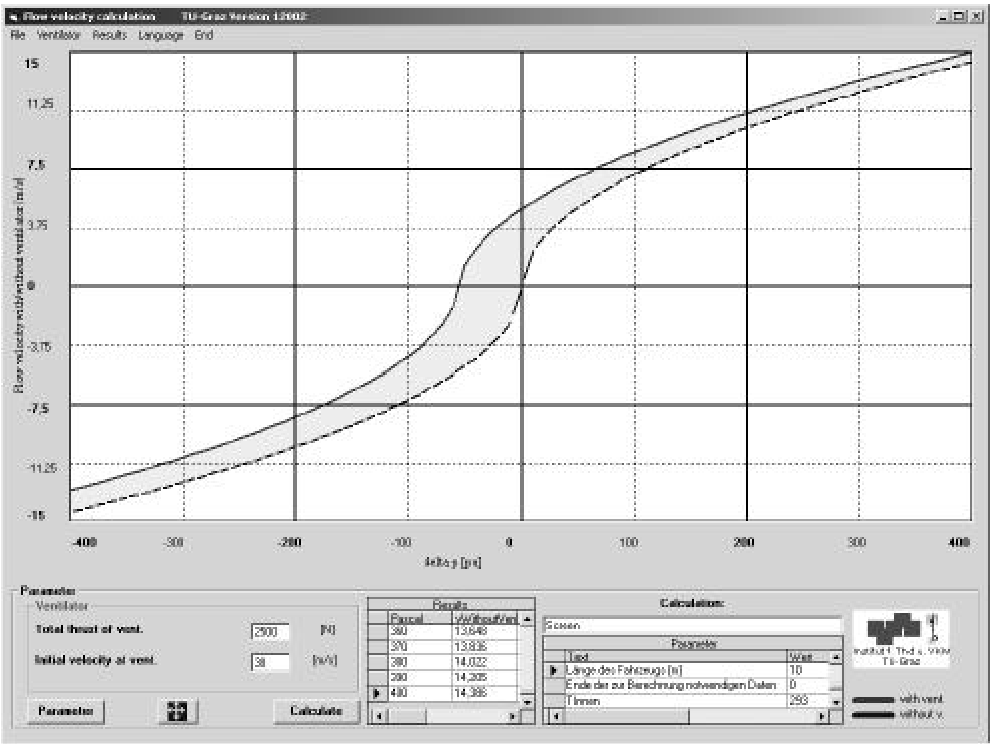

Fig. 12: One-dimensional calculation of the flow characteristics

6 SUMMARY

Unless counteractive steps are taken, the risk of accidents in tunnels with serious consequences will continue to rise in future firstly due to the steady increase in traffic volume, and secondly due to the constantly growing percentage of underground road sections.

A critical factor for improving the situation of all the people involved in an accident is dispelling the heat and smoke. One option is certainly to upgrade the stationary ventilation systems. There are however large numbers of shorter tunnels that cannot be equipped with full cross ventilation and extraction dampers in the foreseeable future. Positive pressure ventilation can constitute a rational supplement to the stationary systems for this group in particular, especially when the tunnel is for one-way traffic. Controlling the airflow conditions substantially improves the situation both for the people escaping, and also for the approaching emergency services.

Calculations and field tests have shown that mobile fans can generate, increase, or even reverse the airflow. Use under realistic conditions during fire fighting exercises has also proved their capability and importance for the emergency services.

To ensure successful use, it is imperative to draw up plans of action for various scenarios. Here the calculations and estimates of fan capacity are a valuable complement to the exercises.

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VERY LARGE VARIABLE PITCH AXIAL FANS FOR ROAD TUNNEL VENTILATION

Helmut Bronowski
Voith-Howden GmbH
Stubentalstraße 44
D 89518 Heidenheim
Germany

ABSTRACT

The paper presents a short technical description, useful information, drawings and photographs of (according to our knowledge) physically the largest variable pitch axial tunnel ventilation fans in the world.

1. INTRODUCTION

The new Motorway Tarsus – Adanaa – Gaziantep (TAG) in the republic of Turkey includes four tunnels. The largest tunnel P 3 with a length of 2860 m consists of two separate tunnel tubes with 3 lanes each for unidirectional traffic. Booth tubes have a combined ventilation system with jet fans and large axial fans located in a ventilation station for each tube. The ventilation station for the south tunnel tube (ST) is situated on top of the tunnel. The ventilation station for the north tunnel tube (NT) is situated sidewise of the tunnel on the mountain.

2. VENTILATION STATIONS

Each ventilation station for the North and the South tube is a separate building and has basically the following aerodynamic equipment: One fan motor unit (VMU) for fresh air supply, one fan motor unit (VMU) for exhaust air, each unit is equipped with an intake transition peace, a diffuser and a large damper to close the air duct. Each fan is equipped with a motor cooling fan and a hydraulic unit for blade pitch control.
The electrical equipment, transformers and control cabinets are also located near the VMU's in the same building.

3. VENTIALTOR MOTOR UNIT (VMU)

The VMU consists of a steel welded housing with the drive motor mounted in the fan hub. The three-phase asynchronous motor has 2 rotational speeds. The impeller is directly mounted on the motor shaft and has hydraulically adjustable blades.
The VMU's for exhaust air are designed to withstand an emergency ventilation case at a temperature of 250°C for one hour and for a further hour at 100 °C. An other precaution for high temperature operation at large fans against blade rubbing at the fan housing due to different thermal expansion coefficients for aluminum and steel are wearing tips at the impeller blade tips.

4. TECHNICAL DATA

The main data are summarized in the following table.

Ventilator		NT1	NT2	ST1	ST2
Function		Exhaust	Supply	Exhaust	Supply
Impeller Diameter	[mm]	5300	5300	6300	6300
Hub Diameter	[mm]	2000	2000	2000	2000
Max. Volume Flow	[m³/s]	590	590	870	1050
Fan speed	[RPM]	295/147	295/147	295/147	295/147
Motor Power	[KW]	200	200	370	660

5. ATTACHMENTS

Fig. 1 Drawing of the VMU ST1
Fig. 2 NT2 Supply fan
Fig. 3 NT2 Supply fan during aerodynamic measurements
Fig. 4 NT Building supply air intake
Fig. 5 ST2 Supply fan
Fig. 6 ST2 Fan after erection
Fig. 7 ST1 Exhaust fan during commissioning
Fig. 8 ST2 Damper
Fig. 9 ST Building

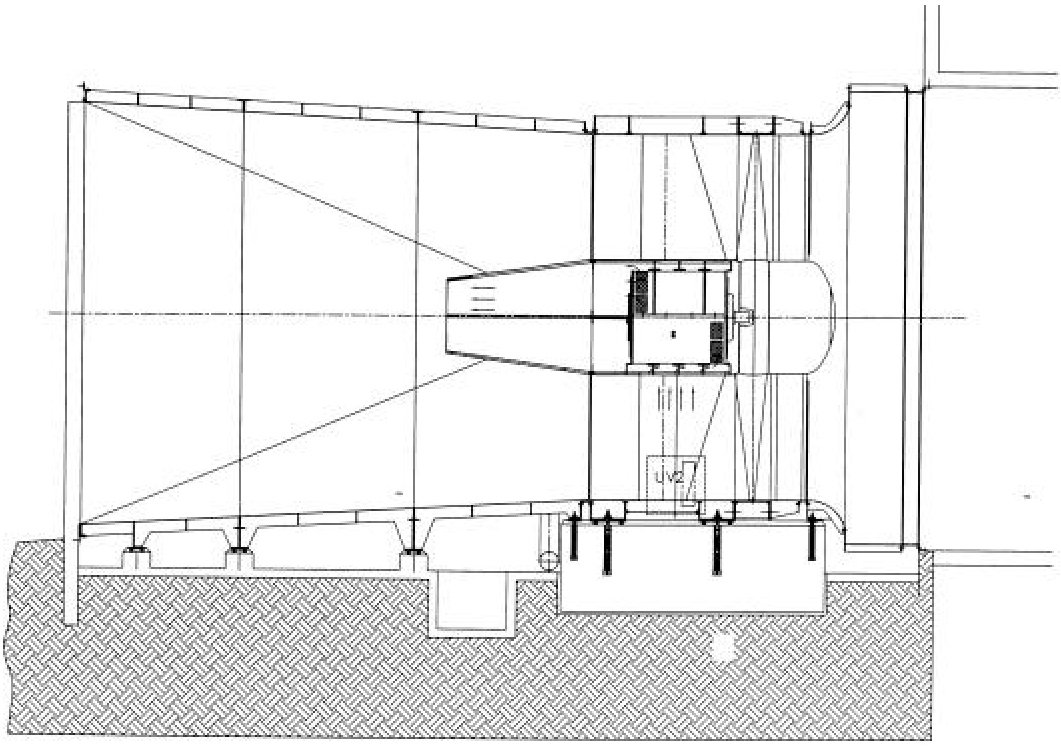

Fig. 1 Drawing of the VMU ST1

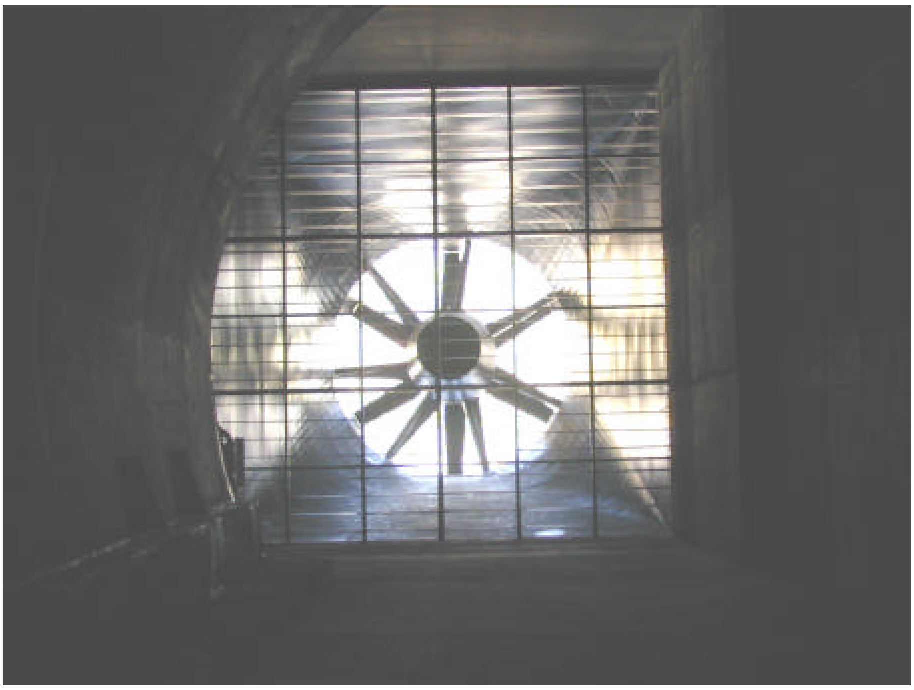

Fig. 2 NT2 Supply fan

Fig. 3 NT2 Supply fan during acceptance tests

Fig. 4 NT Building supply air intake

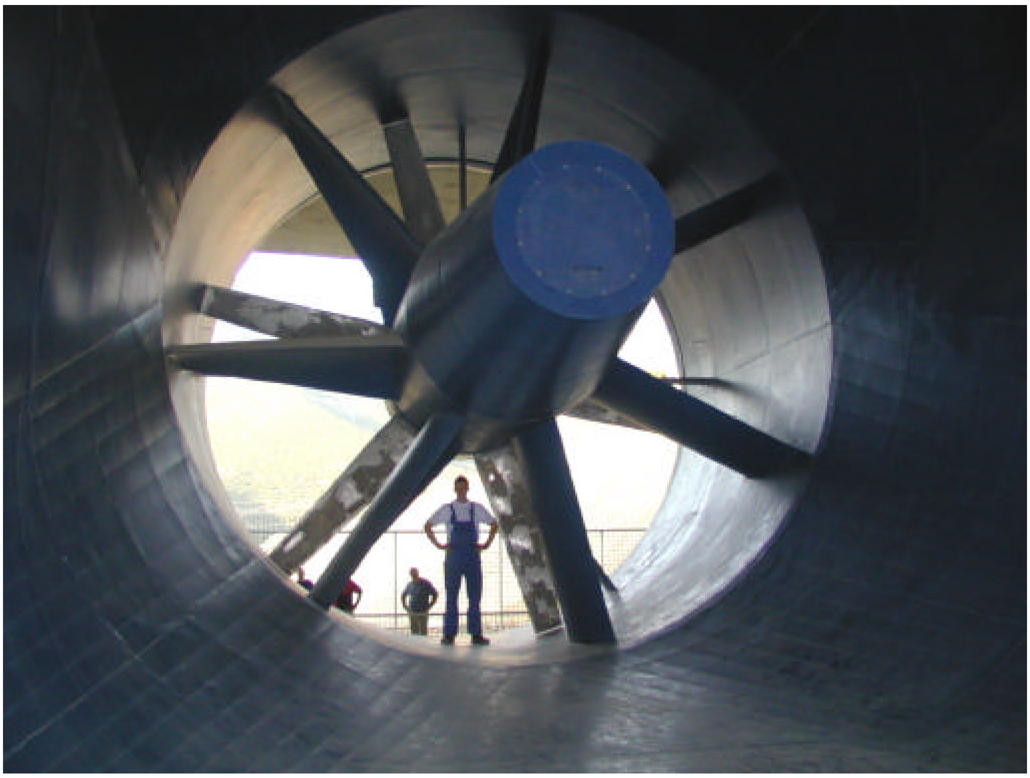

Fig. 5 ST2 Supply fan

Fig. 6 ST2 Fan after erection

Fig. 7 ST2 Exhaust fan during commissioning

Fig. 8 Damper for ST2 fan

Fig. 9 ST Building

DEVELOPMENTS AND MODIFICATIONS OF TUNNEL VENTILATION FANS FOR EXHAUSTING HIGH TEMPERATURE GAS DURING A FIRE EMERGENCY

Wolfgang Müller, Thomas Neff
Turbo Lufttechnik GmbH (TLT), Gleiwitzstraße 7, 66482 Zweibrücken, Germany

ABSTRACT

A study of the operating performance of TLT axial flow tunnel ventilation fans in regards to meeting the requirement of RVS 9.261 for operating in the case of a fire emergency for 60 or 90 minutes at a temperature of 400 °C.
Also a presentation of experiences and results of a thermal finite element calculation of the essential fan components.

1 HISTORY OF EXHAUST AIR SYSTEMS

The devastating tunnel fires of the recent past demonstrate the need to improve tunnel safety systems. TLT has designed, engineered, and supplied complete tunnel ventilation systems for many years, including many systems installed in Austria. Our experience with these systems has provided us with the opportunity to study the problems of controlling the exhaust gas and smoke of tunnel fires in both new and existing facilities as well as the change in the tunnel temperature following a fire emergency. The investigation reports of tunnel fires and fire tests have shown that the main cause of death in previous tunnel fires wasn't temperature but rather the inhalation of smoke that asphyxiated the people. In addition, considerable time was required for the temperature in the tunnel to reach a level low enough to allow emergency personnel to enter the tunnel.

In the past smoke and hot gas was exhausted through relatively small openings in the tunnel ceiling covered with either louvers or dampers. These louvers or dampers were opened either thermally or electrically in the area of or near the area of the fire. The ventilation equipment installed in this type of system was required to operate for 60 minutes at a temperature of 250 °C. The temperature rating of 250 °C was determined considering the effect of mixing the hot gas with relatively cool air drawn into the system further away from the fire. Exhausting hot gas with such a system has proven inadequate.

According to the current guidelines in Austria RVS 9.261 the tunnel ceiling openings must be much larger and are to be installed with damper systems. The openings are spaced along the tunnel length in order to be opened very close to the fire source to quickly remove the life-threatening smoke with a maximum volume. If the source of the fire is in close proximity of the exhaust fans, very high temperatures will occur at the exhaust fans because there will be little mixture of cooler air with the hot gas from the fire. Such a fire situation requires the fan design to take into consideration operation for a period of 60 or 90 minutes at a temperature of 400 °C. The requirement is defined in the Austrian RVS 9.261 (Guidelines and prescriptions for street construction) as 400 °C / 60 minutes and the German RABT (Guidelines for the equipment and operation of traffic tunnels) as 400 °C / 90 minutes.

2 TERMS OF REFERENCE OF THE STUDY

In the case of traffic tunnels with openings covered with louvers or dampers the axial flow exhaust fans are normally equipped with impeller blade modulation during operation or automatic speed control with impeller blade modulation during standstill. The fans are selected to meet the ventilation requirements according to the characteristics of the system resistance.

The experience acquired from tunnel fires present the manufacturer of tunnel ventilation systems installed according to the previous standards with the following key questions:

1 Which materials meet the higher temperature requirements ?
2 Which types of motor construction can be used in the fan-motor-unit ?
3 What kind of installation and construction measures must be considered in order to control the additional strains caused by the higher design temperature requirements ?
4 How can the entire system be optimized through an integration of fans and exhaust air dampers ?

Our paper will concentrate on points 1 and 2. TLT has prepared a study investigating the effects on the rotating impeller mechanism while operating at the required elevated temperature. The mechanism, a technically challenging design at normal temperatures, presents additional technical considerations at 400 °C.

The study addresses the following:

- Short-time operation for 90 minutes at a maximum of 400 °C in new or existing facilities
- Long-time operation for 48 hours after a fire emergency. The time duration is the estimated length of time required for the temperature in the tunnel to reach a level low enough to allow emergency personnel to enter the tunnel.

The objective of the investigation is the verification by Finite-Element-Method of the design of axial flow ventilation fans, with impeller blade modulation during operation, exposed to increased temperatures in the event of a tunnel fire. Hot combustion gas at 400 °C is considered to be present for 60 and 90 minutes. The results can be compared with the findings of fire tests for installed fans (conducted by independent institutes).

The fire test results and Finite-Element-Method calculation reach the same conclusions.

Our study considers the stresses that occur at maximum rotational speed. The investigation includes how the dynamic heat transfer within the fan components takes place, the temperature distribution, as well as the stress distribution. Time periods are after 5 minutes, 90 minutes and 48 hours (long time operation after a fire emergency).

3 FINITE-ELEMENT-METHOD-CALCULATION

3.1 Mathematical model

For the calculation, the Finite-Element-Method (FEM) is employed by using the program system MSC/ NASTRAN. It is based on the assumption of linear geometry and material behavior. The results provide the basis for determining the correct choice of material for new facilities and what must be considered to up-grade existing exhaust fans for operation at 400 °C.

For the FEM mathematical model, the impeller of an axial flow tunnel ventilation fan with blade modulation during operation is modeled (figure 1). Exhaust fans with similar impeller designs are installed in several existing ventilation systems e.g. in the Arlberg-, Bosruck-, Gleinalm-, Tauern-, Felbertauern- and Katschberg-tunnels.

The symmetrical sector selected reflects the essential elements of the impeller design. The impeller blade of the axial fan is depicted simplistically in the geometry (flat plate), but with the correct dimensions and surface area. The details of the contact surfaces in the area of the blade shaft bearing are exactly as designed. Here the sliding socket on the hub jacket, as well as the balls of the axial deep-groove ball bearing are to be designated with their contact surfaces to the adjacent parts. The mathematical network is constructed from 8 nodal hexaeder elements. Only the stiffeners in the impeller are replicated with shell elements. The inside system border is formed by the shaft of the drive motor of the fan-motor-unit (figure 2).

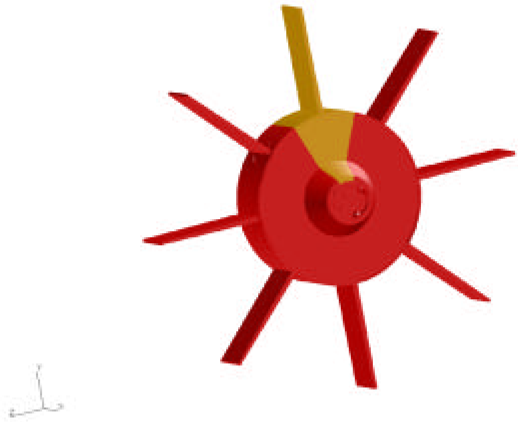

figure 1: FEM-model overview

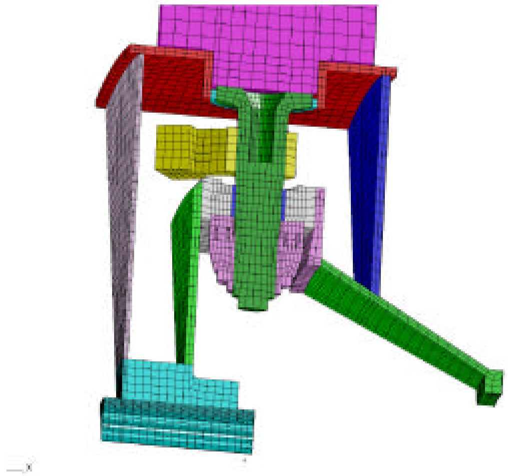

figure 2: FEM net

3.2 Assumptions and boundary conditions

Our FEM calculations are based upon the following assumptions and boundary conditions:

The model is fixed in all directions within the area of the motor shaft. Beside the definition of the thermal boundary conditions for the calculation of the transient temperature field the centrifugal force is considered as a load case corresponding to a blade tip speed of 164 m s-1. The study is based on the assumption of linear thermal conduction. The material characteristic values are accepted as constant for the considered temperature range.
With the known formulas of thermodynamics for fan blades in the hot gas stream, the heat transmission co-efficient α = 325 W m-2 K-1 for the turbulent flow is obtained from the relative inflow velocity of the blade vane at the maximal operating point. For such surfaces, which are in direct contact with the hot combustion gases (blade and impeller outer jacket), this heat transmission co-efficient is used for the temperature field calculation (forced convection). The temperature of the hot combustion gas is a constant 400 °C. The surface of the impeller side panels are cooled by the flow of outside air at a constant temperature of 40 °C (figure 3). The starting temperature of the entire structure is 40 °C at the point in time t = 0 s. The surfaces in the inside of the structure are expected as adiabatic. This means that the influence of radiant heat transfer between individual components is not considered in the analysis. This simplification is appropriate because the impeller jacket includes insulation installed inside the impeller, which shields the components from the hot surface.

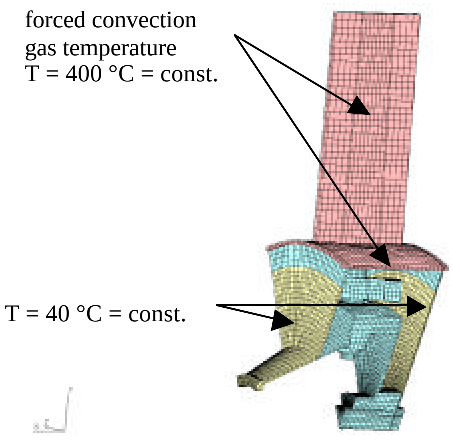

figure 3: Thermal boundary conditions

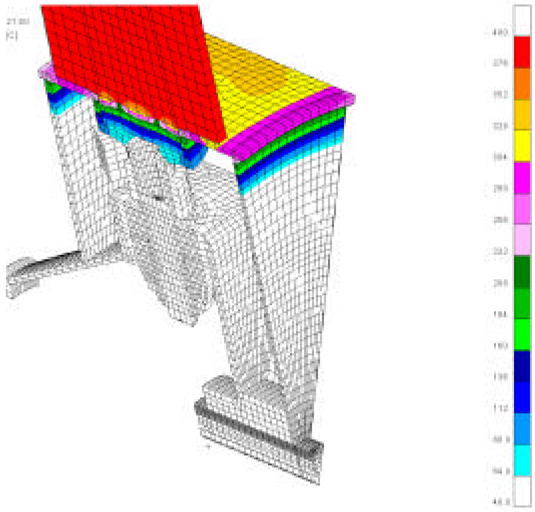

figure 4: Temperature distribution at t = 5 min. [°C]

3.3 Calculations

The transient temperature calculation is considered over a period of 48 hours. The temperature distributions are recorded at various points in time and the displacements resulting from the elevated temperatures are used for a stress analysis. These stresses are superimposed to the stresses resulting from the centrifugal force from operation.

3.4 Results

3.4.1 Transient temperature fields

After 1 minute the surfaces in direct contact with the hot gas have attained the temperature of 400 °C. The heat conduction to the inside of the impeller occurs very slowly as the conditions illustrate after 5 or after 90 minutes (figures 4 and 5). The calculation method is also used to predict the stress of the fan components during a shutdown of the tunnel over a period of 48 hours after a fire emergency (figure 6). The long term calculation does not consider any reduction of the exhaust gas medium temperature.

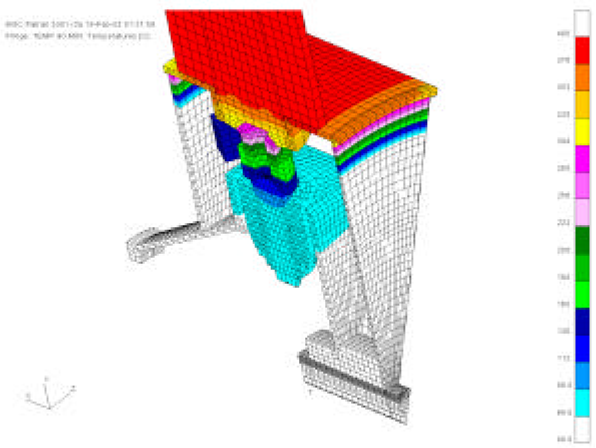

figure 5: Temperature distribution at t = 90 min. [°C]

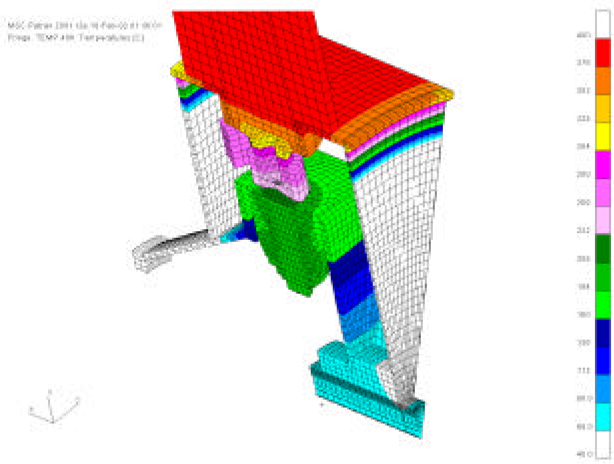

figure 6: Temperature distribution at t = 48 hours [°C]

3.4.2 Stress

For the evaluation of the stress, the temperature influence at various points in time is considered. High stress occurs where high temperature gradients are present. This is the case in the impeller outer jacket and in both the impellers' cover plates where a very high gradient is present at a very small radial distance. These plates are cooled by 40 °C seal air.

The maximum local stress is approx. 600 N mm-2 in the impeller outer jacket.

The maximum stress of the main load carrying components is approx. 200 N mm-2 (figure 7) after 90 minutes.

Finally, the stress resulting from the increased temperature after 90 minutes is superimposed with the centrifugal force. The influence of the centrifugal force on the material stress is negligible in the event of fire (figure 8). Please note that even after 48 hours the additional influence of temperature on stress compared to the 90 minutes values is very minimal.

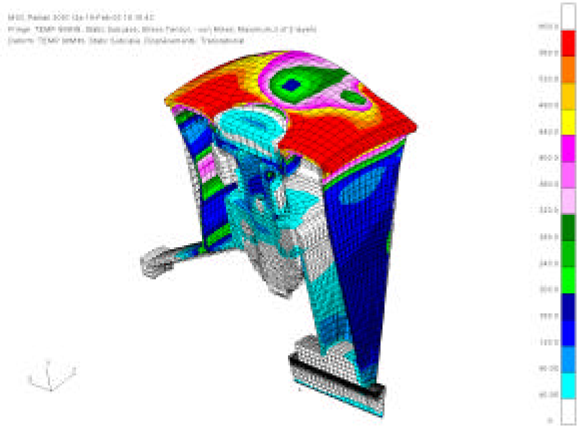

figure 7: Stresses [N mm-2] at t = 90 min. no centrifugal load

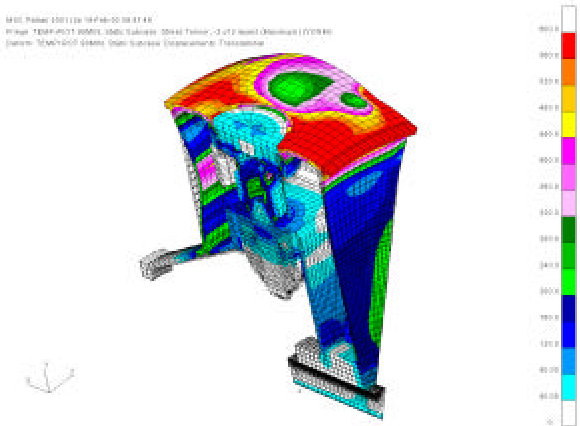

figure 8: Stresses [N mm-2] at t = 90 min. temperature + centrifugal load

4 SUMMARY

4.1 Fundamentals

Tunnel axial fans with impeller blade modulation during operation can be built to meet the requirement of 400 °C operation for a period of 90 minutes if they are designed with the proper operating systems and constructed with the proper materials.

4.2 Consequences for new facilities

In the case of new facilities impeller blades fabricated from nodular cast iron should be utilized. This type of blade construction has a proven record of operation in hundreds of induced draft installations in the power station industry. Heat transfer from the impeller blade to the motor shaft and into the adjacent components of the motor has not been experienced within the short-time operation of 90 minutes and is not expected for longer operating times under conditions of a fire emergency.

Heat-resistant materials are not necessary for the motor shaft. In addition, extremely large bearing clearances are not required.

Supplementary to our thermal investigations of the fan, we have been informed of a new development in the design of motors for use in tunnel exhaust air fans designed for operation up to 400 °C for the duration of 90 minutes. Motors have been developed with a totally enclosed construction (protective class IP 54/55), surface-cooled, which are certified for operation at 400 °C for the duration of 120 minutes. The motors do not require separate cooling. The appropriate certificates have been submitted by the manufacturers.

4.3 Consequences for existing facilities

Fan rotors with aluminum impeller blades designed for operation at 250 °C (in individual cases up to 350 °C) cannot be employed at 400 °C. Aluminum impeller blades represent a high safety risk for exhaust air fans in the event of fire.

The fan impeller design with nodular cast iron blades designed for new facilities will have considerably larger component masses and moments of inertia. If such an impeller were considered for replacement in an existing facility it would require replacement of the entire fan assembly. In order to be able to use as much of the existing fan assembly as possible, impellers with similar dimensional relationships as the existing facilities must be used. Choosing the blade material to replace nodular cast iron is especially important due to the influence the blade weight has on the operating characteristics of the fan. A sensible mechanical and economic choice would be Titanium impeller blades. Optimizing the number of blades, profile thickness and the resulting lighter impeller construction will result in dimensional relationships and center of gravity distances similar to the initial installation.

The existing motors can be used for the 400 °C specification for the period of 90 minutes by modifying the cooling system and with simple changes to the fan housing.

Through these manageable revisions to the existing installations shutdown of the traffic flow in the tunnel would be minimized. It is likely that a shutdown of the tunnel need only take place for several hours at a time.

4.4 Consequences of a long time, 48 hour, shutdown of the tunnel in the event of a fire in new facilities

Utilizing the newly developed motors designed for high temperature operation in connection with an additional external ventilation system, as well as a sealed fan hub with internal insulation, longer motor operating time can be realized at 400 °C medium temperature. In addition, a longer operation time during cooling down of the tunnel after a fire emergency can be achieved with this design concept for new facilities.

An additional advantage also exists. Even if the external ventilation system fails the original specification of 400 °C for a period of 60 or 90 minutes could be achieved.
From our perspective this concept should be taken into consideration as a further enhancement of tunnel safety in the event of a fire emergency.

5 FINAL REMARKS

The study results demonstrate that tunnel safety can be enhanced through appropriate measures.

It is our opinion that up-grading existing facilities with equipment meeting the new standards is imperative. The cost for refurbishment of existing equipment required to meet these new standards can be minimized by selecting the respective materials for the application.

In the case of new facilities we recommend the use of exhaust fans designed for operation at 400 °C with nodular cast iron blades and motors designed for operation in hot gas.

Development of TLT exhaust fans capable of operating at 400 °C has been completed as far as possible. The focus of future research and development activities will be the development of other system components such as dampers.

p.s.: Interested parties may contact TLT to get a colored copy of the pictures.

MANAGERIAL AND TECHNICAL ASPECTS OF TUNNEL SAFETY REGARDING NORMAL AND EMERGENCY MODE

Uli Barth
Deutsche Montan Technologie GmbH – Gas & Fire Division, Bochum
RISC Ruhr GmbH – Zentrum für Brandschutz- und Rettungsdiensttraining, Dortmund

Dieter Tetzner
Deutsche Montan Technologie GmbH – Gas & Fire Division, Leipzig

Dirk Aschenbrenner
Berufsfeuerwehr Dortmund

Rainer Koch
Universität Paderborn

ABSTRACT

The safe operation of a traffic tunnel may be compared, in a certain way, with the operation of a production plant. Here the employees expect a safe work environment just as people passing through a traffic tunnel is expected to have a firm believe in the tunnel's safety and in the responsibility of the tunnel's operators. System analyses of traffic tunnels, as well as the latest catastrophes show that the tunnel's operation does involve a variety of risks. Among these risks, (besides traffic accidents with hazardous materials) a tunnel fire is certainly one of the most dangerous ones.

Due to the stochastic character of such risks the question is not if a tunnel fire could start or not but when. Whenever a tunnel fire occurs, it has the real potential to endanger persons in the tunnel, in the form of smoke inhalation, heat exposure and confined spatial conditions, as many tragic events have showed us. Therefore a modern operation of traffic tunnel-systems requires a safety management-system that integrates technical- and organizational aspects. This provides a safer operation and it prepares one for adequate reactions in unexpected incidents (small or large).

Such a management-system must be prepared to cover unexpected events with its own resources, up to a certain level. Above this level, which certainly must be (politically) discussed and defined, the management must be able to provide a functional interface between a variety of agents, services and other organizations, in order to counter even the largest of incidents.

A generic element of such a management-system is the fact, that at the top a single person becomes responsible for safety. Further generic elements are an adequate organization, tailor-made standardized practices and procedures and a functional method to supervise the whole management process.

Due to the steady reduction of vehicle emissions by new technical developments the air flow requirements in normal tunnels were recently decreased. Whereas the ventilation system was designed for normal operations (to dilute and remove vehicle emissions from the tunnel itself) now, in a case of a fire, it has however, to ensure a smoke-free evacuation route for tunnel users. The tunnel ventilation system has now become an elementary and vital function for the tunnel users, but also for key personnel and emergency services responders. In other words, a potential fire scenario is now the determining factor, when designing tunnel ventilation systems.

1. INTRODUCTION

The number of extended street and railway tunnels increases continuously. Consequently we have to cope with much more traffic which might cause fatal accidents such as release of dangerous substances or (major) tunnel fires. The recent fire disasters in the European Alps focused the public interest on problems concerning traffic and safety. Shortly after the fire in the Mont Blanc Tunnel the Deutsche Montan Technologie GmbH (DMT) having its origin in mining has been caring for safety and people and equipment in mining for about 100 years. DMT as an expert body for tunnel safety carried out a preliminary audit for twenty tunnels on the most important holiday routes in Austria (12), Switzerland (4), France (2) and in Germany (2) on behalf of the Allgemeine Deutsche Automobil-Club (cf. [4], [10]). Thereby a comparative picture concerning the state-of-the-art of particular tunnel systems, in other words of safety practise and of single safety elements has been worked out in an objective manner. That time almost the half of them were assessed as "risky" or even "sub-standard". Only 5 tunnels were quoted "good" and the best mark "very good" was not awarded at all. However several organizational and/or technical safety elements could be identified in all cases, there was an indication to improve the state-of-the-art due to the implementation of a safety management system (SMS). Due to the implementation of a SMS in particular the risk caused by major fire disasters can be reduced for a new tunnel as well as for an existing tunnel to a small acceptable level. Therefore the integral approach proposed by DMT and RISC RUHR GmbH considers a tunnel more as a living organ than as a static building. This is why the individuality of a tunnel system and the financial effort to maintain the safety technique and the safety management system are taken into account.

2. MANAGERIAL ASPECTS

2.1 Analysis of the DEPOSE-System

In terms of safety engineering and safety science every tunnel can be interpreted as a DEPOSE-system (Design, Equipment, Procedures, Operators, Supplies and Materials, Environment) within a certain system-environment. The system itself may contain several sub-systems containing units and parts. Dependent on the quantity and individual character of the components of a particular system there is a certain degree of coupling and interaction between the components of a system. Perrow (cf. [13]) examined various types of systems an rated them in this concern. Fore example a nuclear power plant system was rated "complex" concerning interaction and "close" concerning coupling in comparison with a coal mine system which was rated "less complex" and "loose". In this concern the interaction of a traffic tunnel system can be rated less "linear" compared to railway transportation systems and the coupling may be rated as "close" as for railway and maritime transportation systems.

The more complex the system is the more difficult it is e.g. to foresee its reaction in case of a failure or emergency mode (e.g. a fire in the tunnel). Related to this it has furthermore to be taken into account, that safety (sub) systems may contribute to an increase the complexity. The closer components are linked together in the system the more a transfer of unintended processes to other components may occur. This coherence may decide on whether the operational personnel may deal with a small initial event (e.g. extinguishing a burning tire) or if this exceeds and finally results in the failing of the whole system (e.g. uncontrollable tunnel fire). Thereby the system analysis of the DEPOSE tunnel system is of essential importance.

2.2 Hazard Analysis and Safety Concept

Based on this system analysis further methods can be used for a systematical investigation and assessment e.g. concerning identification of hazards and assessment of its probabilities and consequences.

Following this a safety concept containing adequate safe guards and a corresponding safety organization can be designed, implemented and maintained. The safety concept must be designed tailor-made for each individual tunnel system and its system environment. Furthermore it must be revised frequently and adopted e.g. whenever the technical and/or organizational character of the system changes, legal requirements are modified or an unintended emergency mode took place.

2.3 Safety Management System

Traffic tunnels contain the risk of a major fire. This risk results from the probability and the consequence of the fire. A look at risk statistics makes it obvious that there is already a frequency for tunnel fires and not only a probability. Furthermore the frequency shows us that also major tunnel fires must not be classified as “rare events”. On the other hand, events such as in the Mont Blanc and Tauern tunnel showed us the consequences could range up to fail of the whole system. In order to end up with an acceptable remaining risk in each case a tunnel must not be seen as a static building any more but as a living organism, a dynamic tunnel system. The result of this approach is to claim for a tunnel safety management system (SMS). Thereby the organizational and technical elements of the system must be able to manage all phases in the life cycle of a tunnel (from “cradle to grave”) in particular the phases of construction, normal operation, maintenance, re-construction, emergencies and shut down, as it is already common practise e.g. in the process industries.

2.4 Generic and Particular Elements of the Safety Management System

DMT holds the opinion that SMS may vary from tunnel to tunnel concerning their particular elements but is based on the same generic (or key) elements (cf. [17]). Based on the approach of Hagenkötter concerning the general management of working processes and the tactical scheme used by fire brigades, the preventive and emergency management of tunnel systems in general can be described with a control loop consisting of four generic elements (cf. [1]). These are:

- Policy
- Organization
- Instruments
- Controlling

For particular tunnel systems then the individual control loop consists of certain individual elements. Following the Periodical Systems of Elements, which is well known in Chemistry a Periodical System of Safety Elements (PSSE), can be set up in order to visualize generic and individual elements of a particular tunnel system (cf. [2]). Due to this transparency is given for all persons on duty with the safety of the tunnel system. Also an easy communication is possible whenever a certain element is replaced or added.

Furthermore the PSSE allows to assign elements intended to fulfil preventive safety requirements as well as those for incidents related to the availability of the tunnel and not related to safety as well as for the various scales of emergencies.

Policy

Management of a tunnel system must have a safety policy, which shows that safety belongs to the major goals. Furthermore this illustrates that the top management stands behind this goal as well as safety belongs to all employees and is an integrated part of all activities of the operating company. In order to illustrate this issue the safety policy should be layed down in a written document, which is made available to all employees and third parties and is subscripted by the top management (cf. [14]).

Organization

The "normal organization (staff)" of a tunnel is intended to operate the tunnel sufficiently under normal conditions. Therefore a clear procedure is required to define the responsibility, the particular tasks and authorization of the line management. Usually extraordinary situations such as construction work, collisions, maintance work etc. can be handled. Experience shows that if a certain point is reached, for example, when an initial fire (e.g. at a tire) in the tunnel gets out of control the pressure on the normal organization might get so high that it leads to collapse.
Therefore an adequate "emergency organization" has to be prepared including employees of the operating tunnel company and external emergency organisations such as municipal or voluntary fire brigade and rescue services. Besides an adequate equipment these persons must provide the necessary competence and in particular an adequate training level (cf. [9]).
Instruments

Tailor-made instruments (in terms of practices, procedures etc.) must be selected and implemented for the individual tunnel system. Examples are the emergency communication plan, permissions for hot working (e.g. tar work), basic safety behaviour training of employees and third parties in order to deal with smaller events (e.g. initial fire at a tire, spill of hazardous materials) and special training of emergency response forces (e.g. municipal/voluntary fire brigade, rescue services) in terms of occupational safety and health as well as for tactical optimisation. Realistic training is one of the very few possibilities to build up experiences which are necessary to deal with greater emergencies like rare huge tunnel fires.

Controlling

In order to ensure that a safety management system once works adequately concerning the defined demands and furthermore is adapted adequately in cases of significant changes within these demands control elements must be implemented and maintained. Therefore a well-known instrument in various industries is safety auditing (cf. [1], [2], [14]).

The role of the audit is to establish an instrument providing a top down and bottom up information flux between management and staff concerning current safety conditions. The audit may be carried out based on checklists. The results are documented in a written report. Frequent audits provide management with the necessary information about possible safety gaps. Management then can maintain those installations or measures. DMT proposes to carry out a very detailed audit the first time taking into account technical documentation and local inspection. After significant changes in the tunnel system e.g. a re-construction, changes at safety installations or a fire an audit is urgently recommended. In case where a tunnel system is operated under normal conditions a frequent repetition of the audit is recommended after two years.

3. TECHNICAL ASPECTS

One of the primary technical aspects is ventilation. Ventilation of traffic tunnels on one hand targets on the dilution and removement of emissions from vehicles. On the other hand ventilation should be capable to control heat and smoke in case of a fire. Due to the fact that the specific emissions from vehicles decreased continuously during the past the required flux of air for a tunnel decreased also for its normal operation but for the case of a fire the requirements mentioned above are still valid. So far the case of a fire determines more and more the design of tunnel ventilation systems. Certain generic types of ventilation (systems) are available to operate the various traffic tunnels:

1. Natural ventilation
2. Longitudinal ventilation
3. Semi-transverse and transverse ventilation

DMT carried out a scientific examination based on certain fire tests (i.e. EUREKA-Project, Memorial-Tunnel-Project and Investigations at the German Test Mine Tremonia), interpretation of fire events (i.e. Caldecott-tunnel, Gotthard-tunnel, Pfänder-tunnel, Ekeberg-Tunnel, Nihonzaka-tunnel), 3 dimensional simulations (i.e. CFD-code) and the corresponding literature. Main results concerning the suitability of tunnel ventilation (systems) are:

- When deciding on a particular tunnel ventilation system it may be to think over a variety of some thousand versions due to the various parameters such as frequency of jam traffic, contra flow traffic, transportation of dangerous goods etc. Therefore DMT recommends using its decision-matrix.
- The DMT decision-matrix and a detailed discussion of the Pros and Cons of particular ventilation (systems) can be found elsewhere (cf. [11]).
- In case of natural ventilation there are no separate measures available for the fire mode. Thereby the use of natural ventilation should be restricted to tunnel lengths of up to 400 m.
- In case of longitudinal ventilation systems good conditions may result in front of the fire in terms of evacuation, rescue and fire fighting for one-directional traffic. Longitudinal ventilation systems shows significant restrictions in case of frequent jam traffic or contra flow traffic. Thereby the use of longitudinal ventilation should be restricted to tunnel lengths of up to 400 m in case of contra flow traffic and up to 800 m in case of one-directional traffic. Generally DMT recommends verifying the suitability for the fire mode of such complex ventilation systems due to fire tests and numerical simulations (cf. [8]).
- In case of semi-transverse and transverse ventilation systems good conditions may result in terms of evacuation, rescue and fire fighting for one-directional traffic and for contra flow traffic as well. Caused by a complete aspiration of smoke near by the fire the smoked zone is limited to a certain part of the tunnel near by the fire. These systems can be optimised taking into account the distance between ventilation openings in the ceiling, their size and the volume rate of airflow.

Beside this “fix-installed” ventilation systems “mobile” ventilation devices can be applied by the fire brigade in case of an emergency mode. Such mobile ventilation devices should be assessed in advance of a fire mode in order to prevent unintended interactions with fixed-installed ventilation systems and expansion of smoke, gases and heat of a fire.

4. FIRE FIGTHING

4.1 Basic Principles

In order to make the tactics more understandable, the common characteristics of the building aeration (necessary) are presented first. The basic physical principles are:

1 generation of an overpressure(and/or directed air flow)
2 creation of a ventilator application of artificial ventilation
3 locking of unwanted apertures.

For the generation of the overpressure several turbo ventilators are combined in series as well as in parallel in order to receive a sufficient service. It is very important that a sufficient distance is kept in front of the smoke filled area so that the cone-shaped air flows bulging themselves cover the entire cross-sectional area of the room. A second access point of the affected building is used as a exhaust if possible.

Tunnel plants (for example subway-system) however are far more detailed and locking of all unwanted apertures is hardly possible. Therefore the solution is a purposeful combination of several ventilators. The lock of the unwanted apertures there results from building an "overpressure-plug" which can be made in the tunnel tube at the neighbouring subway station. By this the smoke, toxic gases and heat are forced into the chosen direction.

The adaptation of these basic principles lead to the concepts for the tunnel fire fighting and aeration:

1 generation of a directed air flow (and/or regular overpressure); in this case list of the exhausts into sufficiently great distance opposite the fire

2 selection of a ventilator (as at building aeration)

3 "lock" of unwanted apertures through

4 combination of the exhausts parallel or in line (as at building aeration).

4.2 Tactical Concept

An application of this is a mission concept for the fire fighting in subway-systems. This concept is based onto the so-called "combat patrol tactics" in combination with artificial ventilation. The task of the “combat patrol” is to fight the fire already in the origin stage and to extinguish the fire by a fast first extinguishing-attack. In parallel the aeration tactics shall provide a powerful and sufficient ejection of smoke in spite of the difficult structural circumstances. This bases on the known overpressure ventilation which allow desired combined aeration tactics similar to the building aeration.

From that a fire inside a standard subway station can be attacked in the following way:

The first unit for the extinguishing-attack is the "combat patrol" (1/4). they proceed through a subway access point, from which none or at least little smoke leaks. In parallel the aeration is initiated by additional fire-fighting forces. At the smoke boundary, the intermediate level in front of the access to the platform is struck, mobile tunnel ventilators are brought into position behind the combat patrol. The fresh air drives away the smoke form the access point the departure too or at least prevents a additional smoke distribution.

Because of the great spatial dimensions of the building at least four mobile ventilators have to be used at this place. Above the last entrance to the platform the air cone should expand to the entire sectional view and to generate a continuous overpressure in the platform tier. The opposite departure of the platform is used as exhaust. As heat, smoke and toxic gases will be spread over the whole floor the are must be searched for fleeing persons before the ventilation can start.

In order to direct the smoke for this purpose, to keep exactly within this area and to avoid to be pressed into the entire subterranean tunnel system, a back pressure is made at the two nearest entrances to the tunnel (neighbouring subway stations or emergency escape hatches) by bringing additional ventilators into the tunnel tube. Also here the ventilators are brought in position that the air cone can expand onto the entire tunnel sectional view.

4.3 Discussion

Practical experiments following the described basic principles - using cold smoke - showed, that the aeration effect in spite of the difficult architecture of the tunnel plants were predictable at a astonishingly high precision. From this, this aeration concept can be fitted to the actual situation without great problems based own judgement individually. Alternatively only partial elements can be applied in order to protect for example a neighbouring cross-breeding railway station against a dangerous heat and smoke distribution.

The intense noise of the ventilators as well as the additional requirement of fire fighting personnel are disadvantageous. On the other hand the described concept gives a more effective fire-fighting operation and an improvement of the safety for the fire-fighting forces. So the raised strength requirement might make itself paid for the aeration. Finally also the expenditure is manageable, from the view of the training as well as from the view of the technique expenditure, since only standard fire fighting devices are applied and since the building aeration tactics is only adapted.

CONCLUSIONS

Based on their specific experiences in auditing European tunnels, system analysing, contributing to safety concepts and training emergency response teams DMT and RISC RUHR conclude:

1) Each traffic tunnel must be seen as a living organism in other words as tunnel system with its individual system-environment.
2) Tunnel fires are no rare events (there is already a certain frequency and not only a probability) and may end up in huge disasters.
3) Within the operational company/institution a single person within the top management must take over the responsibility for safety.
4) The operational company/institution must not leave the responsibility to deal with huge disasters exclusively to the fire brigade.
5) In order to achieve best management of safety based on limited human and financial resources an integral approach is substantial.
6) Safety of tunnel systems may be marked individually but must in principle be managed systematically.
7) In order to end up with a small acceptable remaining risk the operational management of a tunnel system must implement and maintain a safety management system.
8) Prior safety goal is to protect people, i.e. users, employees, third parties and emergency response forces. Operational measures and technical measures thereby must be capable to manage escape and rescue. In this manner installations and/or mobile devices for smoke control are of primary importance.

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Further information:

Deutsche Montan Technologie GmbH www.gasandfire.de and www.dmt.de
RISC Ruhr GmbH www.risc-ruhr.de

SMOKE PROPAGATION AND VENTILATION OF THE VEHICULAR TUNNEL MRAZOVKA IN PRAGUE

Jaroslav Katolicky[1], Miroslav Jicha[1], Ludvik Sajtar[2], Jiri Zaparka[2]
[1]Brno University of Technology, Faculty of Mechanical Engineering
Technicka 2, 61669 Brno, Czech republic, e-mail: katolic@dt.fme.vutbr.cz
[2] SATRA, s.r.o., Sokolska 32, 120 00 Praha 2, Czech republic

ABSTRACT

Fire in a vehicular tunnel and knowledge about its propagation is extremely important issue from the point of passengers' safety. Prior to design of a ventilation system for smoke venting, information must exist how the smoke propagates inside the tunnel under various conditions. Smoke propagation is influenced by several factors. They are either directly connected with the fire (released energy and amount of smoke generated) or with the conditions inside the tunnel (ventilation system and traffic that establish an initial flow field inside the tunnel, starting speed of emergency ventilation system, slope of the tunnel and meteorological conditions outside the tunnel close to tunnel portals).

In the present study a part of the tunnel Mrazovka in Prague has been solved. The tunnel has three traffic lanes and the total solved length was 860 m. Fire was placed in the middle of the length. An energy source of 5MW and 20MW and corresponding smoke amount simulated the fire. Several variants were solved with various initial velocity and direction of the flow field inside the tunnel and with tunnel slope between 0% and 4.5%. In all variants, the temporal development of the smoke plume and smoke stratification inside the tunnel was solved. Simulation was done using CFD code StarCD with standard k-epsilon and Large Eddy Simulation models of turbulence.

Key words: emergency ventilation, smoke propagation, CFD simulation, fire

1. INTRODUCTION

One possible way how to assess a possible propagation of fire and a chance to manage it is to use CFD modelling. With this tool we can predict the resulting velocity and temperature fields in the tunnel tube. The propagation of the fire (technically smoke from the fire) can be modelled with two approaches:

- Direct analysis of the combustion processes. In this case it is necessary to apply an appropriate model of combustion and to assume a fuel

- The fire is modeled as a source of energy and the propagation of smoke is simulated as the concentration of passive scalar. The combustion is not solved in this case. This approach is less expensive than the previous one from the point of time and complexity of the calculations. This approach was employed in the solved problem.

2. MODEL DESCRIPTION

Three-lane part of tunnel was chosen for calculations of the fire propagation. The length of the tunnel was 430 m on each side of the fire, it means that the total length of the solution domain was 860 m. Smoke in the space nearby the fire is extracted through the ventilating outlets from the tunnel tube and passes through side channels into a channel under the roadway of the tunnel (Fig.1). The cross-section area of extraction outlet is 1,5 m^2, dimensions of the side channels are 0,25 m x 1,5 m. The distance between each of extraction outlets is 20 m. In the calculations, ten extraction outlets on each side from the fire were open.

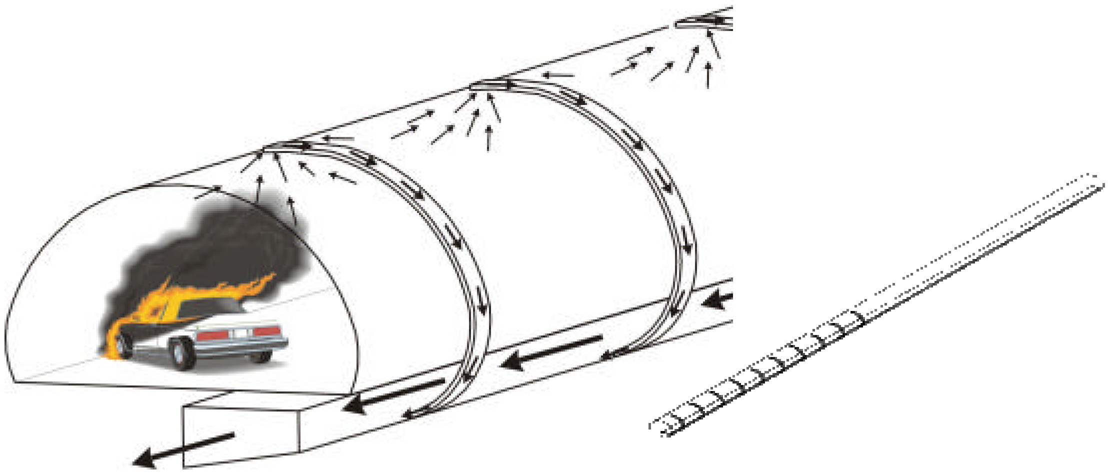

Fig. 1 Layout of smoke extraction inside the tunnel

Several variants, which differs in fire capacity, slope of the tunnel, initial conditions and operation of ventilation systems were solved:

1) fire capacity **20 MW,** zero initial velocity of flow field
   a) slope of the tunnel **0 %**
   b) slope of the tunnel **0,7 %**
   c) slope of the tunnel **4,5 %**
2) fire capacity **20 MW**
   a) slope of the tunnel **0 %** , initial velocity of flow field **+2 m/s**
   b) slope of the tunnel **4,5 %**, initial velocity of flow field **+2 m/s**
   c) slope of the unnel **4,5 %,** initial velocity of flow field **- 2 m/s**
3) fire capacity **5 MW,** zero initial velocity of flow field, slope of tunnel **0 %**
4) fire capacity **20 MW,** zero initial velocity of flow field, slope of tunnel **0 %** , ventilation system is switched **on** (extraction flow rate was 150 m^3/s)
5) fire capacity **20 MW,** zero initial velocity of flow field, slope of tunnel **0 %** , ventilation system is switched **off**

3. SHORT MATHEMATICAL DESCRIPTION

The problem was solved using a set of equations for incompressible, unsteady turbulent 3D flow. The equation for a general variable f has the well-known form:

$$\frac{\partial}{\partial t}(r\,f)+\frac{\partial}{\partial x_i}(r u_i f)=\frac{\partial}{\partial x_i}\left(\Gamma\frac{\partial f}{\partial x_i}\right)+S_f \qquad (1)$$

where the variable f substitutes velocity components u, v, w and temperature T . In the case of energy equation, S_f is a source of energy from the fire. As a model of turbulence, standard k-ε and LES models were used. The set of equations was solved using the control volume method and CFD code StarCD.

4. RESULTS AND THEIR DISCUSSION

The results of the computations are shown in a brief form in the following figures. There are shown concentrations fields of passive scalar, which simulates propagation of smoke from the fire. Concentration of 5 % was assumed as a limiting value of smoke area. Figures 2 to 7 show propagation of the smoke from the fire after 140 s from the fire initiation. In Fig 2 we can see propagation of the smoke for the Variant 1a. In this variant, with 0% slope of the tunnel, smoke propagation is symmetrical on both sides of the fire. Speed of the smoke propagation is relatively high, approximately 370 m in 140s – see Fig. 2. There we can also see that the smoke fills up approximately one half of the cross-section of the tunnel tube.

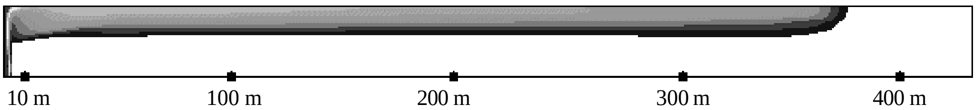

Fig. 2 Var.1a - 20MW, slope 0°, zero initial velocity

As soon as the tunnel is in the slope (Variants 1b and 1c), the smoke propagation is faster in the direction of the buoyancy force – see Fig.3 and Fig. 4. It can be seen that the smoke fills up the tunnel cross-section area more than in the previous variant.

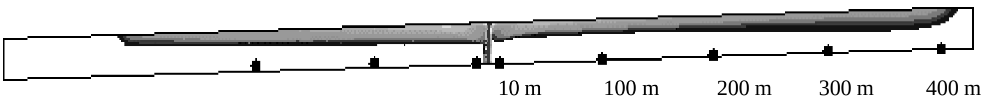

Fig. 3 Var.1b - 20MW, slope 0.7°, zero initial velocity

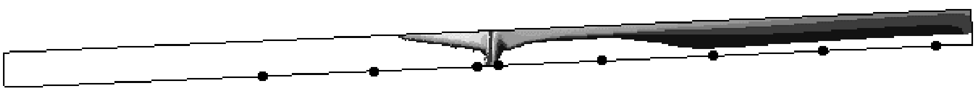

Fig. 4 Var.1c - 20MW, slope 4.5°, zero initial velocity

The influence of an initial velocity of air inside the tunnel is shown in Fig.5, 6 and 7 (variants 2a, 2b and 2c). In the case that the initial flow rate is directed opposite to the buoyancy force, the smoke fills up practically the whole cross-section of tunnel – see Fig. 7. In this variant, the distance of the smoke propagation is shorter.

Fig. 5 Var.2a - 20MW, slope 0°, initial velocity +2 m/s (from left to right)

Fig. 6 Var.2b - 20MW, slope 4.5°, initial velocity +2 m/s (from left to right)

Fig. 7 Variant 2c -20MW, slope 4.5°, initial velocity -2m/s (from right to left)

In Fig. 8 can be seen comparison between variants 4 and 5. In the variant 4, the ventilation system is switched on and in case of variant 5 the ventilation system is switched off. We can see the time development of smoke propagation for both variants. We can see that initiation of the ventilation system causes the mixing of the smoke. The ventilation system reduces significantly distance of the smoke propagation and also the filling of the tunnel cross-section. We can see that after 180s, the smoke fully fills the cross-section area of the tunnel, if the ventilation system is switched off.

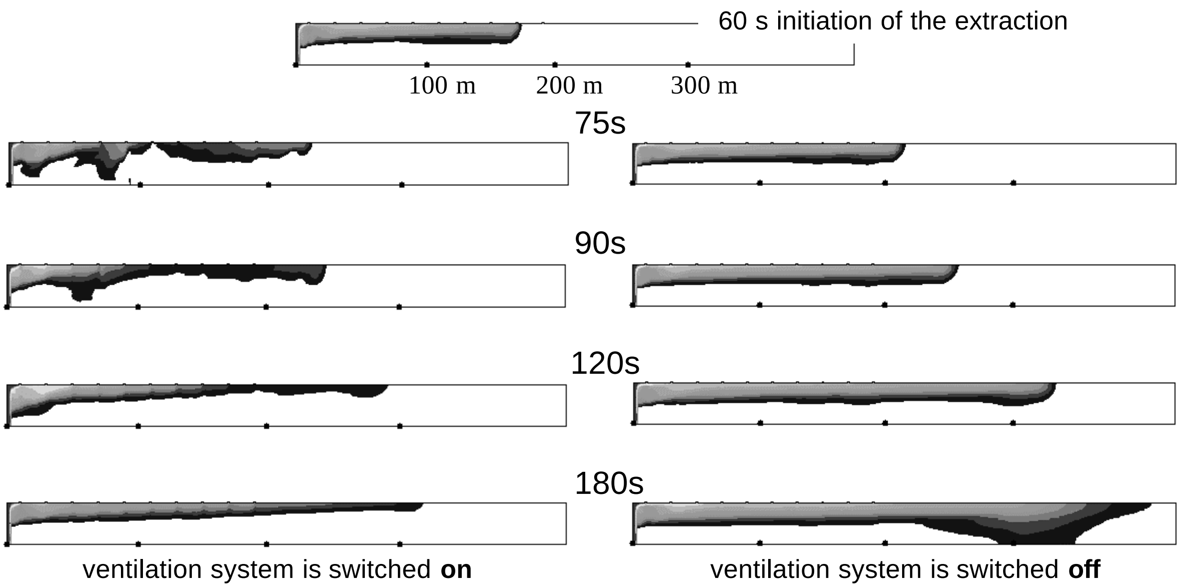

Fig. 8 Var.4 and 5 - 20MW, slope 0°, zero initial velocity

ACKNOWLEDGEMENTS

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CFD-SIMULATION OF SMOKE PROPAGATION AND VENTILATION EFFICIENCY OF TUNNEL FIRE INCIDENTS

Martin Mann, Christoph Segalla
arsenal research,
Business Area Transport Technologies, Faradayg. 3, A-1030 Vienna

Ernst Pucher
Institute for Internal Combustion Engines and Automotive Engineering,
Vienna University of Technology, Getreidemarkt 9/315, A-1060 Vienna

ABSTRACT

The objective of this project was the development of a prediction method for the propagation of smoke and the temperature distribution in a tunnel during a fire incident. The goal was to generate deeper understanding of the flow phenomena during a tunnel fire and to provide constructors with an instrument to support ventilation design.

The 3D-simulations were carried out using a commercial CFD-software to benefit from well established programs and models. For special physical phenomena, like soot-radiation interaction, special models were implemented. A large number of calculations was performed to investigate grid resolution sensitivity, influence of turbulence models and different approaches of modeling the fire.

During the investigations three main points turned out to have predominant impact on the quality of simulation results: the modeling of the fire by means of heat and volumetric source, gas and soot radiation and boundary treatment at the tunnel walls.

In order to limit computer effort the fire was substituted by an energy source for the required heat release and a mass source which produced the combustion products. The correct smoke quantity and composition were of crucial importance because they are directly related to convective and radiative heat transfer. The combustion products (largely carbon dioxide and water vapor as well as soot particles) are optically dense, which implies that there is a strong interaction with the radiation emitted from the fire. In order to correctly regard these effects an improved version of the 'Weighted Sum of Grey Gases Model' (WSGGM) was implemented, which combines the effect on absorption coefficient by gaseous and soot components.

Test cases from the Memorial Tunnel Project were used to verify the newly developed methods and showed remarkable improvement over previous simulation runs omitting the mentioned radiation effects.

Key words: tunnel fire, numerical simulation, soot, radiation, tunnel ventilation

1 INTRODUCTION

In recent years, the safety of road and rail tunnel users has become an increasingly important issue. Apart from increased safety standards, this was partly initiated by a number of catastrophic incidents, where fatal tunnel fires caused tremendous loss of life. A discussion on tunnel ventilation and fire safety concepts resulted, sometimes ignoring the involved costs. Yet conventional design procedures for tunnel ventilation systems leave some amount of uncertainty about the actual system performance in case of fire. Normally it is not possible to carry out full scale fire tests of significant intensity in newly constructed or refurbished tunnels due to the immense costs generated (contamination and even damage of new facility, locking for traffic, etc).

At the same time advances in computer simulation technology open up new opportunities to investigate the heat and mass transfer phenomena occurring during tunnel fires. Consequently the current work concentrates on developing methods, using state of the art computational fluid dynamics (CFD) software to be able to simulate smoke propagation and temperature distribution during a tunnel fire. The goal is to provide design engineers of tunnel ventilation systems with a sufficiently accurate tool to efficiently predict performance. This way design changes can be realized or modifications to the control system can be anticipated prior to actual construction.

2 PHYSICAL PHENOMENA

Tunnel fires are in most cases caused by vehicle defects, where overheating sets afire components, or by accidents, where fuel or transported goods are ignited. In any case, a fully burning truck can typically release a heat load of 30 MW for a period of up to 90 Minutes. The heat is confined by the tunnel walls, leading to rather high temperatures of well above 1000K in the vicinity of the fire. The temperature gradients result in strong buoyancy effects, causing vertical stratification in the tunnel. This and the volumetric source of the gaseous combustion products lead to high flow velocities away from the fire. Due to lack of oxygen and to the combustion of materials like plastics and rubber (aside from various payloads) the smoke contains numerous poisonous components. Further complicating matters is the large amount of soot in the smoke, quickly bringing visibility to zero.

For safety considerations, the first minutes after the outbreak of the fire are of importance. Passengers must find a layer free of harmful smoke with sufficient visibility to be able to escape. Later on, accessibility for the fire brigade is the issue. In any case, smoke stratification and the build up of fresh air zones is to be achieved by the fire ventilation system.

Due to the high temperatures, a large amount of the energy is emitted by radiation. As simulation results later showed, heat transfer by radiation and by convection are of similar order. The optically dense smoke absorbs a significant amount of radiation energy, influencing the dynamics of smoke propagation considerably.

All these physical phenomena had to be simulated, to get realistic results of the temperature distribution and smoke propagation.

2.1 Modeling Combustion

The simulations were performed using the CFD-Package Fluent, which provides models for the simulation of heat and mass transfer including buoyancy and radiation.

As one of the major goals of the project was the efficiency of the simulation method, the fire was not modeled by a sophisticated (and computationally expensive) combustion module. Instead transport equations for the species N_2, O_2, CO_2 and H_2O were solved and in the region of the fire, mass sinks and sources where defined according to stochiometric combustion. Additionally a heat source was introduced corresponding to the combustion equation. Errors in smoke volume due to incomplete combustion were neglected. The soot concentration was estimated following the lines of Köylü [1] with 0,0095 kg per kg of burned carbon. It was supposed, that the soot particles were sufficiently small to be drawn with the smoke without significant changes of momentum. Thus the concentration was set to be constant in relation to the smoke concentration. However soot concentration varied with the density of the smoke in the tunnel air.

2.2 The Soot-Radiation Model

To simulate radiation, the Discrete Ordinate (DO) model [2] was used, which is capable of regarding optical dense media, where energy is absorbed or emitted not only at walls but also within the media. For a mixture of gases, a novel method to describe the absorption properties is the "Weighted Sum of Gray Gases Model" (WSGGM) [3]. It expresses the emissivity *e* of the real gas by the weighted sum of gray radiating and non-radiating gases.

$$e = \sum_{i=0}^{I} a_{e,i}(T)\left[1-e^{-k_i P s}\right] \qquad (1)$$

Here a_e is the weighting factor depending on temperature, *k* is the absorption coefficient, *P* the partial pressure of the radiating gases and *s* the equivalent path length for a number *I* of gases. For the weighting factors a number for approaches are given by Smith [3] and Coppale [4].

To include the radiation from soot, an extended formulation had to be implemented. The entire WSGG-model was recoded and implemented into the flow solver via user defined subroutines. If soot is considered to exhibit gray radiation properties, the total emissivity of a soot-gas mixture can be formulated according to Siegel [5] as

$$e_{s+g} = e_s + e_g\left(1-e_s\right). \qquad (2)$$

For the DO-model the absorption coefficient *a* is required which according to Bouguer's law results to

$$a = -\frac{\ln(1-e)}{s}. \qquad (3)$$

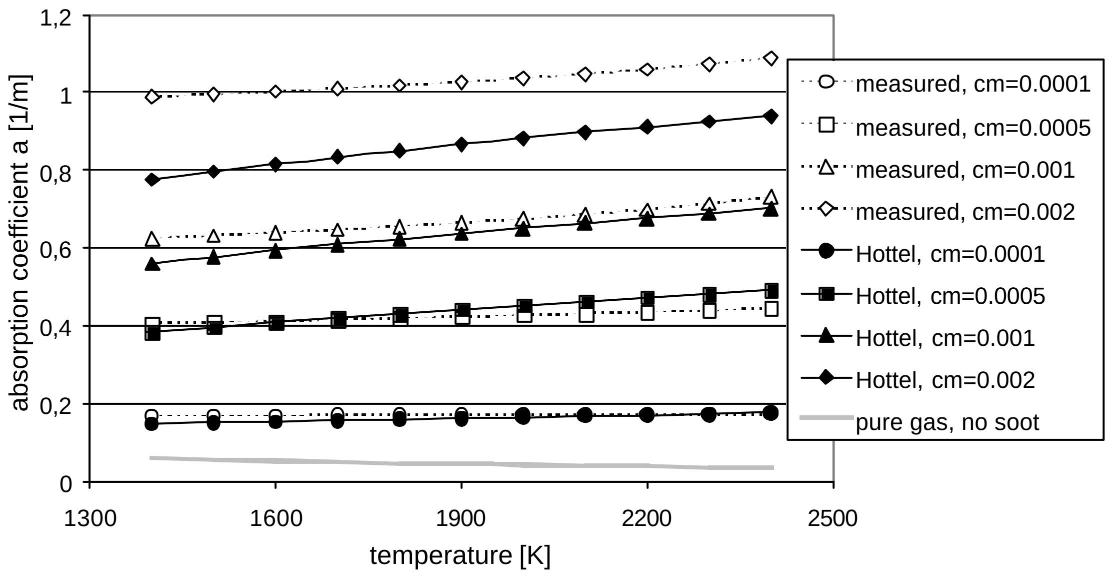

Figure 1: Absorption coefficients for a CO_2-H_2O mixture containing various concentrations *cm* of soot ($cm=f_v/r$), compared to pure gas mixture

Combining equations (2) and (3) the absorption coefficient for the soot-gas mixture can simply be expressed as

$$a_{s+g} = a_s + a_g \, . \qquad (4)$$

For soot absorption Hottel [6] suggests the following approach:

$$a_s = \frac{4}{s} \ln\left(1 + \frac{k\, f_v\, s T}{c_2}\right) \qquad (5)$$

The soot volume fraction in the tunnel is f_V which is evaluated by the simulation, k and c_2 are empirical constants. To judge the influence of soot, the model was compared to measured data (Taylor [7]) as demonstrated in figure 1. As can be clearly seen, soot dramatically increases the absorption of the gas mixture. The model discrepancies increase with larger soot concentrations, yet the error remains in a range of tolerable 20%. In lack of data, the model was extrapolated to lower temperatures. The error introduced by this simplification should be limited, since radiation scales to the 4th power of temperature. During simulations, soot concentrations (*cm*) of up to 0.002 appeared in the vicinity of the fire, underlining the necessity to account for particle radiation in tunnel fire simulations.

3 THE TEST CASE

To be able to compare the simulation results to real events, a number of trial runs of the Memorial Tunnel test program [8] were simulated. The actual tunnel was 853 m long with a cross section below the ceiling of 36 m^2 and an inclination of 3,2% downwards from north to south. The cross section above the ceiling accommodated ventilation ducts which were connected to the roadway by ventilation openings of 10m^2.

To not exceed the scope of the paper, only one representative test run is explained in detail. A pan of 10 m^2 with gasoline was positioned 43 m to the south of the ventilation opening. This pool fire was dimensioned to generate a nominal heat load of 20 MW. Naturally, the actual heat production was irregularly oscillating over time, but after 20 minutes a rather steady state was reached. Prior to the fire, a natural air flow of 1 m/s from north to south prevailed throughout the tunnel. The ventilation system was activated 2 minutes after ignition and was drawing tunnel air and smoke with an estimated 140 m^3/s through the ventilation opening. After 23 minutes the ventilation was increased to 186 m^3/s.

Only a section of 160 m was modeled to reduce calculation times by cutting of 530 m at the north and 163 m at the south. Additional pressure drop was added at the model's "portals" to account for the additional tunnel length. To simulate the natural longitudinal flow, a pressure

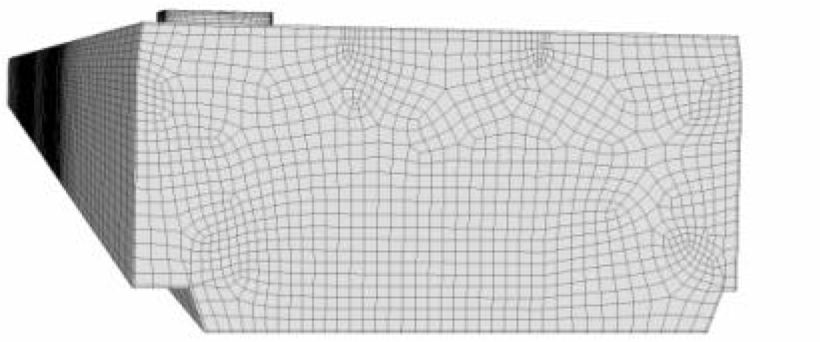

Figure 2: Tunnel model volume mesh

drop of 3 Pa was applied over the model's length. The computational grid of the test section (see figure 2) contained approximately 380.000 hexahedral cells, which were additionally stretched in longitudinal direction. Previous runs showed, that this grid resolution was sufficient to resolve temperature and velocity profiles in the tunnel because calculations with larger grids did not change results. Local mesh refinement was applied near the pool fire and the ventilation opening.

For the given run – 20 minutes after ignition – the mass and heat sources were set to resemble a 20 MW combustion of heptane. Ventilation was simulated by an appropriate mass-flow boundary condition at the ceiling vent. Natural longitudinal convection was allowed by specifying pressure boundaries at the portals. Wall heat transfer was regarded by applying a 1D-conduction boundary condition across a 0,05 m layer of concrete. This was the result of preliminary calculations, which showed, that at given temperature levels and after 20 minutes, just 0,05 m of the concrete wall participated in heat transfer. The temperature on the outer side of the layer was set to 291,5 K. The absorption coefficient of the tunnel walls was defined with 0,95 which effected significant radiation of energy to the walls in the vicinity of the fire.

Preparatory runs demonstrated, that calculation times would be too long to do the necessary number of unsteady calculations. Consequently, steady state calculations were performed, trying to reproduce a phase of the real fire, which mostly approximated a steady condition. Nevertheless, to reach a converged steady solution on a UNIX workstation (HP J5000) took about 7 days, mostly caused by very poor convergence. The bad convergence performance of mixed convection flows is well known, but the strong coupling between radiation and momentum equation – caused by the soot radiation – additionally complicated numerical robustness. After a number of runs, solver settings were found, which reliably would result in a converged solution by somewhat sacrificing calculation speed.

3.1 Simulation results

The simulation started with fresh air at 280 K initialized throughout the tunnel. With the fire, the natural longitudinal flow was easily overwhelmed and a strong flow from the fire to the ventilation duct developed (south to north). Some back-layering occurred, as can be seen from the temperature plot in figure 3. The strong suction by the ventilation system caused the fire to be drawn to the north. The high smoke temperatures above 1000 K assisted in pronounced stratification of smoke and temperature profiles. Yet the large quantities of hot smoke and radiation prevented the formation of a sufficient low temperature layer in the vicinity of the fire. The ventilation was able to remove the entire volume of smoke, preventing it to enter the northern tunnel section aside from insignificant quantities. Near the tunnel floor, the flow velocity was directed towards the fire, obviously providing the combustion with oxygen.

To visualize the shape of the stratification layers, an iso-surface at 450 K is depicted in figure 4. This surface displays the limit between regions of more than 450 K (above the surface) and less than 450 K. Clearly visible is the box-shaped pool and the rising plume. In the vicinity of the fire, radiation causes the temperature at the tunnel walls to increase significantly. The longitudinal flow causes some swirling around the fire plume and some irregularities in the iso-surface. Yet the stratification is quite stable. In the foreground of the picture, the rectangular opening in the ceiling can be seen, through which the hot gases are leaving the tunnel.

Apart from these qualitative evaluation of the calculation results, a more detailed comparison was necessary. At selected cross sections of the tunnel, temperature profiles were available from the Memorial tunnel program. The measured profiles were averaged from a period of 17 to 21 minutes after start of fire to minimize effects of the combustion oscillation.

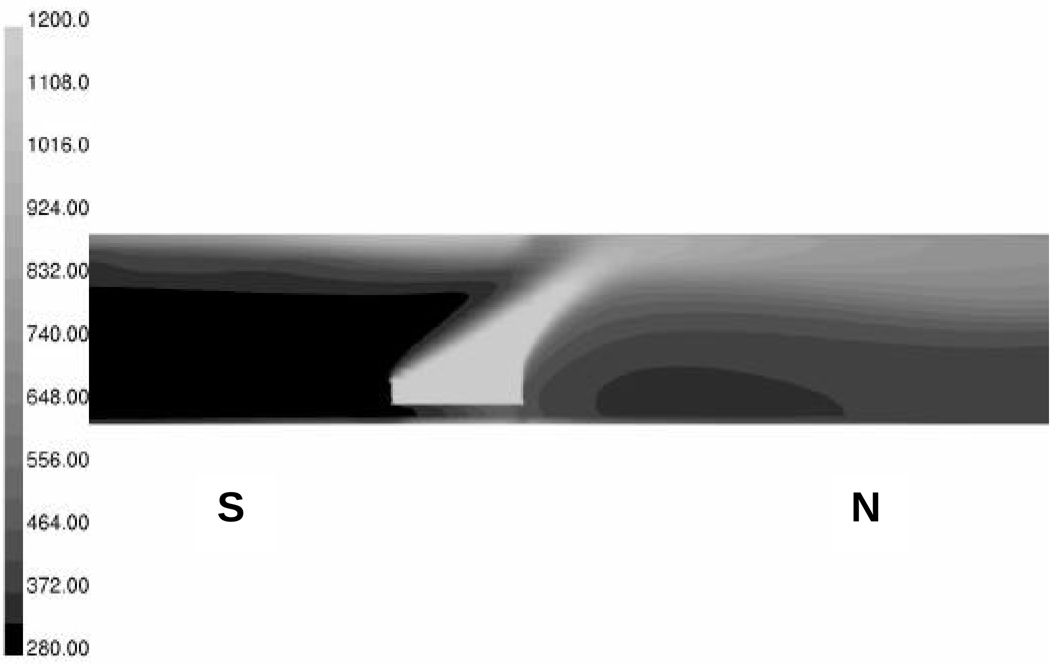

Figure 3: Temperature contours [K] in plane of symmetry (tunnel height: 4,3 m)

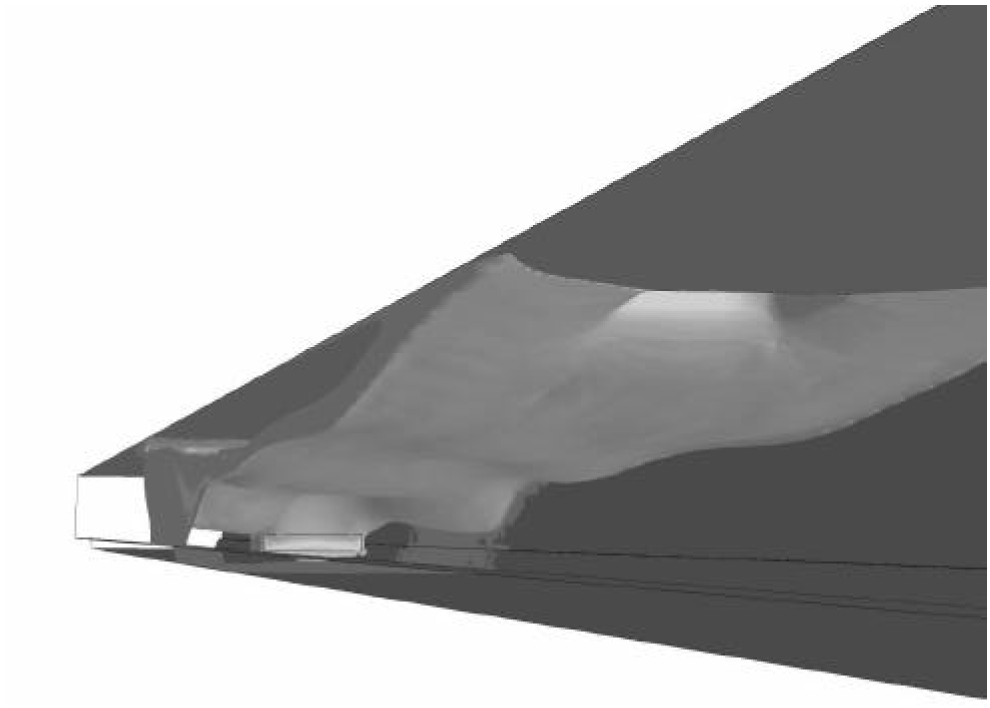

Figure 4: temperature Iso-surface at 450 K demonstrating stratification

A number of calculation runs were performed, using different turbulence models and also comparing the effect of the soot radiation model to pure mixed convection calculations. Temperature profiles for four positions in the tunnel are given in figure 5.

In principle, all turbulence models gave similar results. However the RNG model exhibited severe convergence difficulties, and hence seemed less suited for practical reasons. The standard k-ε model showed some weaknesses in the vicinity and upstream of the fire – the back-

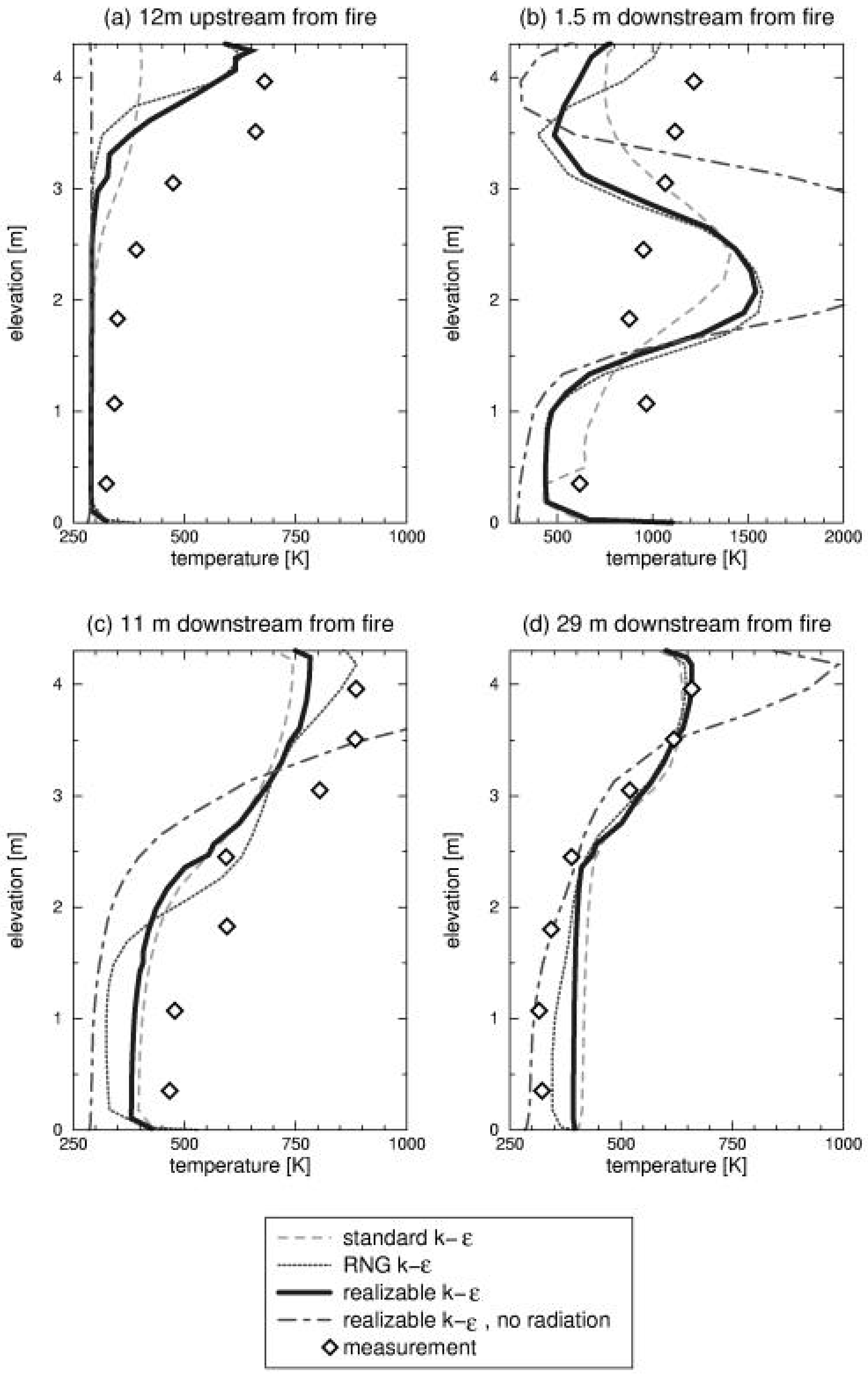

Figure 5: Simulated and measured temperature profiles at positions (a) 12 m upstream, (b) 1,5 m downstream, (c) 11 m downstream and (d) 29 m downstream from fire

layering was greatly under-predicted. So the realizable k-ε model [2] was chosen for the rest of the calculations, which resulted in reasonable coincidence with measurements. Only in the immediate vicinity of the fire, coincidence was poor. This was thought to be produced the simplified modeling of the fire by sinks and sources, which also influenced the local flow and temperature field.

Most significant were the results without activating the radiation module (dot-dashed lines in figure 5). Peak temperatures were greatly over-predicted, on the other hand the stratification was much more pronounced, generating a cooler zone near the floor. The back-layering was not initiated at all. These effects are easily explicable – radiation spreads energy to a wider area. The optically dense smoke absorbs a large amount of energy, convecting it to cooler tunnel zones, where radiation is emitted again. So radiation smoothes temperature peaks, but by this also reduces stratification.

4 CONCLUSION

The present work gave valuable insight into the physics and involved flow phenomena during tunnel fires. The calculation model including soot radiation greatly improved the quality of the results, reproducing effects like back-layering and smoke stratification. The important influence of radiation can not be neglected in further numerical investigations. On the other hand, there is still some room for prediction accuracy.

One of the primary goals for improvement are the long calculation times. Apart from increasing computer resources by parallel computing, optimization of solvers is one of the directions further research is presently aiming to. It is reasonable to assume, that unsteady calculations can be achieved with reasonable calculation times within short term, enabling accurate simulation of smoke propagation during the fire initiation phase. This is most interesting for escape scenarios and will help to make future tunnel traffic safer.

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VIRTUALFIRES a virtual reality simulator for tunnel fires

Gernot Beer, Thomas Reichl and Gunther Lenz
Institut für Baustatik, Graz University of Technology, Austria

ABSTRACT

The project VIRTUALFIRES, which is being funded by the European Commission and involves eight partners from five European countries, is presented. The aim of the project is to develop a simulator that allows to train fire fighters in the efficient mitigation of fires in a tunnel, using a computer generated virtual environment. This will be a cheap and environmentally friendly alternative to real fire fighting exercises involving burning fuel in a disused tunnel. The simulator can also be used to test the fire safety of a tunnel and the influence of mitigating measures (ventilation, fire suppression etc.) on it's fire safety level.

Key words: Visualisation, Virtual Reality, Tunnels, CFD

1. INTRODUCTION

Recent serious fire accidents in tunnels have highlighted the problems that currently exist with respect to the prevention of serious fire incidents and with respect to fire mitigation once the fire has started. There is a need for action on a European scale with respect to

- Ascertaining the safety level of existing tunnels and retrofitted tunnels (i.e. Mont Blanc tunnel).
- The specification of the required safety features and installations for new tunnels.
- Training of rescue personnel in order to increase the efficiency of fire and smoke mitigation procedures.
- Training of drivers with respect to correct behaviour in the case of a fire emergency.

With respect to ascertaining the safety level of existing and retrofitted tunnels much reliance is still placed on real tests using fire/smoke pans or vehicles set on fire. Such tests have been recently performed for example in the refurbished Mont Blanc Tunnel. Fire fighting exercises are usually carried out on a regular basis using burning vehicles or cold smoke generators.

The disadvantages of real tests are that they are expensive, can only be carried out at certain times and are not environmentally friendly since toxic smoke is produced. The main aim of the VIRTUALFIRES project is to develop an alternative to real tests by replacing them with virtual tests. In an virtual test the tunnel and the fire emergency only exists in computer memory. Using computational fluid dynamics (CFD) computations, the spread of fire and smoke in a particular tunnel is calculated.

The tunnel including the safety installations, traffic signs, vehicles etc. is visualised together with the results of the CFD calculations using the method of virtual reality. Under the term virtual reality we mean total immersion in a three-dimensional data set. The effect should be very close to reality. The simulator can be used as a training tool for fire fighters and for assessing the safety level of existing or retrofitted tunnels. It may also be used to check the design of a planned tunnel.

The simulator will be equipped with a user friendly program for the input of data which comprise the shape of the tunnel, ventilation characteristics, safety installations, vehicles, emergency exits etc. Two versions of the simulator will be developed: One where the CFD simulations are carried out prior to the visualisation (pre-calculated scenario) and one where the CFD simulations are carried out concurrent with the visualisation. The advantage of the second type would be that ventilation characteristics may be changed during the visualisation (i.e. one may check the effect of reversing the ventilation on the spread of smoke and fire). The first type of system can be used for the training of fire fighters and drivers and for checking the fire safety of existing tunnels.

2. DESCRIPTION OF SIMULATOR

2.1. Hardware

The simulator will be implemented on two hardware platforms: a portable version consisting of a Laptop PC with a head-mounted display connected to it for off-line simulation and a more powerful and interactive version running in a distributed computing environment and a CAVE as the visualisation front-end.
A headmounted display (HMD), like the one shown in figures 1 & 2, contains 2 liquid-crystal displays and a 3DOF tracking sensor. Due to the possibility of displaying images from different viewpoints to the each eye, the user gets a threedimensional impression of the scene. The tracking sensor, which delivers the rotation-angles around the 3 principal axis in realtime, allows for synchronisation of the users head movement with the viewing direction of the rendered scene.

Figure 1: User wearing a headmounted display

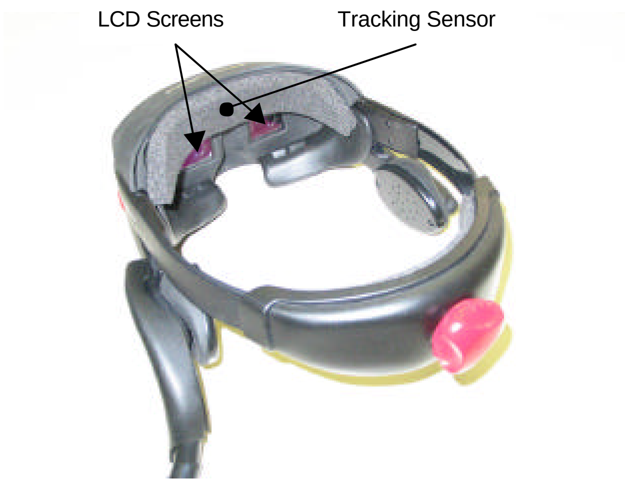

Figure 2: interior view of a HMD

A CAVE is a multi-person, room-sized, high-resolution, 3D video and audio environment. Graphics are backprojected in stereo onto the walls, the floor and the ceiling, and viewed with shutter glasses (see figure 3). As a viewer wearing a position sensor moves within the display boundaries, the correct perspective and stereo projections of the environment are updated in realtime by the rendering system, and the images move with and surround the viewer. Hence stereo projections create 3D images that appear to have a continuous presence both inside and outside the projection room. To the viewer with stereo glasses, the projection screens become transparent and the 3-D image space appears to extend to infinity.

Both display-systems have some advantages and drawbacks.

HMD:

- \+ portable and lightweight device
- \+ moderate computing power for image rendering: only 2 different images of the scene need to be generated at the given framerate
- \- user not fully immersed into the scene due to the limited field of view, impression is more like watching the scene through divers-glasses
- \- low resolution of the display

CAVE:
+ wide field of view, so the user is fully immersed into scene
+ very high resolution of the rendered scene
- stationary installation
- high computing power needed for rendering: dependent on the number of backprojected walls 10 or 12 images are required at the given framerate

Figure 3: User in a CAVE wearing shutter glasses (courtesy of KTH)

Due to the limited computing power of the mobile version of the system there will probably be no possibility of changing parameters of the simulation in realtime. This system is more thought of an interactive threedimensional movieplayer for the precalculated simulation results. Nevertheless it will be possible to change parameters at any given timestep and to continue the simulation from this point with the new values.

2.2. Software

Since CFD computations of fire and smoke spread are already at a fairly high level of sophistication the emphasis of the project is on the further development of methods of visualisation and virtual reality. New developments are only envisaged in concurrent CFD calculations using massive parallel computers.

There are two aspects that need to be considered in the visualisation:

Size of data: The amount of data produced by a CFD program is quite large. Depending on the length of the tunnel being considered in the simulation and the time span modelled they are in the order of several Gigabytes. Before such a large amount of data can be displayed in real time one must apply data compression/optimisation techniques.

Feeling of reality: The simulator will only find acceptance if the simulation is realistic, i.e. gives a feeling of reality. A realistic display of the tunnel and its safety installations for example is important, as is the use of realistic textures. Questions to be answered are: how does one visualise fire and smoke, temperature and toxicity etc.

2.3. Rendering system and user interface

Not all of the potential users (i.e. fire fighters, rescue personnel, etc.) are familiar with VR-Equipment, so the userinterface must be simple and easy to understand in a straightforward manner. The planned System will be capable of defining missions prior to the simulations as well as interactive interaction during the execution of such a mission, like "freezing" the scenario, changing some parameters, i.e. start the ventilation, or move forward or backward in time.

3. SYSTEM SPECIFICATIONS

The specifications of the system capabilities are still being worked out but can be summarised as follows:

- VR-System
  Tunnel geometry and safety installations will be visualised with realistic textures. Traffic signs, emergency exits, escape tunnels, vehicles must be displayed very realistically for the evaluation of safety features.
- CFD calculation
  Calculation of fire and smoke spread after a vehicle has been set on fire. Level of detail sufficient for realistic visualisation (higher level close to observer, lower further away) and for calculation (using 1D or 3D-Models). Type of output expected: Flame spread, smoke density, temperature and toxicity. Time step may be governed by stability criteria but updating of transient data for visualisation is only required every 4 ms (equal to 25 frames per Second) to ensure smoothness of display.
- Display of CFD data
  The rendering of the simulation results needs to fulfil two different criteria: For those tasks where a visual evaluation of the scene is necessary, like in checking the readability of traffic signs, the display of the smoke distribution data must be as realistic as possible, including changing fog density and turbulent flow (see figure 4). On the other hand the rendering of temperature and toxicity-values needs a meaningful and rapidly interpretable representation like the one shown in figure 6, where colour is used to discriminate the different levels of danger (blue: safe area, red: dangerous). To observe the velocity and direction of the flow of the smoke the system will allow traces of particles to be shown (see figure 5).
- User navigation
  User moves through virtual space with a three-dimensional input device (space ball or hand held input device). Speed of movement is controlled to simulate walking, running. Head movement is detected by positioning devices. Collision detection is implemented to prevent users from going through tunnel walls. Pull down virtual menus are used to select type of display.

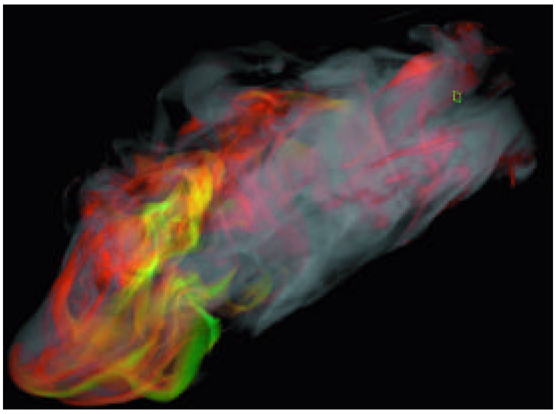

Figure 4: smoke visualisation
(courtesy of UMN)

Figure 5: tracelines of particles
(courtesy of ems-i)

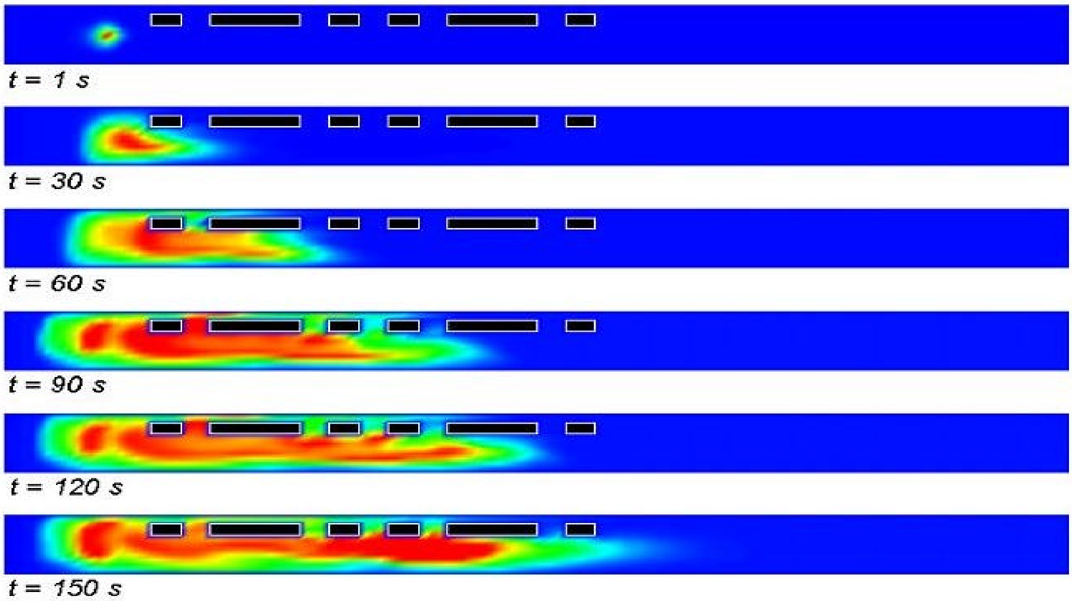

Figure 6: temperature values for different timesteps (courtesy of ACT)

4. EXAMPLES OF APPLICATION

4.1. Mission planning for firefighters

In this application is designed to allow a fireman to evaluate the effectiveness of a planned mission in a specific emergency-scenario. After defining the necessary mission-parameters like number of firemen involved, type of equipment and direction of attack, the simulation provides some quantities for ranking the success of the mission like set up time for equipment, time to extinguish, level of impact of the fire or toxic load exposure of the firemen.

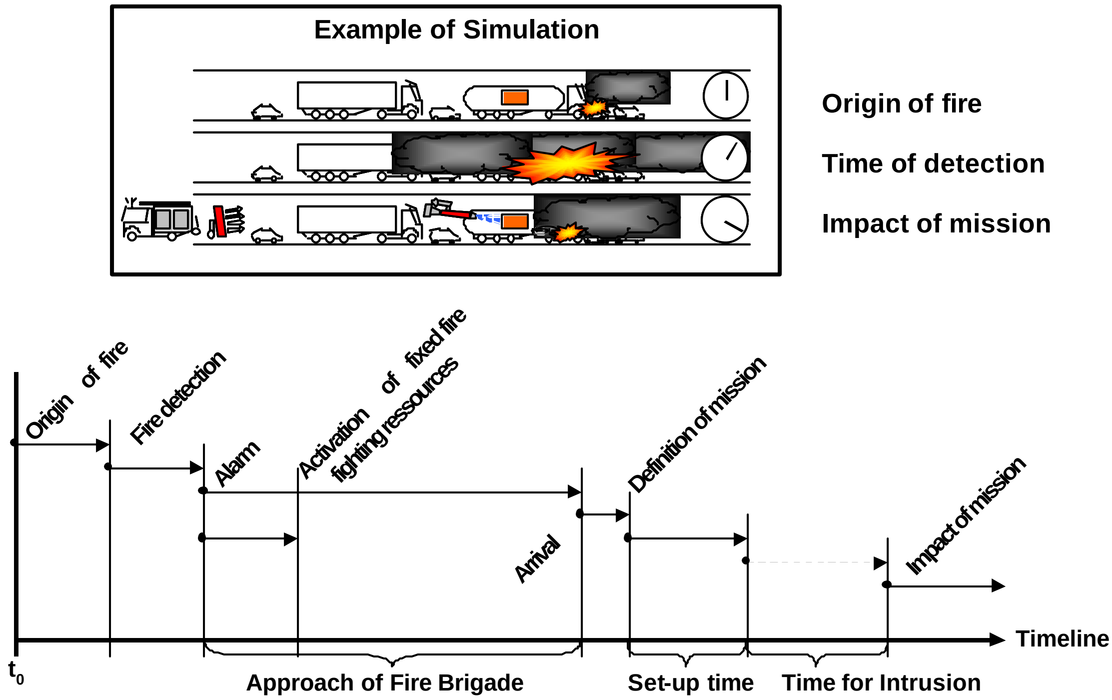

Figure 7: Resulting timeline of a simulated mission
(courtesy of FDDo)

4.2. Evaluation of tunnel safety equipment

The authority or planner of the tunnel infrastructure can use this tool to objectively evaluate the functionality and usability of the safety equipment. This task includes checking the visibility of road-signs in a smoke environment, testing the amount of fresh air supplied to the emergency cabins or evaluating the performance of the ventilation system.

4.3. Evaluation of fire countermeasures performed by tunnel operators

As the operators sitting in the control-rooms are the first persons to respond to an emergency, these people need to be trained for specific situations. With the help of the simulator an operator can monitor the consequences of his set actions.

4.4. Training of drivers for firesituations in tunnels

Several incidents in road tunnels have shown, that the majority of the drivers reacts totally wrongly due to panic and missing information about the things that can happen. The simulator can give a trainee the experience of an accident of a lorry with flammable goods and he/she can try different strategies of escape from the tunnel to a safe environment without the danger of getting harmed by a wrong reaction.

5. SUMMARY AND CONCLUSIONS

The project aims at the building of an interactive and high-performance simulation environment for fire incidents in tunnels. This development will lead to an objective tool for evaluating the safety infrastructure of a tunnel and provides a cheap alternative for verifying the effectiveness of fire fighting missions and for training of drivers and tunnel-operators in the case of an emergency.

6. ACKNOWLEDGEMENTS

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QUANTITATIVE RISK ASSESSMENT OF HEAVY GOODS VEHICLE TRANSPORT THROUGH TUNNELS – THE TAUERNTUNNEL CASE STUDY

H. Knoflacher, P. C. Pfaffenbichler, H. Nussbaumer
Institute for Transport Planning and Traffic Engineering
Vienna University of Technology
Gußhausstraße 30/231, A-1040 Wien

ABSTRACT

This paper has to principle objective. The first is to present the concept of quantitative risk assessment. The second is to assess the risk reduction potential of proposed mitigation measures. A definition of risk and how to measure it is given. A quantitative risk assessment software, developed in an international research project, is presented. One of its purposes is to calculate the effects of mitigation measures. Following a series of catastrophic events in European road tunnels several measures were proposed by experts and politicians. The assessment results for two of them are shown here. The Tauerntunnel was selected as case study. The first measure which is already in action is an improved emergency ventilation. The second measure which is proposed by French authorities for the Mont Blanc tunnel is forcing heavy goods vehicles to stay 150 meter clear from vehicles in front of them. The QRA calculations show that both measures have significant potential to reduce the risk caused by heavy goods vehicles in tunnels.

Key words: societal risk, dangerous goods, emergency ventilation, mitigation measures

1. INTRODUCTION

The work presented here was mainly carried out as part of the research project "Transport of Dangerous Goods Through Road Tunnels (ERS2)". ERS2 was part of "The Road Transport and Intermodal Linkages Research Programme (RTR)" by OECD (Organisation for Economic Co-operation and Development). The following countries and organisations participated in the project: Australia, Austria, Belgium, Denmark, France (Chair), Italy, Japan, Netherlands, Norway, Spain, Sweden, Switzerland, United Kingdom, United States, World Road Association (PIARC) and European Commission. Within the task "Methodologies relating to risk assessment and decision process" two software products were developed: a "Quantitative Risk Assessment (QRA) Model" and a "Decision Support Model (DSM)". Subject of this paper is the QRA model. It was developed by a consortium of consultants from France, England and Canada. The model calculates the risk caused by road traffic with heavy goods vehicles (HGV). A special focus was laid on the transportation of dangerous goods (DG). During the period 1999 to 2001 the QRA software was validated based on data from existing tunnels in Austria, France, Netherlands, Norway, Sweden and Switzerland. The Institute for Transport Planning and Traffic Engineering was chairing the validation group. The following chapter 2 gives a brief overview about the basics of the QRA model. In chapter 3 the application of the QRA software to an Austrian case study is shown.

2. THE QUANTITATIVE RISK ASSESSMENT MODEL

Risk is defined by two aspects: the occurrence probability of an event and the consequences of an occurring event. A common way to describe societal risk is to calculate F/N curves. F/N curves illustrate the relationship between accident frequency and accident severity. On the abscissa the number of victims x (fatalities, injured people or both) is shown in logarithmic scale. On the ordinate the corresponding yearly frequencies F(x) for the occurrence of accidents with x victims are shown (also in logarithmic scale). For each given situation (population, traffic, DG traffic, route, weather, etc.) one F/N curve represents the societal risk. Figure 1 gives an example for an F/N curve.

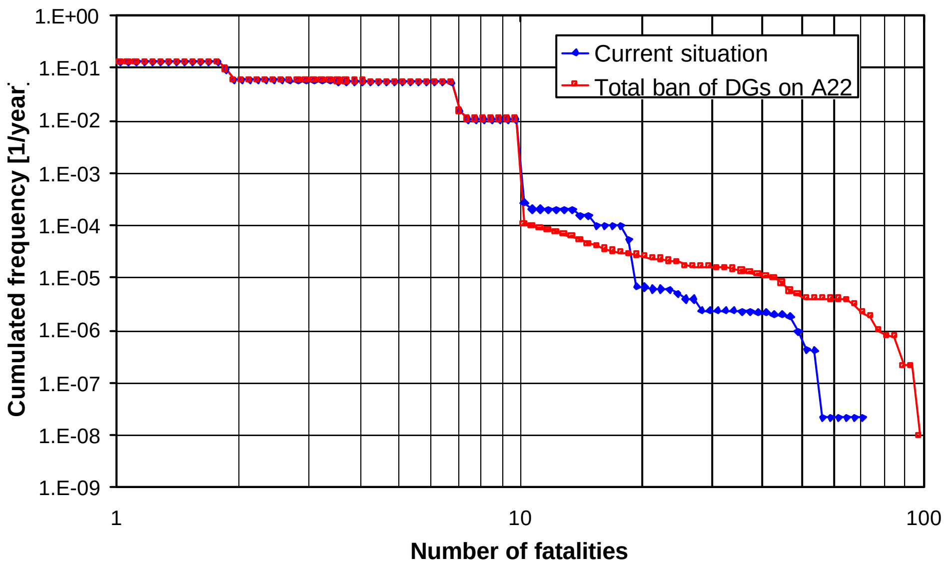

Figure 1: Example F/N curve (Knoflacher, Pfaffenbichler, 2001)

A complete assessment of risks caused by transport of DGs would require the consideration of all kinds of dangerous materials, all meteorological conditions, all accidents, sizes of breaches, vehicles fully or partially loaded etc. As the coverage of all circumstances is impossible, simplifications have to be made. The QRA model developed by the OECD is based on the following steps:

1. Choose a relative small but representative number of goods;
2. Select a relative small but representative number of accident scenarios involving these goods;
3. Determine the physical effects of these scenarios (for open road and tunnel sections);
4. Determine the physiological effects of these scenarios on road users and local population (fatalities and injuries);
5. Take into account the chance to escape and/or shelter
6. Take into account different risk reduction measures and
7. Determine the associated probabilities of occurrence.

Table 1 shows which scenarios were selected as representative in the QRA model. Two scenarios are relating to fires of medium and high intensity involving HGVs without DG. These scenarios represent a quite serious risk in tunnels. The other scenarios involve dangerous goods loading. The DGs are selected to represent various groupings of dangerous goods. They have been chosen to examine different severe effects: overpressure, thermal effect and toxicity.

Table 1: Main characteristics of the 13 scenarios modeled in the QRA

Scenario No.	Description	Capacity of tank	Size of breach (mm)	Mass flow rate (kg/s)
1	HGV fire 20 MW	-	-	
2	HGV fire 100 MW	-	-	
3	Boiling liquid expanding vapour explosion (BLEVE) of liquefied petroleum gas (LPG) in cylinder	50 kg	-	
4	Motor spirit pool fire	28 tonnes	100	20.6
5	Vapour cloud explosion (VCE) of motor spirit	28 tonnes	100	20.6
6	Chlorine release	20 tonnes	50	45
7	BLEVE of LPG in bulk	18 tonnes	-	
8	VCE of LPG in bulk	18 tonnes	50	36
9	Torch fire of LPG in bulk	18 tonnes	50	36
10	Ammonia release	20 tonnes	50	36
11	Toxic liquid (Acrolein)	30 000 l	50	24.8
12	Toxic liquid	100 l	4	0.02
13	BLEVE without thermal effects	20 tonnes	-	-

Key: BLEVE = Boiling liquid expanding vapour explosion; LPG = Liquid petroleum gas; VCE = Vapour cloud explosion
Source: (OECD, 2001)

3. THE TAUERNTUNNEL CASE STUDY

3.1. Background

The Tauerntunnel is a 6,401 meter long, rural, drilled, one bore tunnel with transverse ventilation. The tunnel is situated on the north-south-bound highway A10 which is an important route through the alps. The Tauerntunnel was already used as a case study in the QRA model validation. Therefore a broad database was already available. When the final version of the QRA software was available it was decided to perform an updated QRA for the Tauerntunnel. Two aspects were of special interests:

- In the aftermath of the 29th May 1999 Tauerntunnel catastrophe the air ventilation system had been modified. QRA runs were made to assess the effects of these changes.
- In the reopened Mont Blanc tunnel HGVs will have to stay clear 150 meters from vehicles in front of them. The potential effect of this mitigation measure is also assessed with the QRA software.

3.2. Traffic related data

For the use in the QRA model the average daily traffic of about 13,300 vehicles per day was sub-divided into three periods (Table 2). The speed limit is 80 km/h for all types of vehicles. Vehicle occupancy is assumed with 1.4 persons for light vehicles, 1.1 persons for HGVs and 40 persons for busses. The accident rate is $0.129*10^{-6}$ accidents per vehicle kilometers (Source: KfV). The QRA model defines five accident locations. In the standard setting the locations are distributed evenly. The expert user interface allows to change the distances. To reflect the circumstance of a higher accident rate near the portals, accident locations have been changed to 150; 180; 3,200; 6,221 and 6,251 meters. The time to stop oncoming traffic is estimated with one minute. Evacuation average speed is assumed with 0.5 m/s.

Table 2: Traffic data

Period	Time	Veh/h	HGVs	Busses	DGs/h
Peak	11:00-19:00	795	22 %	2 %	3.12
Normal	5:00-11:00; 19:00-22:00	556	17 %	2 %	1.69
Quiet	22:00-5:00	261	30 %	1 %	1.40

Source: (bmvit, 2001), information by telephone Mr. Santner, Tunnelwarte Tauerntunnel

Table 3: Share of DGs transported on the Tauern route

Dangerous Goods	Share
Flammable liquids in bulk (motor spirit, diesel oil, ...)	53 %
Fraction of flammable liquids that can potentially lead to a VCE	23 %
Propane (flammable liquefied gases) in Cylinders	0.2 %
Propane (flammable liquefied gases) in Bulk	0.8 %
Ammonia (Toxic gases) in bulk	1 %
DG potentially leading to a large (100 MW) fire (except liquids)	16 %
Others (Potentially leading to at least a 20MW fire)	29 %

Source: Registration list DG transports Tauerntunnel (January to March 2000)

3.3. Ventilation data

The Tauerntunnel ventilation system is divided into four segments (Figure 2). Three segments are 1,500 meter long and one segment is 1,900 meter long. In the normal ventilation regime the system runs at 70% of its maximum power. 133 $m^3/s*km$ of fresh air is blown into the tunnel and 80.5 $m^3/s*km$ are extracted from the tunnel (Source: Information given by Mr. Santner). The QRA software uses a rather simple ventilation model which is based on a modified American model. The model uses a constant volume flow. Figure 3 shows how the normal ventilation is modeled.

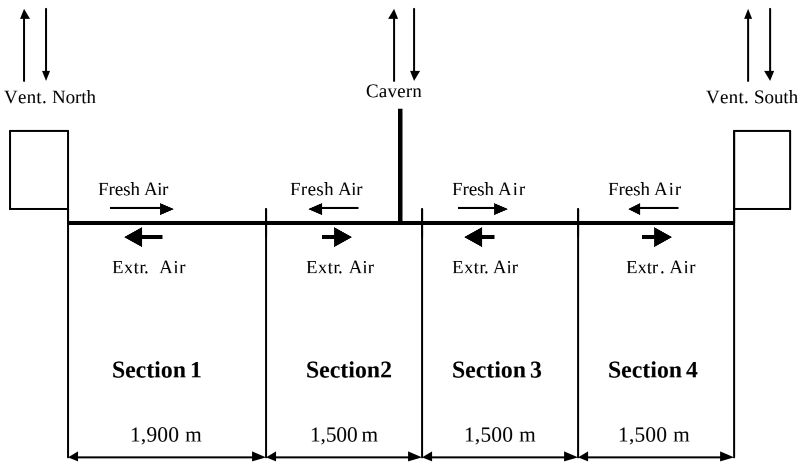

Figure 2: Outline ventilation system Tauerntunnel

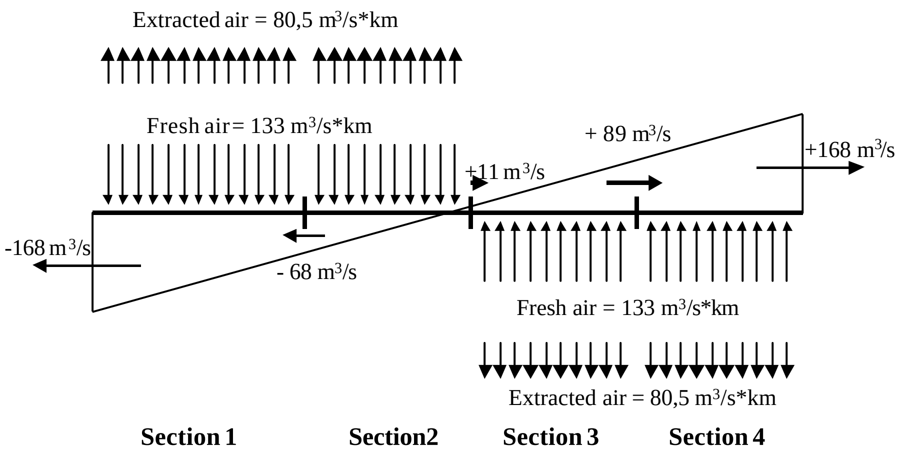

Figure 3: Normal ventilation as it is represented in the QRA model

In the old ventilation system air was extracted through slots. Figure 4 shows the way the old ventilation system is represented in the QRA model. It is assumed that the emergency ventilation needs 4 minutes to reach its full extraction flow.

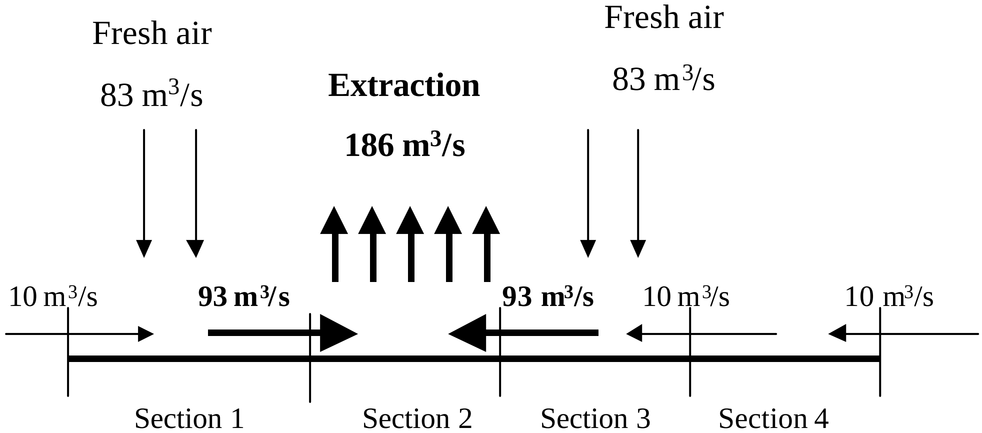

Figure 4: Modelling of the old emergency ventilation system

In the modified ventilation system there are 126 discrete openings (jalousies, every 50 m) along the whole tunnel. During normal ventilation all are opened. In cause of emergency all will be shut, except the one nearby the fire where the air will be extracted (See Figure 5). Because with the new system a smaller air mass has to be moved, it is assumed the emergency ventilation needs 2 minutes to reach its full extraction flow.

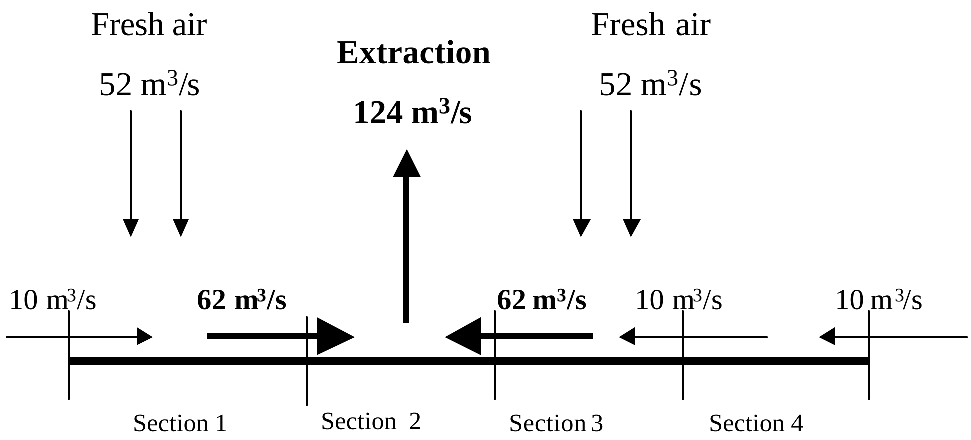

Figure 5: Modelling of the modified emergency ventilation system

3.4. Modelled mitigation scenarios

In the scenario OLD the emergency ventilation regime of the old Tauerntunnel as described in the previous chapter is used (Figure 4). In the scenario NEW 1 the modified emergency ventilation is applied as described in Figure 5. Scenario NEW 2 also uses the new emergency ventilation. Additionally it is assumed that the 150 meter distance regulation is applied. In the model this means that if the traffic stops in the case of emergency it is ensured HGVs keep a distance of 50 meters to vehicles in front. Scenario NEW 3 also uses the new emergency ventilation but additionally it is assumed that HGVs keep a 100 meter distance in emergency cases. This way to model the 150 meter distance regulation is conservative. It is not taken into account that in reality the accident ratio for HGVs would be reduced by this measure.

4. RESULTS OF THE QRA CALCULATIONS

Table 4 shows the expected values (EV) for the different event and mitigation scenarios. The expected value is the integral under the corresponding F/N-curve. The new ventilation system reduces the expected value of all scenarios involving HGVs with and without DG by about 30%. The highest reduction potential was calculated for the scenario toxic products (about 80%) while the lowest was calculated for propane in bulk (2%). The behavioral changes reduce the expected value further (all scenarios 40% to 57%). The scenarios 20-100 MW fire and flammable liquids have the highest reduction potential (40% to 57% and 46% to 64%). Again propane in bulk has the lowest reduction potential.

Table 4: Tauerntunnel Improvement of Expected Values (fatalities/year)

	OLD	NEW 1	NEW 2	NEW 3
All Scenarios	$1.428*10^{-2}$	$9.807*10^{-3}$	$5.901*10^{-3}$	$4.177*10^{-3}$
20–100 MW fires	$1.046*10^{-2}$	$7.688*10^{-3}$	$4.146*10^{-3}$	$2.766*10^{-3}$
Flammable liquids	$3.143*10^{-3}$	$1.853*10^{-3}$	$1.501*10^{-3}$	$1.175*10^{-3}$
Toxic products	$5.008*10^{-4}$	$9.367*10^{-5}$	$8.691*10^{-5}$	$7.335*10^{-5}$
Propane in bulk	$1.764*10^{-4}$	$1.728*10^{-4}$	$1.677*10^{-4}$	$1.627*10^{-4}$

F/N-curves for the different mitigation scenarios are given in Figure 6. It could be seen that the new ventilation system has its main potential for incidents with a high number of fatalities. The behavioral measure does nearly not effect the risk for incidents with high number of fatalities. The main potential of this measure is to reduce the risk for medium number of fatalities accidents.

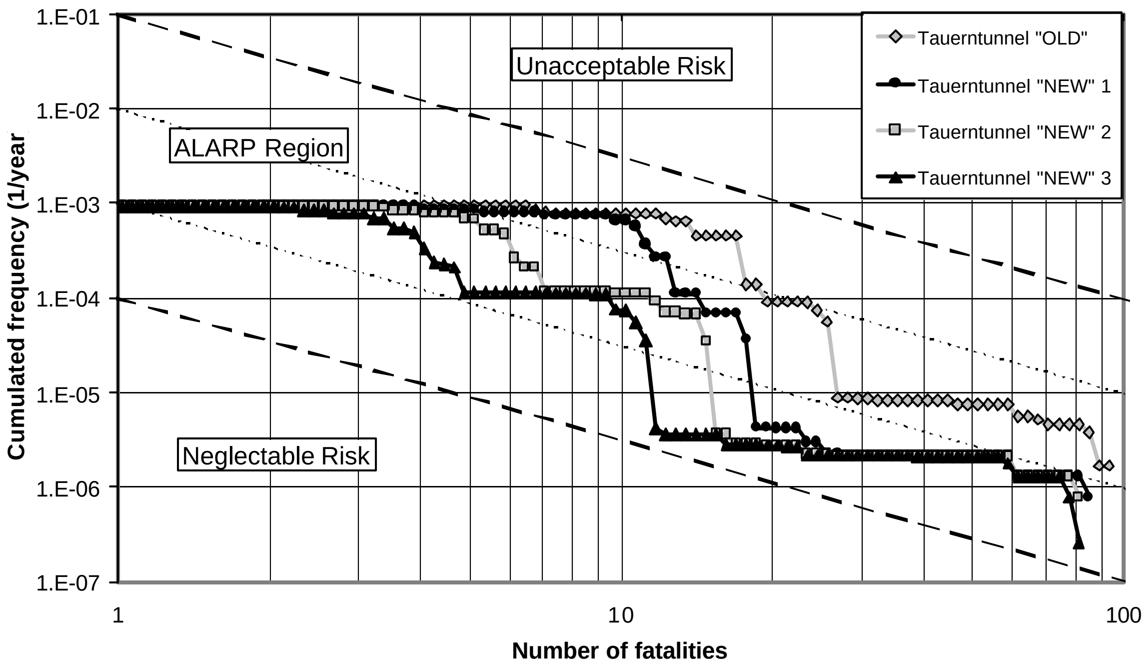

Figure 6: Results of the QRA for the different scenarios

5. CONCLUSIONS

After a series of very severe accidents in road tunnels experts and politicians proposed a huge number of measures to counteract risk of road transport through tunnels. A quantification of risk is necessary to assess the effectiveness of mitigation. The OECD project ERS2 produced a QRA model applicable to this task. This paper describes the application of QRA software to an Austrian case study - the Tauerntunnel.

Two different mitigation measures were tested: one of infrastructural and one of behavioural nature. Despite the necessary simplification the QRA modelling has proven that both measures have a significant risk reduction potential (Figure 6). The emergency ventilation improvement has its main potential in reducing risk of incidents with a high number of fatalities. Whereas the increased distance between HGVs and vehicles in front has its main potential for medium number of fatalities.

Currently there is an ongoing discussion to define an Austrian risk acceptance criteria. The thick dashed lines in Figure 6 indicate a criteria suggested by the Institute for Transport Planning and Traffic Engineering. Above the upper dashed line risk would be unacceptable. Between the two dashed lines is the so called ALARP (as low as rational possible) region. Within this area mitigation measures have to be assessed and put into action in a cost effective way. Under the lower dashed line risk could be neglected. Figure 6 shows that it was necessary to improve safety standards in the Tauerntunnel. Modifying the ventilation system went in the right direction. Nevertheless it is necessary to find further cost effective ways to reduce risk. The regulation that HGVs have to stand 150 meter off from vehicles in front could be an appropriate measure to reach this objective.

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ADDITIONAL SAFETY EQUIPMENT OF THE BOSRUCKTUNNEL

Klaus Schinagl
Österreichische Autobahnen- und Schnellstraßen AG
A-8010 Graz, Wilhelm-Raabe-Gasse 24

ABSTRACT

After the tragic accident and fires that occurred in the past few years in long bidirectional tunnels, ÖSAG has worked out a plan to improve safety in Austrian tunnels.

The Bosruck Tunnel was the first of the long bidirectional tunnels that has been provided with an additional safety equipment in the last year. In substance, the improvement consists in the installation of escape routes and the update of the ventilation system.

Moreover, the SOS niches have been transformed into protected accessible niches and phosphorescent reflectors as well as orientation lights have been installed.

As a result of the investigations carried out by a group of experts the tunnel has been recoated, so-called "rumble stripes" have been milled into the road surface and the lighting has been improved.

INTRODUCTION

Pursuing the aim of raising tunnel safety the Österreichische Autobahnen- und Schnellstraßen-Aktiengesellschaft (ÖSAG) is providing the old long bidirectional tunnels with a wide range of additional facilities.

In a first step the 5,5 km long Bosruck Tunnel on the A9 Pyhrn Autobahn, opened in 1983, has gradually been provided with an additional safety equipment. The work began in April 2001 and was completed in December 2001. The work in the main tunnel has been done between September 10 and mid-November 2001 by night with traffic lights in operation at the portals in order not to obstruct road traffic.

The Bosruck Tunnel is divided into three parts:

- The 5500 m long eastern bidirectional tube (main tunnel)
- A parallel running gallery at the western side which is divided into the northern ventilation gallery (1387,5 m in length), the drainage gallery (2727 m in length) and the southern ventilation gallery (1356 m in length)
- The two parallel running tubes are linked with crosscuts every 400 m. In the area of the drainage gallery these crosscuts are on the same level as the two tubes whereas in the area of the ventilation galleries they are on a higher level and therefore connected with the tubes by means of a special construction (i.e. a shaft with a ladder inside)

Being provided with a parallel gallery linked with the main tunnel by crosscuts the Bosruck Tunnel differs substantially from other bidirectional tunnels in so far as in case of fire tunnel users have the possibility to flee through the emergency exits into the crosscuts and wait for the rescue service. But they also may save themselves by fleeing into or through the parallel tube.

1. Measures that have been taken

1.1 Parallel gallery

To make the parallel gallery passable along its whole length the following measures had to be taken:

- Raising the road surface of the ventilation galleries
- Removal of rock broken apart and installation of a reinforced shotcrete shell in the drainage gallery
- Installation of an emergency lighting running along the whole length of the tunnel
- Laying of 20 kV-cables to supply two transformers
- Installation of a radio facility

Ill.1: Parallel gallery with cable system

1.2 Crosscuts

The crosscuts have been transformed into waiting areas which required the following work to be done:

- Installation of a T90 door to separate the crosscut from the main tunnel
- Installation of an emergency lighting
- Installation of information boards with emergency phones, first-aid boxes fire-extinguishers and safety advice
- Installation of places to sit down
- Installation of video cameras switched on automatically when the door is opened
- Installation of a loudspeaker system
- Installation of hooks going in rails to elevate and let down injured people and heavy loads within the shafts
- Installation of a ventilation system

Ill. 2: Equipment of the waiting areas

The crosscuts that have been transformed in waiting areas are separated from the main tunnel, the ventilation galleries and the drainage gallery by tight doors. It is important that, in comparison with the main tunnel, there will always be an over-pressure. On the other hand, the over-pressure is to be kept on a relatively low level to permit the doors to be opened. In case of fire-alarm the ventilation system blows approximately 2 to 3 m³/s of fresh air into the crosscuts, regardless of whether there is high or low pressure in the ventilation galleries.
The construction of the 14 crosscuts differs because the floor level of the main tunnel and the ventilation galleries differs from that of the drainage gallery. In case of fire-alarm the ventilation valves which are closed by magnetic mechanisms are opened by springiness or gravity and the ventilation system is put into operation. A kickback valve prevents the air from flowing back into the ventilation gallery. When the main ventilation units are not in operation the pressure of the waiting areas is kept at approximately 70 Pa. Thus, the air flows back into the ventilation gallery. In case of higher pressures caused by air intake into the ventilation gallery a second kickback valve leading to the main tunnel is opened because of over-pressure (from 100 Pa onward) and pressure in the waiting areas is reduced.
When the emergency exit is opened pressure diminishes, the kickback valves shut and fresh air is blown through the open door and prevents smoke from flowing into the waiting area. All kickback valves are moved mechanically by springiness or gravity. Between the drainage gallery and the ventilation galleries tight doors are installed. In case of fire alarm valves movable by springiness or gravity are opened by means of a solenoid switch in order to take in fresh air into the drainage gallery.
Thus, air flows from the waiting rooms into the main tunnel only when there is an over-pressure of more than 100 Pa or when the emergency exits of the main tunnel are opened. In case of fire-alarm all magnetically moved valves are opened and all ventilation units start to operate. Hence, the air circulates flowing from the ventilation/drainage galleries to the waiting areas and back to the ventilation/drainage galleries. Because the volume of air is 100.000 m³ a rise in temperature or a significant rise of harmful substances is not to be expected.

The Austrian Guideline Code for the Planning, Construction and Maintenance of Roads (RVS) provides over-pressures of 50 Pa and an air speed of 0,75 m/s with open valves in order to keep the staircases of buildings free from smoke. In tunnels, because of the higher volume of smoke and the stronger fluctuation of pressure a maximum difference of 100 Pa is approved in order to raise air speed to up to 1,5 m/s with open emergency exits in the main tunnel.

The kickback valves installed between the main tunnel und the waiting areas have to meet special standards and are fireproof according to the category F30.

1.3 High-voltage supply

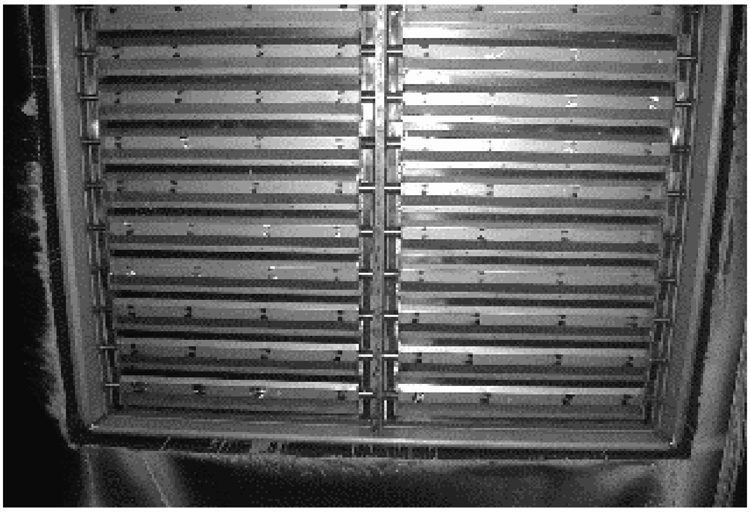
In the crosscuts 5 and 10 two additional transformers were installed in order to supply with power the motors of the waste air blinds, the ventilation unit of the waiting areas and the emergency lighting in the ventilation galleries and the drainage gallery. The two transformer units consist of a 10 kV-control system with 4 switchboards and a 400kVA-distributor. These units are supplied by transformers at the portals by means of a high voltage cable system including holding devices which has been installed in the ventilation galleries and the drainage gallery.

1.4 Waste air blinds

After the fire disasters in some European tunnels we had to reflect on how to increase the safety of tunnel users. To reach this aim, above all as far as bidirectional tunnels are concerned, it was necessary to update the facilities that remove the smoke. The Bosruck

Tunnel was provided previously with waste air openings of the first generation installed every 12 m in the intermediate ceiling of the tunnel. These waste air openings had fixed vents which, in case of fire, could not be opened or shut completely. Thus, in case of fire, the smoke intake within the section could not be modified. Therefore, wide waste air blinds which can be moved separately by a motor have been installed. The motors are installed in the fresh air intake ducts and connected with the cable system by means of light wave cables. The cables in the intake ducts run in ducts made appropriately for this purpose. In case of fire one or more waste air blinds in the area of the source of fire are opened whereas the others remain closed in order to guarantee an effective removal of smoke.
Investigations have shown that the waste air blinds should be more or less of the same extent as the surface of the waste air duct which in this case is approximately 9 m².
Totally, 51 waste air blinds, one every 100 m, which had to meet the following standards have been installed in the intermediate ceiling:

- Every single part of the blinds (i.e. frames, lamellas, bearing axels, rod linkages etc.) are made of stainless steel material no. 1.4571
- The blinds resist temperatures ranging from –25° C to +40°C, in case of fire the valves must be fail save for two hours time with temperatures up to 400°C.
- The valves resist pressure fluctuations of ± 2500 N/m² caused by the percussive power of the passing vehicles.
- The leak rate is less than 0,15 m³/m²/s with pressure fluctuations of 2500 N/m²



Ill. 3: waste air blinds

1.5 Modification of the SOS niches

The emergency call niches set up on the side of the carriageway with driving direction to Linz were modified in safe accessible niches and have been provided with separate fresh air intake ducts. In addition to that, the niches have been provided with emergency call boxes.
The tunnel users had to make their emergency calls previously on the pavement with the traffic passing by. The modification of the emergency call niches and other measures that have been taken i.e. the provision of the niches with fire emergency masks and the updating of the emergency call system represent an important step to raise the safety of the tunnel users. The technical plants in the niches are isolated from the main tunnel and the emergency call unit in order to protect them against fire.

Fresh air supplied by two compressors (one at each portal) is blown in by means of 6/4" polyethylene pipes laid under the pavement. The compressors have a power of 18,5 kW, the volume of fresh air supplied is 2,31 m³/min with 12,7 bar. The SOS niches are provided with fresh air intake ducts installed in a height of approximately 1,70 m by means of which the ventilation is accomplished. They are switched on automatically or by a hand lever. In case of a break of the main distribution conduct a safety device keeps the pressure at 1,8 – 2 bar.

Abb4. SOS niche and fresh air intake ducts

1.6 Indication of escape routes

According to the Austrian Guideline Code (RVS) 9.282, point 9.4.2 special lightings which help to find the next emergency exit indicating the direction and distance have been installed between the SOS niches.

In order to make the emergency exits to be found more easily the contours of the doors have been set off by not soiling phosphorescent plastic tubes fixed on the wall between the main tunnel and the crosscuts along the contours of the doors by means of spacers.

1.7 Phosphorescent reflectors on the kerb

The sides of the carriageways have been specially marked by means of phosphorescent reflectors. The reflectors are fixed on both sides on the emergency pavements and are lighted by means of light emitting diodes (LED) on the front and on the back (red on the right side, white on the left side). They are supplied with power by cables running under the pavement.
At the entrance area of the tunnel they are installed every 15 m and in the inner part every 25 m.
Investigations have shown that drivers keep more distance from the car ahead and the oncoming cars when LED-markings are installed.

Ill. 5: LED – reflectors on the kerb

1.8 Breakdown bays

To make the breakdown and turning bays to be found more easily from greater distances, they have been painted in a lighter colour and were provided with Metal Halide Lamps of a different colour, which produces a halation effect that breaks the monotony of the tunnel lighting and makes the bays more visible. In addition to that, the respective distances from the portals are indicated.

Ill. 6: Breakdown bay with emergency exit leading to the waiting area

2. Additional measures

In addition to the measures explained above the following safety measures have been taken as a result of investigations carried out by a group of experts set up by the former Minister of Innovation, Technology and Transport, Monika Forstinger:

2.1 Coating

The whole tunnel has been recoated. After the grounding had been prepared a water-soluble epoxy-painting colour ("magnolia") which is resistant against all types of emissions and salt and has a light-reflecting-power of 78% was coated on up to a height of 4,5 m.

2.2 Lighting of the main tunnel

The power of the lighting has been raised installing 150W-High Pressure Sodium Lamps instead of 100W-lamps. In addition to that, the walls are lighted more efficiently by means of reflectors. These measures did substantially improve the whole lighting of the tunnel.

2.3 Rumble stripes

In the area of the middle traffic-line millings 8-10 mm in depth and 30 cm in width have been cut every 30 cm. Investigations have shown that these millings produce good effects. Passing over these stripes the car gets into strong vibration and, in addition to that, the strong rumbling noise calls the attention of the driver to the danger.

The work was finished in December 2001
The total amount of costs is EUR 8,3 million

FIBER OPTIC TRANSMISSION SYSTEM "OTN"

Joris Fleerackers
Siemens Atea nv.
Atealaan 34
B-2200 Herentals
Belgium

ABSTRACT

OTN (Open transport Network) is an optical fiber based system for voice , data , LAN and video applications, allowing to interconnect most electronic equipment one finds in a Motorway and Railway environment.

It offers a multitude of interfaces that enable the user to transfer in a transparent way information from different types of applications over long distances. Its high degree of reliability and redundancy makes sure that it is suitable for use in critical environments like motorway and railway tunnels.

1. OPEN TRANSPORT NETWORK

1.1. Network Topology

The basic OTN network topology consists of a double fiber optic ring. (See Figure 1) One ring is used for information transport (active), the second ring (standby) is used as a backup for redundancy reasons. The network has the ability to automatically reconfigure in case of fiber breaks or node failures.

Due to the large number of interface cards that have been developed for OTN during the last decade, all applications (analog or digital) are connected directly to the network nodes (See Figure 1). This means that no intermediate media-converters or multiplexers are used. In this way, no extra single points of failure are introduced in to the network.

Overview of the number of interface cards directly available on OTN:

a) Audio/Voice interface cards

- Analog telephony
  - 2 wire a/b
  - 4 wire E&M
- Digital telephony
  - S0
  - $U_{P0/E}$ / U_{P0}
- Trunk
  - E1 (2.048 Mbps)
  - T1 (1.544 Mbps)
- Voice PA
- High Quality Audio (15 kHz)

b) DATA interface cards

- RS-232, -422, -485 (Point to point, Multi point, Multidrop)

c) LAN Interfaces

- Ethernet (10/100 Mbps)
- Token Ring IEEE 802.5

d) Video

- PAL, NTSC (M-JPEG compression)

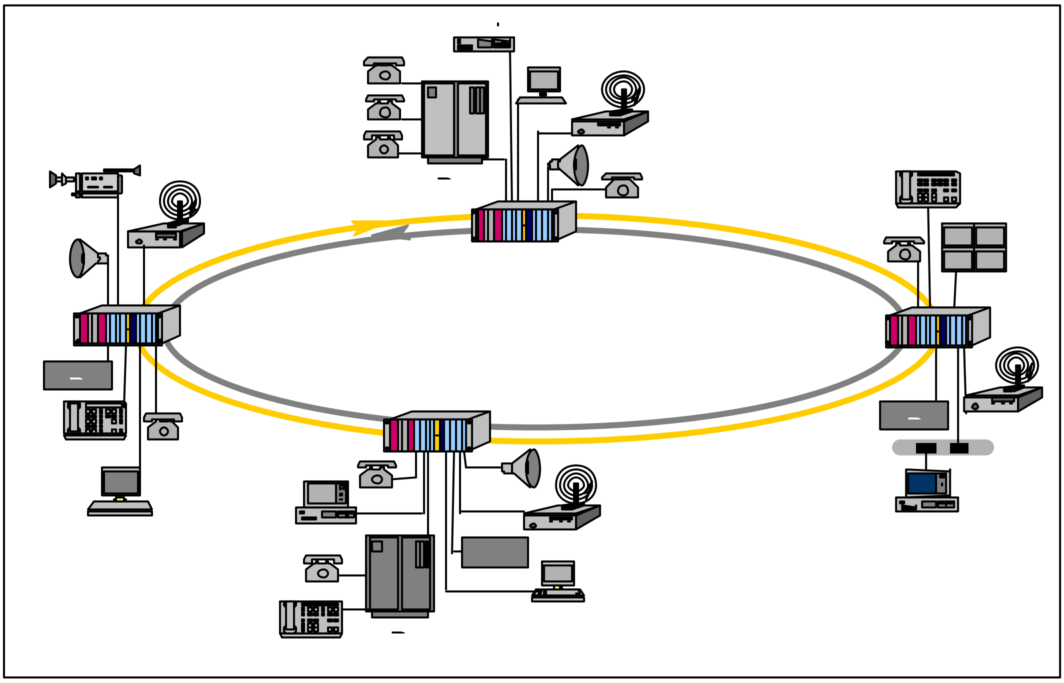


Figure 1 : Typical OTN network

Analog signals are sampled and converted to a digital bit stream on the interface cards. Then they are transported over the fiber optic network. On the other side, the signals are again converted to the original analog signal. The advantage of digital transmission is that the digital signal can be regenerated without loss of quality, thus allowing the transport of the signal over long distances (1000km).

1.2. Transmission technology : TDM

OTN is an access and transport network , based on TDM technology. Time Domain Multiplexing (TDM) is a well-known technique in digital communications. It allows to transmit different signals , over one physical cable by allocating a timeslot to each signal. TDM is used in PDH (Plesiochronous Digital Hierarchy) and SDH (Synchronous Digital Hierarchy) transmission equipment, and also in OTN (Open Transport network).
The advantage of TDM technology as opposed to packet based technologies (such as ATM or Ethernet), is that fixed timeslots can be allocated to a signal. Because of this no information is lost (even when the network capacity is used for 100%) and timing relations are maintained.
In critical environments, as for instance tunnels, every application that is connected to the main transmission backbone is considered to be important in case of an emergency. In these moments no loss of information can be admitted.

1.3. OTN ring types

OTN provides rings with different capacities: 150Mbit/s, 600Mbit/s or 2,5 Gigabit/s. This allows the network to be designed optimally for the amount of bandwidth required by the applications. Another way of optimizing the use of the backbone capacity is the fact that bandwidth is allocated to the applications in small steps of 32 kbit/s. In this way no bandwidth is wasted and low speed applications like analogue telephony and serial data connections (RS232,…) can be handled in an economical manner.

1.4. Networking with OTN

If required, OTN ring networks can be coupled, using the OLM (OTN Link Module). This module allows the transfer of data between rings, using an E3 (34Mbps) or DS3 (45Mbps) link. Depending on the amount of data to be transferred between rings, one ore more OLM links can be used.

In the case of OTN150 (150Mbps) nodes can also be connected using SDH/SONET STM1/OC3 links. This allows the creation of OTN rings, which go partially or completely over an SDH/SONET network. This also allows SDH/SONET radio connections to be used for sections where it is not possible to install fiber optic cable.

1.5. OMS (OTN Management System)

The complete OTN network can be managed using OMS (OTN Management System). Using OMS, it is possible to monitor the complete OTN network from a central location, but also distributed network management is possible. The OMS can interact with other management system using SNMP (Simple Network Management Protocol).
OMS uses a relatively inexpensive PC operating under Windows NT as hardware platform.

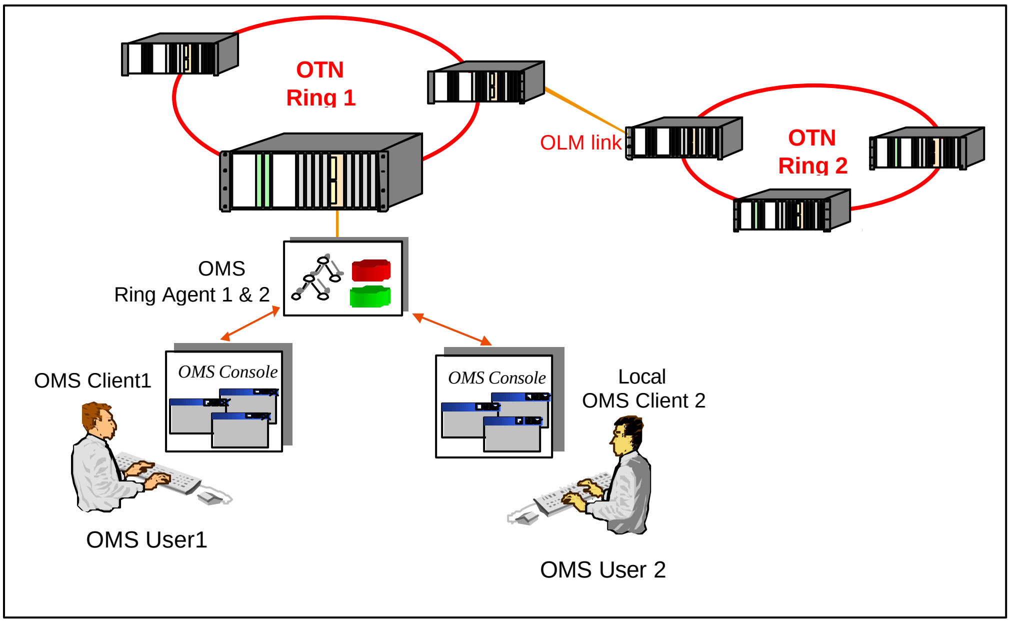


Figure 2 : OTN networking and OMS

2. DIGITAL VIDEO SWITCHING ON OTN

Any type of video equipment (cameras, monitors, recording equipment), including the associated control signals, can be connected directly to the OTN system. The video switching capabilities are embedded in the OTN system itself, enabling any incoming picture to be displayed on any monitor connected to the OTN. This is a substantial advantage to security installations, reducing the (fiber optics) cabling enormously and reducing the extra cost for switching matrices and crossbars.

OTN's video interface cards use M-JPEG for the transmission of high quality video signals. Both PAL and NTSC standards are supported. The video-input cards (camera side) and video-output cards (monitor or recorder side) are equipped with up to four video inputs/outputs and five data ports for e.g. PTZ control.

The bandwidth allocated to a channel can be assigned individually and can vary from one Mbps up to 12 Mbps. The picture quality can be customised by adjusting the colour information, the horizontal and vertical resolution and images/sec, all on a per channel basis.

3. CONCLUSION

The OTN product is meant for customers having vast premises, who are capable of installing their own optical fiber cabling and who need a wide diversity of communications. The maximum benefit of the system can be applied in applications such as railways, subway and tram networks, pipelines, intelligent highways, tunnels, airports, mines, industrial plants, harbors, etc.

INTELLIGENT IMAGE PROCESSING AND VIDEO OVER IP

Otto Groh (O.G)
Isabel Kock (I.K)
Fa. Arti*Brain* Forschungs- und Entwicklungsgesellschaft mbH
Egon Schiele-Gasse 24
A-3400 Klosterneuburg
Phone: +43/1/3344356-771 or 779; Fax +43/1/3344356-154
Mail: ogroh@artibrain.at

ABSTRACT

As an accident in an tunnel can be crucial, every second can save lives and keep material damage to a minimum.

The system developed by ArtiBrain, ABT2000 (Arti Brain Tunnel 2000) improves the way events are filtered, evaluated and made visible in a meaningful form for decision making.

The major advantages of ABT2000 for existing as well as new tunnel systems (road and railway tunnels) are

- *significant shortening of reaction times*
- *specific, event-triggered raising of alarms*
- *exact evaluation of danger situations*
- *smooth integration into the process control system*
- *use of standard hardware*
- *cost reduction*

ABT 2000 consists of the following modules

- *Digital traffic television and digital image recording*
- *Traffic flow analysis*
- *Distance measurement*
- *Classification of vehicles*
- *Measurement of visibility quality (early detection of smoke)*
- *Detection of hazardous goods plates*

Key words: *Digital traffic television/image recording, Traffic flow analysis, Distance measurement, Classification of vehicles, Detection of hazardous goods plates*

1. The company

ArtiBrain was founded in 1993 by staff members of the Vienna Technical University.

In the beginning, artificial neuronal networks were the main area of research.

The algorithms for pattern recognition out of video images that were created then (as a by-product, so to speak) became the basis for subsequent ArtiBrain projects as the company's focus shifted towards commercial products in the field of image processing.
Years of experience and existing research cooperations (e.g. with the Joanneum Research in Graz) enable ArtiBrain to offer custom-made applications for the market.

The company today

Twelve employees, nine of them working in R&D, covering a wide range of skills in

- computer engineering and software development
- industrial electronics
- mathematics
- physics

2. The challenge/Critical situation: accident in the tunnel

When an accident happens in a tunnel, seconds can be crucial. Fast and efficient coordination of the rescue effort is of the utmost importance. Only this way danger can be avoided, human lives saved and material damage kept to a minimum.

An ongoing flow of status and alarm messages converges in the tunnel operations centre where it has to be analysed and evaluated for the decision-making process by the operation personnel.

3. Improvement on the status quo

Modern image processing techniques can be used in order to improve the way events are filtered, evaluated and made visible in a meaningful form for decision-making.

The tunnel safety system developed by ArtiBrain called ABT2000 (ArtiBrain Tunnel 2000) sets new standards in the automated acquisition and intelligent evaluation of data regarding the whole spectrum of hazards in tunnels, as well as optimisation of rescue effort logistics.

The major advantages of ABT2000 for existing as well as new tunnel systems (road and railway tunnels)

- significant shortening of reaction times
- specific, event-triggered raising of alarms
- exact evaluation of danger situations
- smooth integration into the process control system
- use of standard hardware
- cost reduction

ABT2000 is an innovative information system based on the principles of digital pattern recognition and intelligent image processing.
Video cameras (and optionally other sensors) are the "eyes" of ABT2000.
The evaluation of situations and the resulting actions (like automatic display of a camera channel on an alarm monitor in the tunnel operation centre) are realized according to mathematical algorithms and methods.
Another part of the software developed by ArtiBrain provides very fast information transport over the networks. Within the LAN (local area network), data transfer is done with a bandwidth of 100 Mb (100 million bits per second.)

ABT2000 consists of the following modules:

- Digital traffic television and digital image recording
- Traffic flow analysis
- Distance measurement
- Classification of vehicles
- Measurement of visibility quality (early detection of smoke)
- Detection of hazardous goods plates

4. ABT2000 system principles

4.1 Standards and interfaces

ABT2000 can be used as a system or as a sensor within a process control system.
For reasons of stability and in order to fulfil the high demands of the complex and time-critical image analyses, LINUX is used as an operating system.

Transparent interfaces enable smooth integration into existing IT architectures.

Using standardized SSI telegrams, the calculated data is made available to the process control system, and instructions are received from it.
The system's hardware consists of scalable computers, sensors, video cameras and standard network components.

There are two different kind of computer units:

a) Systems on location in the tunnel
These units are used for image capturing, image analyses and streaming.
Because of their long lifetime and minimal failure rate, only embedded systems are used for the tunnel units. Up to four cameras can be installed on one tunnel unit.

b) Systems in the tunnel operation centre
These units are used for handling display requests for live and recorded images.
Up to four monitors can be installed on one display unit.

4.2 Traffic television

Functionality:

- broadband live streaming
- digital recording and playback
- reconstruction of alarm and accident situations
- remote accessibility of recorded images
- optimised planning of emergency operations
- reduction of reaction times

Workflow:

The images are captured in standard PAL/NTSC format, hardware-compressed on the tunnel units, and streamed to exactly those display units in the tunnel operation centre that have requested display of the specific camera channel.
The frame rate is 25 full images (= 50 half images) per seconds.

The image is displayed on the requested monitor with a video key that contains the camera number, timestamp, display mode (Live/Playback) and a freely configurable text field. (for instance: a situation dependent text giving the reason why the automated display on an alarm monitor was switched on.)

The compressed video stream is also stored with a frame rate of 25 full images per second. Storing is done either locally to disk on the tunnel unit or centrally in the tunnel operation centre. Default storage size per camera is 75 minutes, implemented as a ring buffer. (the oldest images are overwritten.)
In case of an alarm, recording is stopped after a maximum of 60 minutes after the event. From this time on, the recorded data is no longer overwritten. This way, the 15 minutes before the

alarm remain available for evaluation. (what constitutes an alarm in this context, as well as the specific lengths of recording time, is configurable as well.)

This recording concept (at full frame rate, as mentioned before), by enabling exact reconstruction of events, provides highly valuable information for the emergency services.

Playback of the recorded image data of each camera can be requested in the tunnel operation centre (via the display unit).
Playback options include the selection of start time, playback direction (forward/backward) and speed (normal, freeze-frame, fast forward/fast backward).

Video data recorded in alarm mode stays write protected until
the operator of the process control system enters a command to the contrary.

4.3 Traffic flow detection and analysis

Functionality :

Detection of

- ghost riders
- breakdown bay occupation
- motion in defined "no-traffic" areas
- Measurement of distance between subsequent vehicles
- Speed measurement per lane
- Vehicle counter per lane
- Rough classification of vehicles ("car"/"truck")

Workflow:

The uncompressed images captured by the camera are analysed using mathematical algorithms for object detection and object tracking.

Calibration and information about well-defined reference data (camera position, camera slant, distance between camera and road markings) are prerequisites for the proper functioning of this module.

For each camera, several lanes (with traffic direction = direction of sight of the camera) can be analysed separately.

The following raw data are computed pre camera and lane:

- speed
- distance between subsequent vehicles
- braking distance
- number of vehicles in the field of vision
- direction of movement (with or against the defined traffic direction)
- rough classification truck/car

Statistical evaluation of this raw data results in the computation of values like average speed, traffic volume and traffic density for specific tunnel sections.

4.4 Classification of vehicles

For the exact classification of vehicles, ABT2000 offers the option of accessing an external sensor that combines ultrasonic/radar/infrared measurements. ABT2000 handles the initialisation and configuration of the sensor, receives the data provided by it, does some statistical analyses (e.g. average speed for each category) and forwards it to the process control system.

At the moment the sensor classifies vehicles in 2+6 classes according to TLS
(car, car with trailer, truck, truck with trailer, container truck, bus, motorbike, others).

The module also supplies information like traffic count, ghost rider detection, speed measurement, traffic flow analysis et al., for further processing by the process control system.

4.5 Measurement of visibility quality (early detection of smoke)

This is a special feature of ABT2000. Using the configuration GUI, one or more areas in a camera's field of vision are defined (including predefined threshold values).
Within this/those area(s) a current value for the visibility quality is computed (using a gradient analysis algorithm). The resulting data is sent to the process control system, where pre-alarm or alarm can be triggered according to configurable threshold values.

4.6 Detection of hazardous goods plates

Functionality:

For preventive risk assessment covering the traffic flow in the whole tunnel area it is necessary to know the number and position of hazardous goods transports as exactly as possible.

This is achieved by detection of the standardized hazardous goods plate by evaluating the image data.

Basic description:

The uncompressed images captured by the camera are analysed in order to find hazardous goods plates according to ADR.

The law requires HGPs to have certain significant properties, for instance:
dimension of 30 by 40 cm, a black edge that is 15 mm wide, orange colour inside.
Those values are used as input parameters for the search algorithm, which, also using inherent characteristics like the horizontal position of the plate in the image, looks for rectangles of the given size and colour in a defined area of the image.

Once a HGP has been detected, the information is stored in the system; combining information from subsequent cameras, the vehicle can be tracked through the tunnel.
This way, the number and approximate position of hazardous goods transports can be computed and displayed for the whole monitored area.

5. Special features of ABT2000

Because of highly efficient integration of the video signals (50 half images/sec per camera signal), ABT2000 is suitable for use as a traffic television system.

Because of the digital processing of the video signals, ABT2000 eliminates the need for a conventional video-switching network, while standard (existing) video monitors can be used for visualization.

ABT2000 provides digital image recording at full frame rate; the default length of the ring buffer per camera is 75 minutes; in case of alarm, this means a default of 15 minutes before and 60 minutes after the event that are available for playback.

Using digital image processing, ABT2000 combines the functionality of several sensors, providing information about traffic status, visibility quality and current system conditions.

ABT2000 increases tunnel safety by detecting hazardous goods plates on vehicles.

ABT2000 strictly adheres to open standardized interfaces, making it compatible with other systems; the data output interface is also openly disclosed.

ECCO - NEW ELECTROSTATIC PRECIPITATOR PILOT PLANT AT PLABUTSCH TUNNEL IN GRAZ

Heinz Aigner
Aigner GmbH
Dieselstraße 13, A-4623 Gunskirchen
e-mail: heinz.aigner@aigner.at

Abstract

We have been researching and developing a filtration system for road tunnels together with the Technical University of Graz since 1991. The first result of this was an electrostatic precipitator based on a 2-stage filter technology with an ioniser and a collector made of parallel plates. During this research work we found a new possibility of collection of dust particles – the ECCO-system. ECCO means Electrostatic Charged Contact. This also contains an ionising part, but for the second stage a special collector without voltage was developed.

Electrostatic precipitators (E.P.) are used in road tunnels, but there is significant uncertainty as to their effectiveness, depending on local conditions and the precise equipment used.

A pilot plant was thus set up within the Plabutsch tunnel in Graz, in order to determine whether EP's are suitable for road tunnel applications. In particular, the initial investment costs, running costs and maintenance interval for a typical installation were studied.

Electrostatic Precipitators can handle only dust particles e.g. diesel soot or tyre wear particles, as well as products of road abrasion. Gaseous components were not investigated in these tests.

1. ASSEMBLY OF PILOT PLANT

1.1. Location

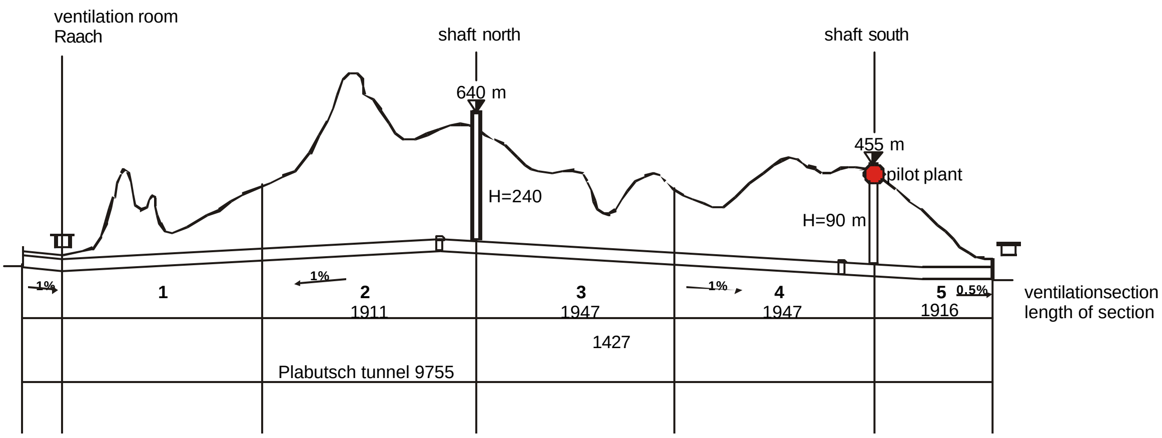


Figure 1 Location of pilot plant

1.2. Technical data

Tunnel exhaust air will be taken of the outlet shaft (figure 1) in the south of the tunnel. The pilot plant consists of the duct system (Ø 630 mm), filter unit, radial fan and cleaning equipment (figure 2).

Airflow max. 15 000 m³/h
High voltage 10-21 kV
Current max. 8 mA

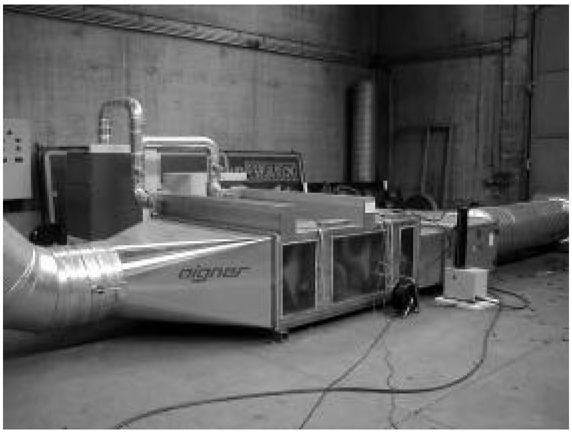


Figure 2 pilot plant

The dust concentration will be recorded upstream and downstream of the filter at the same time, velocity and pressure drop will be recorded too as one-minute mean values.

2. PRINCIPLE OF OPERATION

2.1. 2-stage electrostatic precipitator

As contaminated air enters the E.P. it must pass by spiked ionizer blades supported between grounded electrodes. The DC voltage creates a high intensity field wherein the particulate matter in the air becomes electrically charged. The charged particles then pass a collector plate section made up of a series of equally spaced parallel plates. Each alternate plate is charged with the same polarity as the particles, which repel, while the interleaving plates are grounded, which attract and collect.
Positive and negative ionisation is possible. Figure 3 shows positive charging.

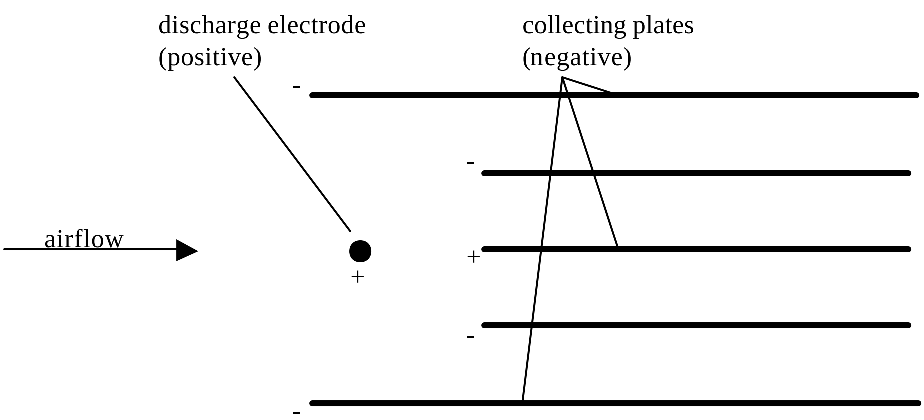


Figure 3 2-stage electrostatic precipitator

2.2. ECCO – system

The particles must pass also the ioniser blades between grounded electrodes. The particles will be charged as shown in figure 3 in the high intensity field created by the DC high voltage. The ECCO collector is a mesh filter and the charged particles must have a contact with the filter. So the particles will be collected at the surface and inside the filter.
To reduce the risk of flashover, negative ionisation can be used.

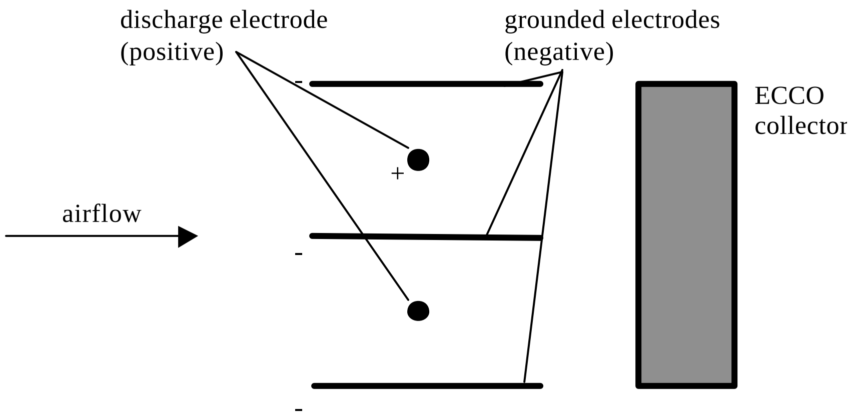


Figure 4 ECCO principle of separation

2.3. Cleaning of the ECCO filter system

Standard E.P. must be washed in offline mode. The complete time for cleaning including the drying of the filter cells need several hours. At this time the filter cannot be used. The waste water includes the whole dust and must be cleaned.

The ECCO collector has no voltage with the advantage that it is possible to clean it in online mode during operation. The collector could be cleaned with an automatic pneumatic system or also a wash system (depending of filter material). With a high pressure nozzle or pressed air (figure 6) dust will be blown away of the filter. At the other side the dust will be collected with a nozzle (figure 5) and separated in a usual dust filter. The ionising part should be washed. There is only a small amount of dust and the time intervals for cleaning are longer. A water treatment with re-circulated wash water can be used.

Figure 5 Nozzle for dust collection

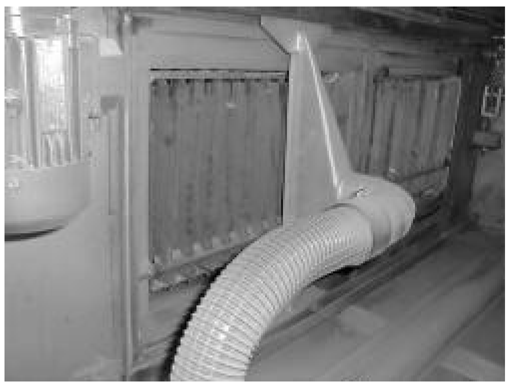


Figure 6 High pressure nozzle

3.1. Measuring instruments

TEOM Series 1400 (Rupprecht & Patashnik) . A filter element vibrates together with the tapered element at a frequency of several hundred Hertz. With increasing dust load on the filter element the frequency of the oscillating sensor diminishes. The electronic system continually registers these changes in frequency (every 2 s) and calculates the overall mass concentration.
Aerosol spectrometer Grimm 1.105. A real-time optical method (laser light scattering). When particles pass the laser beam they scatter light. These signals are collected by a photo diode detector and classified by multi-channel pulse height analyzer for size classification.
STE 12 (Ströhlein). A gravimetic method with glass fibre plane filter. The mass of suspendend particles was gravimetrically determined with a microbalance after drying for 1 hour at 150 °C.
We have compared the different systems to obtain more confidence in the results. In partcular, the laser technology always required a second system to determine weight factors for each dust.

3.2. Efficiency

Different systems are compared, as there are:
- standard electrostatic filter unit
- XT special tunnel filter cell
- ECCO filter system

One of the goals in development of filter systems is to have a small filter to reduce costs for rock excavation and installation. This means higher velocities in E.P. as common in standard applications. Standard equipment cannot really be used because the efficiency reduces rapidly with higher velocity.
This leads to the development of special tunnel filter cells with optimised distance between the collector plates, length of collector and high voltage.
The efficiency of these units is about 85 to 90 %.
The problem of high velocity is shown in figure 7. Collected dust can be blown away if the thickness of the dust layer is increased and the velocity high.

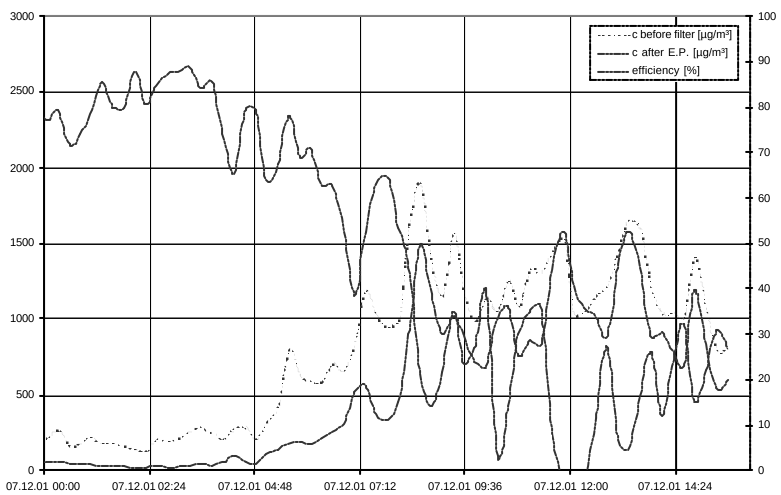


Figure 7 unintended cleaning

For this reason it is recommend not to design to high air velocities or to long intervals between filter washing.

The efficiency of the ECCO filter is up to 90 % with a mean value about 85 % and shown in figure 8. The efficiency also depends on the used material in the ECCO collector.The pressure drop is higher than with an E.P. with collector plates. Depending of the velocity through the filter, the pressure drop for an ECCO filter is between 150 and 250 Pa. Because the ECCO collector is also a mechanical filter, it is possible to handle all particle sizes. The efficiency would be even greater if larger particles are contained in the exhaust air.

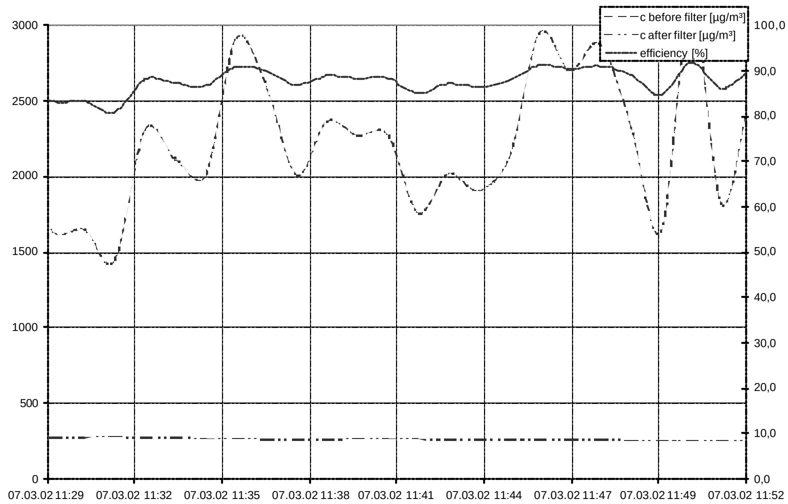


Figure 8 ECCO system

The best result was obtained with the combination of ECCO with the XT tunnel cell . This gave an efficiency of up to 95 %, since the benefits of both systems are additive. The diagram shows that the efficiency is higher if the inlet concentration increases, since the outlet concentration remains more or less constant.

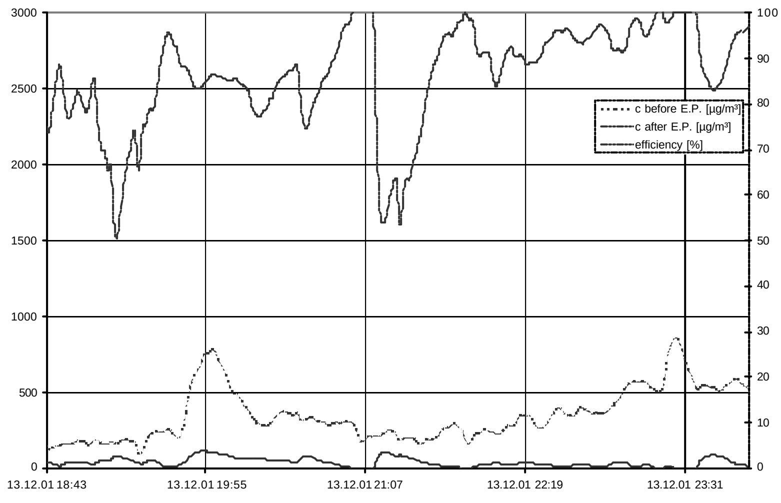


Figure 9 ECCO with XT tunnel cell

As mentioned previously, the size of the filter plant is very important. The construction of the filter units needs frames and so the velocity in the filter is not the same as in the cross-section of the tunnel. Table 1 compares the possible airflows.

Table 1 Airflow m³/s per m²

	Airflow in m³/s for 1 m² cross section			
Eficiency [%]	**Standard E.P.**	**XT**	**ECCO**	**ECCO-XT**
75	3,5	5,6	6,4	
80	3,0	4,8	6,4	
85	2,6	4,2	6,4	4,6
90		3,8		4,2

Table 1 shows that a standard E.P. as used in some tunnels requires more than 60% room compared to special equipment designed tunnel air filtration.

3.3. Particle analysis

The analysis of heavy metals as Pb, Cu, Co, Ni, Cd, Sb showed no significant contents.

The samples were also analysed for **DME (diesel-motor-emission)** as elemental Carbon. During the measurement the range was from 13 to 18%. The efficiency for DME was about 60%.

The particle size analysis showed that about 30% are smaller than 2,5 µm. About 60% are between 2,5 and 10 µm, and 10% bigger than 10µm. (These results are from the measurement with the Grimm instrument and will be confirmed with an impactor shortly).

4. INVESTMENT AND RUNNING COSTS

The initial investment costs depend on the wishes of the customer and governmental regulations, which can be different in different countries.
The running costs consist of power supply for E.P. and fans, water or pressed air for filter cleaning and for maintenance.

4.1. Investment

The price factor to compare ECCO with an E.P. with parallel collector plates is about 1,3 for aluminium and 2,2 for stainless steel higher than the ECCO filter. This factor includes only the filter cells and no other equipment.

4.2. Running costs

The power consumption of an E.P. is very low because the current is only a few mA. The pressure drop across the filter results in higher fan capacity.

The figures are calculated for an airflow of 100 m³/s.

Power consumption of E.P.:
(for 12 hours a day and 365 days a year) 12264 kW/a € 12.300,--
1 kw = € 0,036

Power consumption of fan:
It depends of the pressure drop of the filtersystem
(ECCO 150 Pa, XT 50 Pa)

50 Pa	0,0625 kW/m³s	19500 kW/a	€ 700,--
150 Pa	0,1875 kW/m³s	58500 kW/a	€ 2.100,--
250 Pa	0,3125 kW/m³s	97500 kW/a	€ 3.500,--

The calculation is made with 10 hours running a day with full capacity, 6 days a week and 52 weeks in a year.

Cleaning of filter:
For pressed air or water for the wash process are necessary about € 4000,-- a year.

Maintainance:
It would be recommended to make minimum one service in a year. The costs depends on different factors and could only calculated for a plant. For an estimate calculate about € 7.000,-- for the ECCO filter and € 11.000,-- fot the XT filter.

5. CONCLUSION

Electrostatic precipitators are a good solution for separating the dust from road tunnel exhaust air. Various negative statements about the efficiency of E.P. are probably based on excessive promises, wrong lay outs and use of standard products.

ECCO has a slightly reduced efficiency compared to E.P. with parallel plates, but many benefits for the user. It is cheaper, easier in construction, has longer lifetime and simpler maintenance. Both systems can be used for tunnel application.

It would be of significant interest to develop a method for determining dust concentration to high accuracy.

6. ACKOWLEDGEMENTS

The author would like to acknowledge the financial support of the Austrian federal ministry of traffic, innovation and technology, ASFINAG, Province of Upper Austria, Styria and Salzburg, who sponsored the pilot plant.

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

E. Forsthuber, Ing.-Kons., ISF, Salzburg
K.Pucher, TU Graz, Inst. f. VKM und Thermodynamik

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 have to be made in a leak proof way. According to water right law this is an indispensable general demand. Otherwise there will be an important interference with groundwater 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.

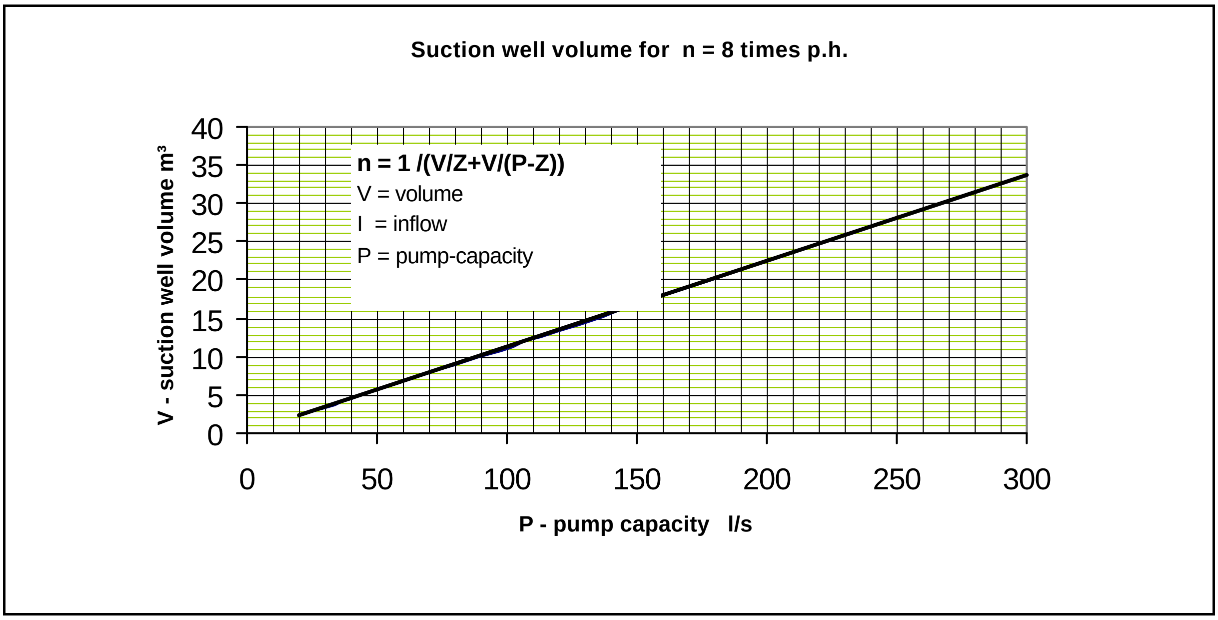
1.2 Pumping stations for rain-water

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. 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.

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.

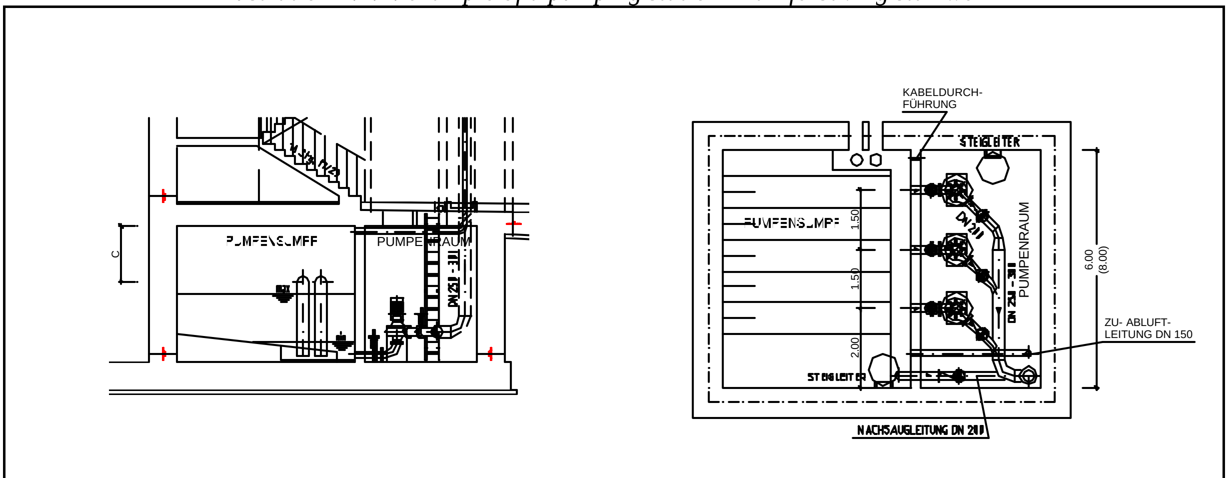
Illustration 1.2.1: suction well volume:



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.

Illustration 1.2.2: 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 many 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. Access from the life-saving tunnels is exclusively granted via a screwed manhole. 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). These guidelines define the state of the art in technology and may be seen 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 at all.

Every 500 m there must be cross connections from the traffic tunnel to the life-saving tunnels or the emergency stairwells respectively. Between the traffic tunnel and the life-saving tunnels/emergency stairwells there must be sluiceways of at least 12 m length.

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 has the be 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 in one of several railway carriages and the train cannot leave the tunnel for technical reasons any more. The people escaping from the traffic tunnel must 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.

At a fire size of about 60 MW, which is the basis for the calculation of the necessary fresh air, the critical longitudinal velocity u/m/s is 3 m/s. With that the necessary fresh-air volume V (m^3/s) can be calculated from the equation $V = A . u$ when the escape tunnel cross section A (m^2) is given.

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. This ratio produces a force which makes the tunnel air move into direction of traffic. 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 lit. /2/.

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.

Illustration 2.4.2.1 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.

*Illustration 2.4.2.1 / distribution of velocity in the main tunnel VOMP (A *cw = 120m*m, train passes, pressure difference p1-p2 = 0 N/m*m)*

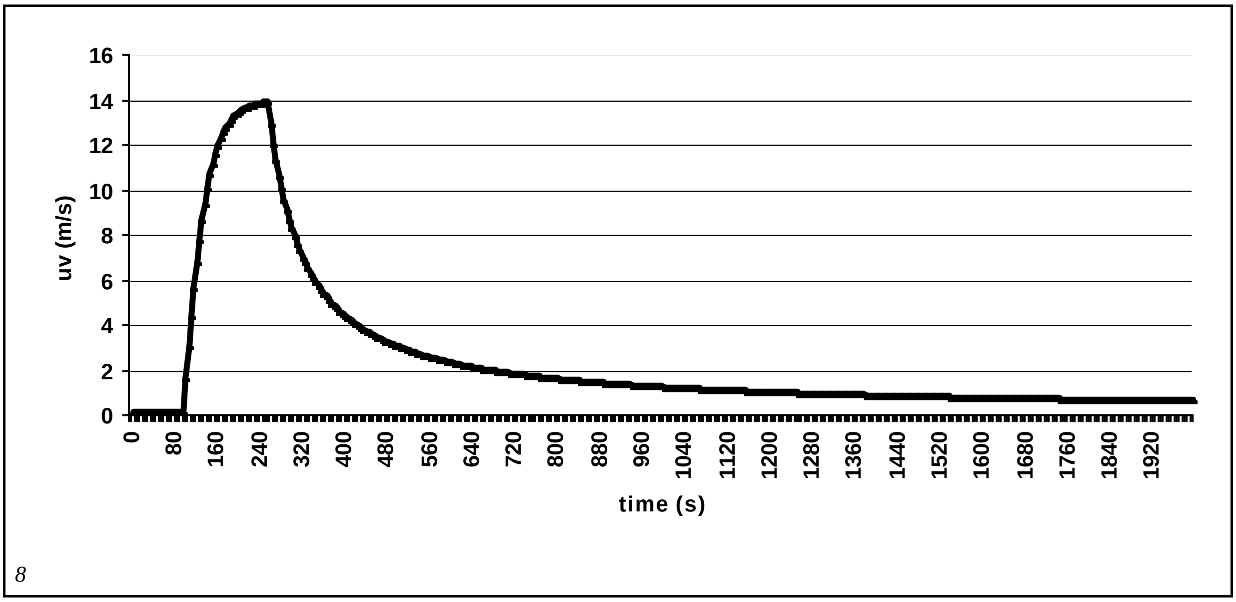
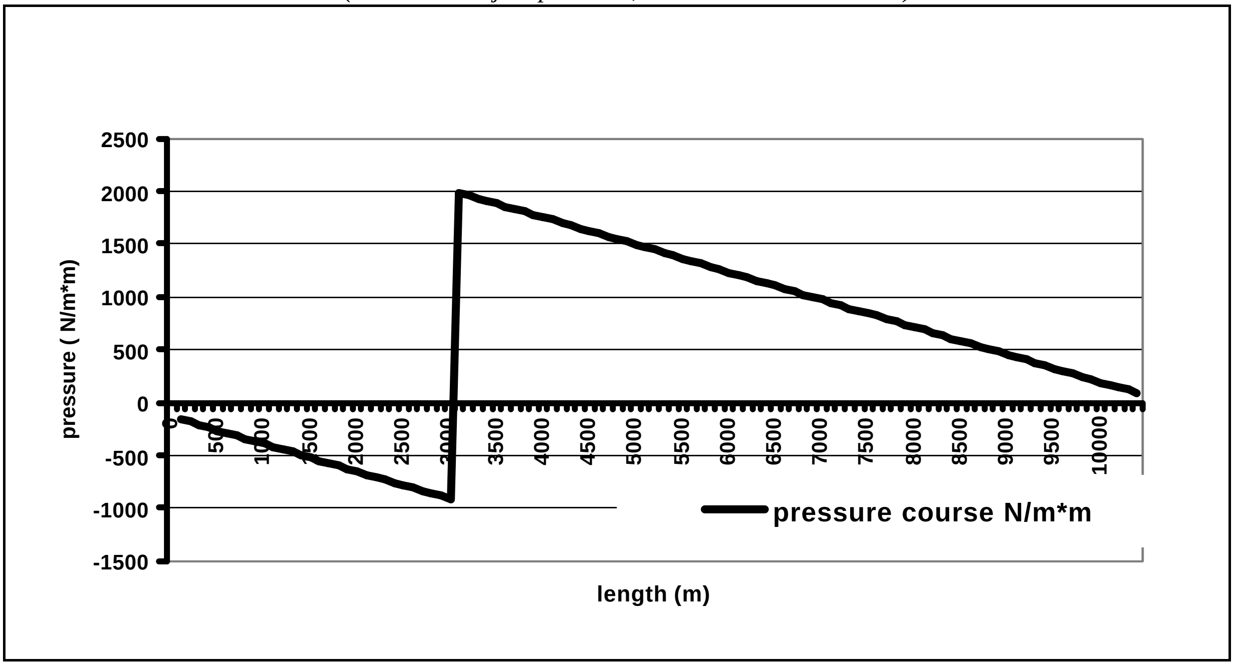


Illustration 2.4.2.2 shows the static changes in pressure to be expected at a travel velocity of 250 km/h in the Vomp tunnel provided that there are no effective pressure differences between the 2 portals and that the engine has just passed 3,000 m in the tunnel. In front of the engine a strong overpressure 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.

Illustration 2.4.2.2 / pressure course in the main tunnel VOMP during passage of a train (the train has just passed 3,000 m in the main tunnel)

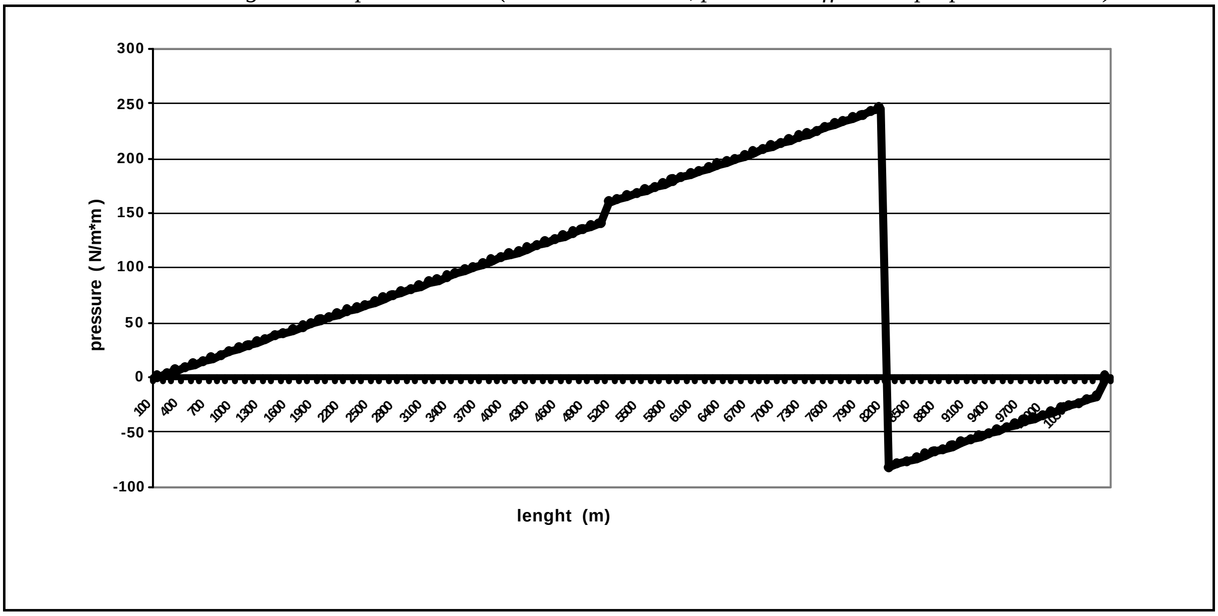


The illustration 2.4.2.3 shows when a train at high speed enters the tunnel through the left portal (km 0) and then slows down. 15 seconds after this an oncoming train reaches the right portal and enters the tunnel. Only in the tunnel the emergency brake is applied. On account of the oncoming train the 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 illustration 2.4.2.3. 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.

*Illustration 2.4.2.3 / 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.pFD (losses by friction, diversion etc.)

diff.pTh (thermic influences)

diff.pTM (influences by train movements in the main tunnel)

The efficiency of the blowers results from the equation:

P = V . diff.pT / ? v 2.5.1

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

diff.pT = diff.pFD + diff.pTh + diff.pTM 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 up to 250 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 sluice gates have to be fire resistant, T 90. It must be possible to open them electro-mechanically 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.

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 / s. In pre-pressed tunnel profiles or tunnels dug by miners the air volume is larger.

In life-saving tunnels the air feed ducts to the sluiceways are the tunnels themselves. From the tunnels the air enters the sluiceways to the main tunnel 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.

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RESCUE TUNNEL FOR THE CASE OF FIRE IN THE RAILWAY TUNNEL

Jurij MODIC
Faculty of Mechanical Engineering
University of Ljubljana
Slovenia

ABSTRACT
Mountains in Slovenia, in the Region Kars, in the direction to the Adriatic Sea are serious obstacle for the railway's traffic. By the new planed railway so are provided a few tunnels all together long about 20 km. Because of safety measures all the tunnels longer than 1000 m they must have a rescue tunnel too. In the rescue tunnel in the case of fire in the main (railway) tunnel it must be higher air pressure as in the main tunnel. In the article the basic information and solutions about this problem are given. Al the solutions are in according with "Richtlinie Anforderungen des Brand – und Katastrophenschutzes an den Bau und Betrieb von Eisenbahntunneln", BRD, 1997

1. INTRODUCTION

On Fig 1.1 the situation is shown. Between Divaca und Koper (Slovenia) there is a new railway with tunnels, about 20.000 long.

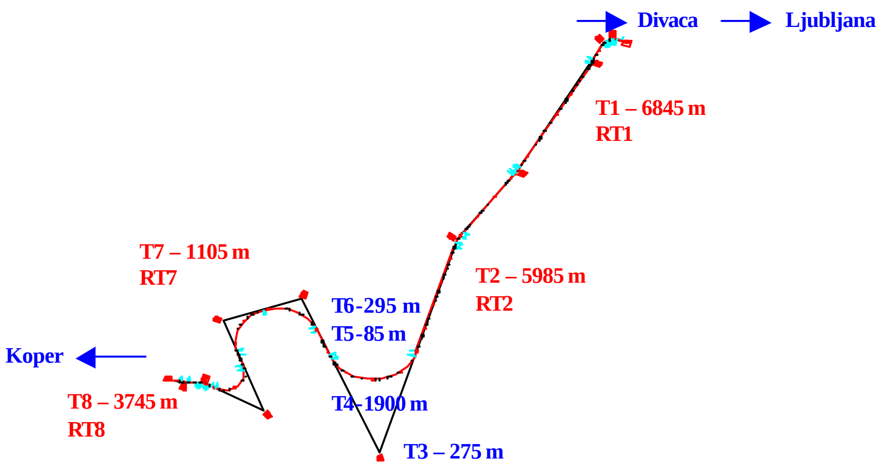

Fig. 1.1: Tunnels and Rescue Tunnels, location and length.

Tab. 1.2: Tunnels and their length

MAIN TUNNEL	RESC. TUNNEL	LENGTH m
T1	RT1	6.845
T2	RT2	5.985
T7	RT7	1.105
T8	RT8	3.745

2. BASIC PRINCIPLES

On Fig. 2.1 the basic principle of the rescue tunnel is shown. Between main tunnel and rescue tunnel they are rescue connections, closed with dour, every 500 m. The length of rescue tunnel is equal as main tunnel (see Fig 1.1 and Table 1.1).

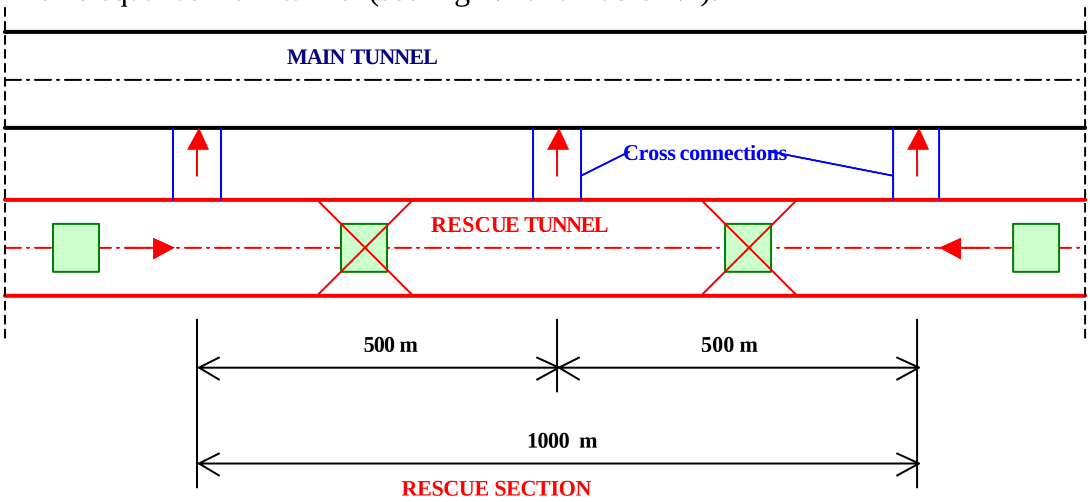

Fig. 2.1: Rescue tunnel and Rescue sections

The fans inside of rescue section are not active; the fans outside of rescue section are blowing the air from both sides (both portals) to the middles of rescue tunnel.

2.1 Rescue section

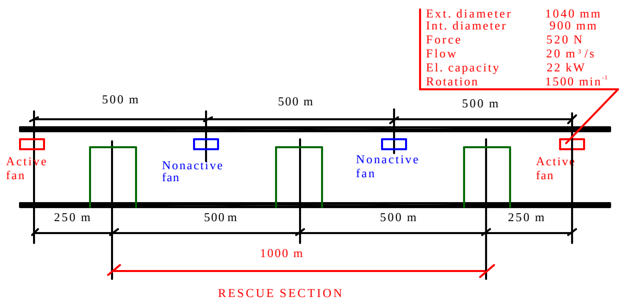

Fig. 2.1: Rescue section

2.2 Air velocity

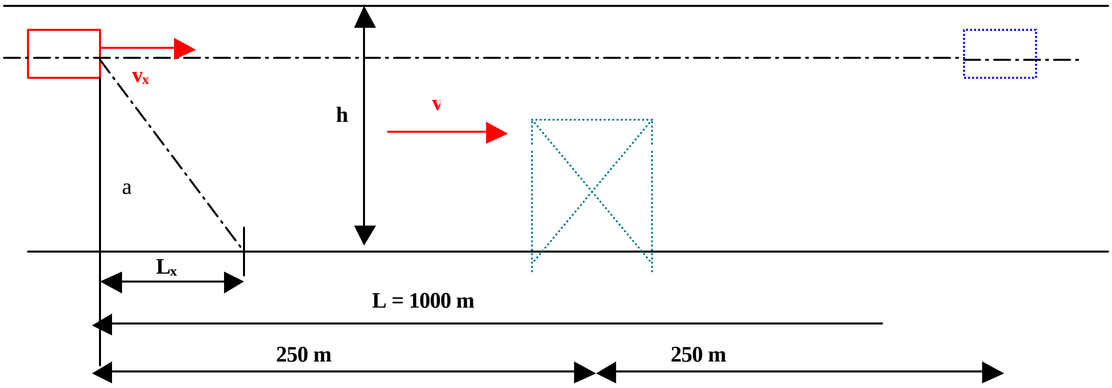

Fig. 2.2.1: Air velocity

Main characteristics of the fans are (see also Fig. 2.2.1):
V = 20 m^3/s
D = 900 mm
n = 1520 n^{-1}
P = 520 N
N = 22 kW

The basic data:
h = 3 m
v_0 = 31 m/s
V = 20 m^3/s
a = 8 °
n = 1
K = 6

With using equations for induction is:

$$L_x = \frac{h}{tg\,\alpha} = \frac{3}{tg\,8} = 21\ \mathrm{m}$$

$$v_x = \sqrt{2}\,\frac{K\,n\,V}{L_x\sqrt{n\frac{\pi d^2}{4}}} = \sqrt{2}\,\frac{6\,.\,20}{21\sqrt{1\frac{\pi\ 0.9^2}{4}}} = 9.40\ \mathrm{m/s}$$

Average air velocity

$$v = \frac{9.40}{2} = 4.70\ m/s$$

and air flow rate

$$V = v\,.\,A = 4.70\,.\,13 = 61\ \mathrm{m^3/s}$$

At air velocity 4.70 m/s is the pressure drop

$$\Delta p = 0{,}02\,.\,\frac{1000}{4{,}30}\,\frac{1{,}20\,.\,4{,}70^2}{2} + 5\,\frac{1{,}20\,.\,4.70^2}{2} = 128\ N/m^2 = 128\ Pa$$

So the air velocity at 1000 m is

$$v = \sqrt{\frac{2\,.\,128}{1{,}20}\frac{1}{\frac{0{,}020\,.\,1000}{4{,}70}+5}} = 4{,}80\ m/s$$

and at 500 m

$$v = \sqrt{\frac{2\,.\,128}{1{,}20}\frac{1}{\frac{0{,}020\,.\,500}{4{,}70}+5}} = 5{,}45\,m/s$$

2.3 Overpressure in the rescue section

Theoretically we may say, that instead of air flow in the opposite direction is a wall. So is:

$$\mathrm{I} = \mathrm{m}\,.\,\mathrm{v} = \mathrm{V}\,.\,\rho\,.\,\mathrm{v} \qquad [\mathrm{kg\,m/s}]$$

$$\mathrm{P} = \mathrm{I}_2 - \mathrm{I}_1$$

and in according with Fig. 2.3.1:

$$\mathrm{P} = 0 - \mathrm{I}_2 = -\,\mathrm{V}\,.\,\rho\,.\,\mathrm{v}$$

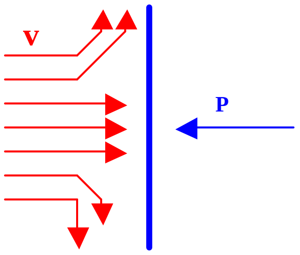

Fig. 2.3.1: Impulse and forces

$$P = 61\,.\,1{,}20\,.\,5{,}45 = 398\ N$$

So the overpressure is

$$p = \frac{P}{A} = \frac{398}{13} = 30\ N/m^2 = 30\ Pa$$

If the cross connections are closed, the overpressure at point D is

p_D = 30 Pa

Airflow from one direction is 61 m^3/s. So the air velocity in the connections is

$$v = \frac{61}{(2{,}50\,.\,3{,}10)+\frac{2{,}50\,.\,3{,}10}{2}} = 5{,}20\quad m/s\ \ (18{,}50\ km/h)$$

At the point A under pressure till point B, where is p_B = 0, is

Approximately we may say that the pressure from point B to point D rises linearly. Distance between two cross connections is about 500 m, from the middle (point D) to point B, where the pressure is 0.00 Pa, the distance is 230 m, all together 730 m.

So is

$$p_C = \frac{30}{730} 230 \approx 10 \; Pa$$

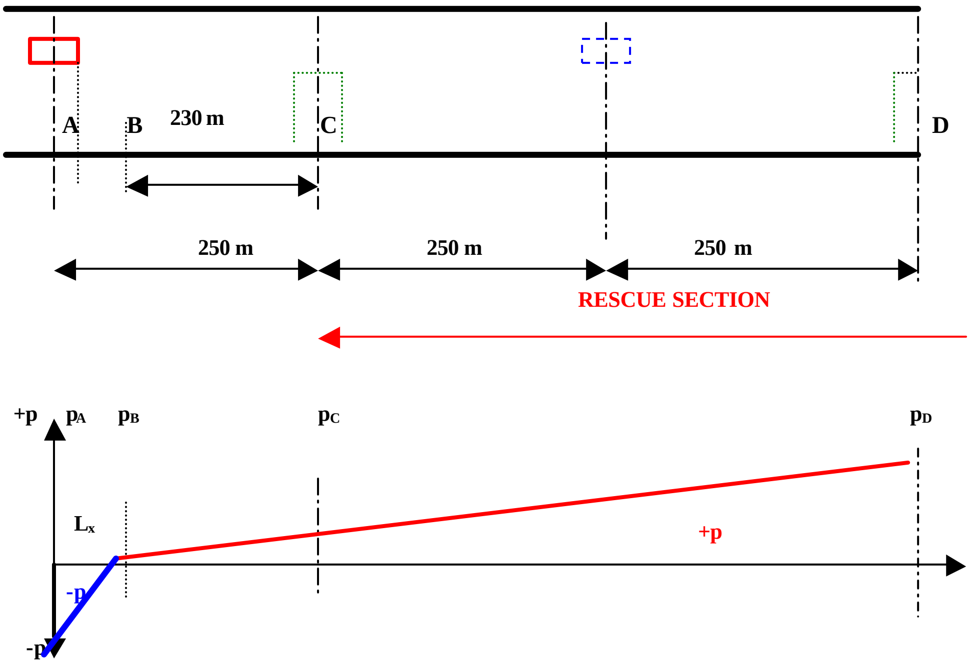

Fig. 2.3.2: Air pressure in the rescue section

3. RESCUE TUNNELS

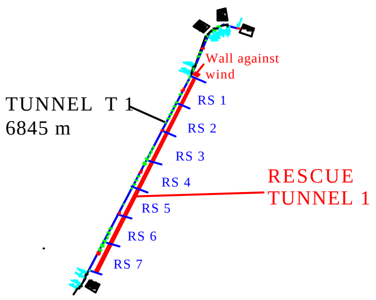

Fig. 3.1: Rescue tunnel 1

On Fig. 3.1 the rescue tunnel 1 is shown. Along tunnel they are 7 rescue sections: from RS 1 to RS 7. On the north part of rescue tunnel is a wall as protection against the wind. Similarly are the rescue tunnels RT 7 and RT 8 shown on Fig. 3.2 and Fig. 3.3.

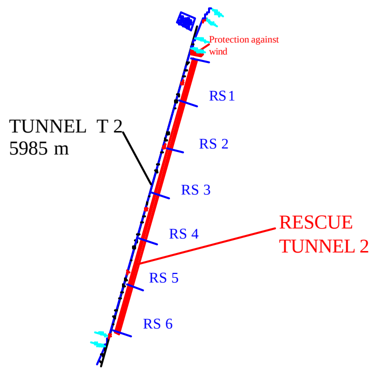

Fig. 3.2: Rescue tunnel 2

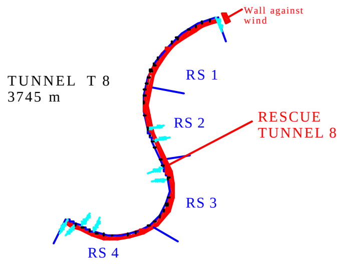

Fig. 3.3: Rescue tunnel 8

4. CONCLUSION

From figures and calculations, made for the case of fire in the main railway tunnel for one rescue section we can see that all of them are useful for all the rescue tunnels, from T1 to T8. In any case the air overpressure is attained, at the middle of the rescue section and at the end. To obtain the air overpressure is possible also when one of the fans in the rescue section failed.

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EMERGENCY VENTILATION OF A RAILWAY TUNNEL BY JET FANS

J.P. Kunsch
Institute of Fluiddynamics
Department of Mechanical Engineering, ETH - Zurich

ABSTRACT
In case of a fire in a long railway tunnel, an emergency stop of a passenger train at an arbitrary location in the tunnel cannot be excluded. In tunnel systems with two single-track tubes, corresponding to the system adopted by the NEAT in Switzerland, passengers can escape through the cross-passages connecting both tubes. The ventilation of the cross-passages,which are opened for escape, by jet fans installed in the portal regions is an interesting option to be discussed in general. Attention has been focused on the time duration required to obtain full ventilation power in the open cross-passage. The influence of the ventilation effect of the traffic is also discussed. A simplified model has been developed to estimate the air-flow rate in the cross-passage opened for escape.

Key words: cross-passage, tunnel fire, critical velocity, smoke control

1. INTRODUCTION

Emergency situations in long railway tunnels, such as tunnel fires, represent important challenges to the tunnel ventilation. The tunnel system chosen for the long railway tunnels of the NEAT (Neue Eisenbahn Alpentransversale) in Switzerland consists of two parallel single- track tubes. The risk of collisions is thereby removed and the risk of derailments is substantially reduced, because the use of points is restricted to the multipurpose stations or emergency stops dividing the tunnel into two or three main sections. At the location of these stations, crossovers or tunnel switches allow the trains to change the tunnel tube. The discussion on the installation of gates in the crossovers is not yet completely closed. The arguments in favour of an aerodynamic decoupling of both tubes by means of the gates prevail over those related to costs, maintenance and operation of the gates.

Detailed risk assessment studies have shown that the probability for a burning or damaged passenger train to be able to leave the tunnel or to reach an emergency stop is high. This scenario is therefore a requirement within modern regulations concerning passenger transport through long railway tunnels (see e.g. Schneider, 1997). For this reason, efforts are focused on the installation of an emergency ventilation in the emergency stations. The emergency stops are part of multipurpose sectors containing rooms with technical installations. These rooms, which are ventilated by fresh air under overpressure, are used as safe-haven areas in case of an emergency.

An emergency stop of a train at an arbitrary location within the tunnel, however, cannot be ruled out. In case of a fire, for example, the passengers will evacuate the contaminated tube through escape shafts (e.g. originally used for the construction of the tunnel) when the overburden is small or through cross-passages, which interconnect the two parallel single-track tubes at uniform distances. These rescue and escape passages ought to be safe-haven areas, where temperature and concentrations of fire gases or toxic materials should be as low as possible. The cross-passages not used for escape remain closed, except small ventilation openings. A major requirement is to generate sufficient fresh-air current through the open cross-passages to ensure an appropriate climate for survival and escape and to prevent the fire gases from entering the sound tube.

One possibility to cope with these problems is to generate a fresh air current in the open cross-passage by means of the ventilation installed in the emergency stations. This is achieved by generating overpressure in the sound tube and underpressure in the contaminated tube, if needed. A major objective is to obtain critical or supercritical velocities for the air flow in the cross-passages preventing backlayering of smoke, i.e. contamination of the sound tube (see e.g. Kunsch, 2002). The possibility to support the ventilation of the cross-passages, in particular those close to the portals, by jet fans installed in the portal regions can be envisaged. The time required to reach the steady-state regime, where full ventilation power is obtained, is an important parameter to be estimated. It is required in the planning of escape and rescue scenarios.

In order to analyse these problems, a simplified model of an idealized tunnel system with two single track tubes is proposed to simulate the unsteady tunnel aerodynamics including the ventilation by jet fans.

2. VENTILATION BY JET FANS AND BY TRAFFIC: basic flow model

In order to illustrate the ventilation effect of jet fans and train traffic in a tunnel, a momentum balance of a single-track tube with length L can be given as

$$r\,L\frac{du_v}{dt} = D\,p_{ve} + D\,p_F - D\,p_R\ . \qquad (1)$$

The different pressure contributions on the RHS of eq. (1) are discussed in what follows.
The pressure loss $D\,p_R$ includes the losses at the entrance portal

$$D\,p_e = \left(1+z_e\right)1/2\,r\,u_v^2 \qquad (1a)$$

and the losses by wall friction

$$D\,p_w = l\,\frac{L}{D}\,1/2\,r u_v^2 \qquad (1b)$$

i.e., $$D\,p_R = D\,p_e + D\,p_w = a\,1/2\,r u_v^2 \ \text{ with } a = 1+z_e + l\,L/D\ . \qquad (1c)$$

The friction coefficient l is roughly equal to 0.030 for the types of tunnels considered here.
The pressure increase by the jet fans can be estimated by means of an integral momentum balance formulated for the control volume in Fig. 1 (see e.g. Meidinger, 1964 or Plaskowski, 1973)

$$D\,p_{ve} = p_3 - p_1 = r\,u_s^2 f\,(1-y) \quad \text{with} \quad f = F_s/F_v \quad \text{and} \quad y = u_v/u_s\ . \qquad (1d)$$

The piston effect exerted by trains on the air in the tunnel is described by means of

$$D\,p_F = b\,1/2\,r\,(v-u_v)^2 = b\,1/2\,r\,u_s^2(w-y)^2, \qquad (1e)$$

where $w = v/u_s$ is the dimensionless velocity of a train travelling with velocity v. b depends on the geometry of the train and the tunnel, i.e. on the obstruction of the cross-sectional area of the tunnel by the train and the wetted area relevant for friction (see e.g. Gaillard (1973)). For a cross-sectional area of the tunnel $F_v = 47\,m^2$ and a length of the train $l = 300\,m$, an estimate of b yields a value of $b = 2.4$.

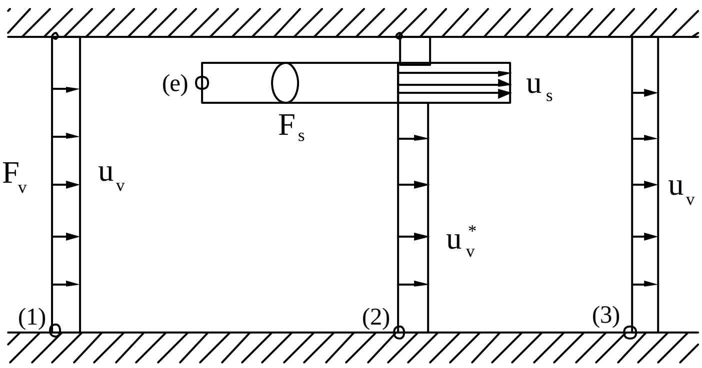

Fig. 1: Tunnel section with jet fan.

Steady-state solution

When the traffic does not vary with time (and when the jet fans are operating steadily) a steady-state ventilation regime is reached after the initial transients. The steady-state velocity is obtained when the RHS of eq. (1) is set equal to zero, i.e.,

$$y_2 = \frac{u_v}{u_s} = \frac{-f - w b + \sqrt{(f + w b)^2 + (a-b)\left(2f + bw^2\right)}}{a-b} . \qquad (2)$$

The velocity induced by traffic only (no jet fans, i.e., $f = 0$) is

$$y_{2B} = \frac{w}{1+\sqrt{a/b}} \; . \qquad (2B)$$

When, on the other hand, the jet fans operate without traffic present in the tunnel (i.e. $b = 0$), we obtain

$$y_{2C} = \frac{-f + \sqrt{2f\,a}}{a} \cong \sqrt{\frac{2f}{a}}\left(1 - \frac{1}{2}\sqrt{\frac{2f}{a}} + \frac{1}{4}\frac{f}{a}\right) . \qquad (2C)$$

The simplified expression $y_{2C} = \sqrt{2f/a}$ will be used in what follows because the expression in the brackets is very close to unity.

Transient solution with jet fans and residual flow in the tunnel $\left(y_o = y\,(t = 0) \geq 0\right)$

Even when the train has left the tunnel, a residual flow with velocity u_{vo} (i.e. $y_o = u_{vo}/u_s$) has to be taken into account. The flow y in the tunnel starts with y_o and converges towards the steady-state regime defined by $y_2 = u_2/u_s = \sqrt{2f/a}$ (eq. (2C)), i.e.,

$$y = y_2 \frac{1 + A\exp\left(-t/c_1\right)}{1 - A\exp\left(-t/c_1\right)} \qquad (3)$$

with $\qquad c_1 = \dfrac{L}{u_s\sqrt{2f\,a}}$ and $\qquad A = \dfrac{y_o - y_2}{y_o + y_2}$.

This expression can be rewritten for two distinct cases

(I) $\qquad y_o < y_2 \qquad y = y_2\, tgh\left[\dfrac{1}{2c_1}\left(t + D\,t\right)\right] \qquad$ (4A)

(II) $\qquad y_o > y_2 \qquad y = y_2\, ctgh\left[\dfrac{1}{2c_1}\left(t + D\,t\right)\right] \qquad$ (4B)

with $\qquad D\,t = -c_1\, Ln|A|$.

Special cases

1. The acceleration in case (I) is given by

$$\frac{dy}{dt} = \frac{y_2}{2c_1}\left\{1 - tgh^2\left[\frac{1}{2c_1}\left(t + D\,t\right)\right]\right\} . \qquad (5)$$

When the flow starts from rest ($y_o = 0$, i.e. $D\,t = 0$), the initial acceleration is

$$\frac{dy}{dt} = \frac{y_2}{2c_1} = \frac{f u_s}{L} \quad \text{or} \quad \frac{du}{dt} = \frac{D p_{ve} F_v}{r L F_v} = \frac{force\ of\ fan}{mass\ of\ air\ in\ tunnel} \qquad (5A)$$

The last expression could be obtained at once from eq. (1) by neglecting frictional effects (i.e., $D\,p_R = 0$). This result clearly shows that the initial flow is dominated by inertia. The mass of air to be accelerated in a tunnel with a length of 20 km amounts to about 1000 tons.

2. When the active flow components such as trains or jet fans are removed, a residual velocity $u_o = y_o u_s$ decreases until the air comes to rest. The decrease of the velocity can be obtained from eq. (1), where $D\,p_R$ is the only term on the RHS.

$$\frac{u}{u_o} = \frac{1}{1 + \left(u_o a/2L\right)t} \qquad (6)$$

When the tunnel is long, the last term in $a = 1 + z_e + l\ L/D$ dominates, i.e., $a \cong l\ L/D$. In this case, eq. (6) yields

$$\frac{u}{u_o} = \frac{1}{1+\left(u_o l/2D\right)t} \quad . \qquad (7)$$

This means that the decrease does not depend on the length of the tunnel!

3. VENTILATION SYSTEM; PRESENT CONFIGURATION

A system similar to that presented in the Introduction will be considered next. The analysis is focused on the aerodynamics of the portal regions of the two single-track tubes shown in Fig. 2. It is assumed that one cross-passage connecting both tubes is opened for escape of the tunnel users in case of a tunnel fire. Reversible jet fans are installed close to the tunnel portals, in order to generate a fresh-air current in the cross-passage, which ensures a climate for survival and escape and which prevents the smoke gases from entering the sound tube. The fans generate overpressure in the sound tube and underpressure in the contaminated tube, if needed. The flow velocities indicated by the arrows in Fig. 2 correspond to a scenario where the upper tube is contaminated. In order to simplify the analysis and to emphasize the effect of the jet fans, the influence of the ventilation of the emergency stops has been neglected.

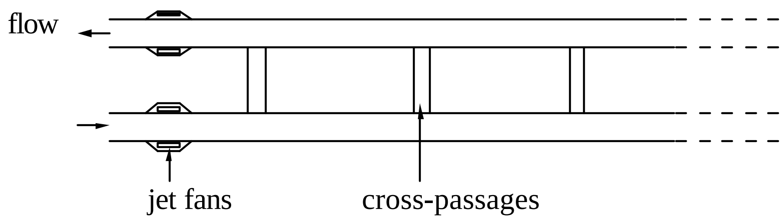

Fig. 2: Tunnel system with two parallel single-track tubes.

3.1 Ventilation by jet fans; influence of traffic

The air velocity generated by a jet fan in a tunnel can be estimated by means of eq. (2C). When the tunnel is characterized by $L = 20\,km$ and $F_v = 47\,m^2$ and the jet fan by $u_s = 38\,m/s$ and $F_s = 0.6\,m^2$, the velocity of the air flow amounts to $u_v = 0.63\,m/s$. The same air velocity could be obtained by the piston effect of a train travelling with a speed of $v = 16.5\,km/h$ (see eq.(2B)). A train with speed $v = 140\,km/h$ would induce an air flow velocity of $u_v = 5.4\,m/s$.

This result clearly shows that the piston effect of a train travelling at realistic speeds, generally exceeding $100\,km/h$, dominates over the effect of jet fans.

A major result of this estimate is that the jet fans are not effective in presence of traffic in a tunnel. It can be concluded that the installation of jet fans should be considered for tunnels with short to medium lengths only; in this case the train would be able to leave the tunnel before the emergency ventilation by jet fans starts.

When the train has left the tunnel, however, the residual air flow still present in the tunnel will decrease until a steady-state regime is reached. This regime is defined by the pressure rise of the jet fan in equilibrium with the pressure losses due to wall friction etc. (see eq. (2C)). The ventilation by jet fans becomes effective only after the time delay corresponding to this decrease.

3.2 Ventilation by jet fans; no railway traffic in the tunnel

3.2.1 Model

The ventilation by jet fans is effective when the jet fans start operating in a quiescent environment. This case will be discussed in this section.

The present model describes the tunnel system shown in Fig. 3. The cross-passages interconnecting both tunnel tubes are assumed to be closed, except for the passage used for escape in case of emergency. In order to keep the analysis as simple as possible, the air-flow rate through the small ventilation openings in the doors in the cross-passages will be neglected in a first approximation.

The ventilation power of the jet fans not only must be high enough to prevent contaminated or smoke gases from entering the sound tube, but also has to be available after a reasonably short time period. One objective of the present study is to estimate how long it will take for the flow velocity in the open cross-passage to reach its maximum value. This time could be relevant for rescue scenarios.

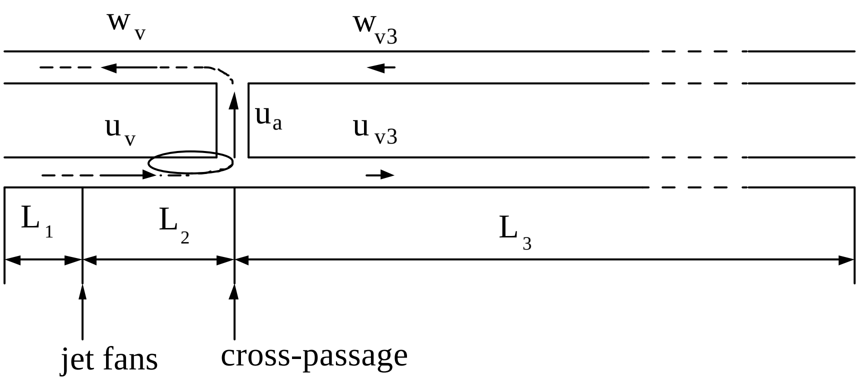

Fig. 3: Short-circuit flow through the open cross-passage ----.

The tunnel configuration to be studied is shown in Fig. 3. It is assumed that only the cross-passage, which is used for escape, is open. The short circuit flow through the cross-passage (velocity u_a) corresponds to the operation of the jet fans shown in Fig. 2.

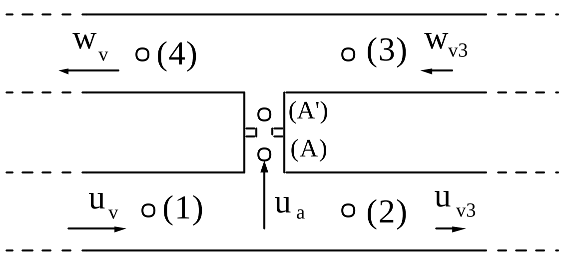

Fig. 4: Cross-passage with door modeled as a flow component with bifurcation and constriction.

The open cross-passage with a door or a gate can be modeled as a combining and dividing junction with additional constriction (see Fig. 4).

The loss of total pressure for dividing flows can be written e.g.

$$\Delta H_l = \left(p_1 + 1/2\,\rho\,u_v^2\right) - \left(p_a + 1/2\,\rho\,u_a^2\right) = \zeta_{pl}^{o}\,1/2\,\rho\,u_v^2 \quad \text{(side branch)} \qquad (8A)$$

$$\Delta H_r = \left(p_1 + 1/2\,\rho\,u_v^2\right) - \left(p_2 + 1/2\,\rho\,u_{v3}^2\right) = \zeta_{pr}^{o}\,1/2\,\rho\,u_v^2 \quad \text{(through flow)} \qquad (8B)$$

Analogous expressions are used for the flow junction. The corresponding loss coefficients can be found e.g. in Miller (1990).

When the configuration of Fig. 3 is considered, a momentum balance analogous to eq. (1), has to be formulated for every section, i.e. for, $L_1 + L_2$ and L_3 in both single-track tubes.

Due to the open cross-passage connecting both tunnel tubes, a system of four coupled ordinary differential equations is obtained, which can be solved by means of a Runge- Kutta integration procedure.

3.2.2 Results and discussion

The first objective of the present study is to estimate the time period necessary to build up full ventilation power and the flow velocity in the open cross-passage when the jet fans close to the portals operate.

Because the ventilation of the passages close to the portals is a major concern, the distance $x = L_1 + L_2$ of the open cross-passage from the portal will be a main parameter in the study. The jet fans are mounted at a distance L_1 from the portals. In order to check the general validity of the results, the influence of the remaining tunnel system is roughly taken into account by varying the length L_3 of the tunnel section behind the cross-passage. Values similar to those found in realistic railway tunnels are used for the other dimensions such as the cross-sectional area of the tubes and of the cross-passages, and the distance of the jet fans from the portals. Each portal is equipped with two jet fans with a ventilation power of 40 to 50 kW each. The velocity of the jet is assumed to be as high as $u_s \cong 38\ m/s$.

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Fig. 5: Time history of the velocities u_v, u_{v3} and u_a in the sections $L_1 + L_2$, L_3 and the cross-passage, respectively.

The flow velocity u_v in the section between the portal and the open cross-passage, the velocity u_{v3} in section L_3 and the flow velocity u_a in the cross-passages are shown in Fig. 5 as a function of time. One part of the volume flow rate produced by the jet fans (velocity u_v) is diverted through the cross-passages (velocity u_a) in order to form a short-circuit flow from portal to portal in the adjacent tube. It can be observed that the acceleration of the air (gradient of u_v) in the section $L_1 + L_2$ between portal and cross-passages dominates over the acceleration of the air (gradient of u_{v3}) in the remaining section L_3 of the tunnel, for reasons of mass inertia of the air in L_3. This temporary blockage by mass inertia of the air in section L_3 is responsible for the rapid increase of the velocity u_a of the short-circuit flow diverted through the cross-passages. It even results an overshooting of the flow velocity u_a in the cross-passages, before a steady-state regime is attained. The time $t_{90\%}$ needed for the flow velocity to reach 90% of its final steady-state value is marked by the circular symbols for the three sections considered, i.e., $L_1 + L_2$, L_3 and the cross-passage. The final steady-state values are marked by the symbols [ ].

The distance x of the open cross-passage from the portal has been varied in the study documented in Fig. 6. The total length L of the tunnel is a parameter. The variation of L shows the influence of additional flow resistance and inertia in section L_3. In a broader sense, the variation of the total length also illustrates how sensitive the results are to an uncertainty in the description of the flow components behind the cross-passage. The distance of the open cross-passage from the portal has been varied from the location of the jet fan towards the midst of the tunnel, i.e. $L_1 < x < L/2$. (So x varies from L_1 to 5000 m for a total length of 10000 m, etc.). The steady-state value of the velocity u_a and the time interval $t_{90\%}$ found for the configuration treated in Fig. 5 are indicated in Fig. 6 by the same symbols as in Fig. 5. The velocity in the open cross-passage u_a and the velocity u_p in the door or opening in the cross-passage (see Fig. 4) are shown in Fig. 6 (a).

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Fig. 6: (a) Steady-state values of the velocity u_a in the open cross-passage and of the velocity u_p in the door in the cross-passage.

(b) Time period $t_{90\%}$ required to obtain 90% of the steady-state values of u_a and u_p. (x is the distance of the open cross-passage from the portal, the parameter L is the total length of the tunnel.)

Influence of the total length L and the location of the cross-passage x

It can be observed that the flow velocity in the cross-passage decreases with increasing distance of the cross-passage from the jet fans.

A variation of the total tunnel length L has an interesting effect on the velocities: the velocity through the cross-passages increases with increasing length of the tunnel when x is kept constant. This can be explained by the blockage effect due to mass inertia in section L_3 behind the open cross-passage.

The time delay $t_{90\%}$ required to obtain 90% of the final steady-state velocities (Fig. 6(b)) increases with increasing distance x and increasing total length of the tunnel. In particular, it can be observed that the time periods $t_{90\%}$ are of the order of one minute when the open cross-passage is located within a distance of 3 km from the portal. Within this range of distances, the velocity u_p in the door of the open cross-passage is larger than 6 m/s. So the velocity u_p will be supercritical, i.e. the fresh air current will be able to prevent backlayering of the smoke gases (see e.g. Kunsch, 2002). The resulting short time intervals required to build up full ventilation power in the cross-passages and the corresponding supercritical ventilation rates would support the choice of jet fans close to the tunnel portals, when the air flow induced by traffic is neglected.

3.3 Ventilation by jet fans; no railway traffic but residual velocity in the tunnel

In order to discuss the operation of jet fans in presence of residual air flow due to traffic, a configuration comprising a single track-tube with a side passage, opened to the free atmosphere, is chosen (Fig. 7).

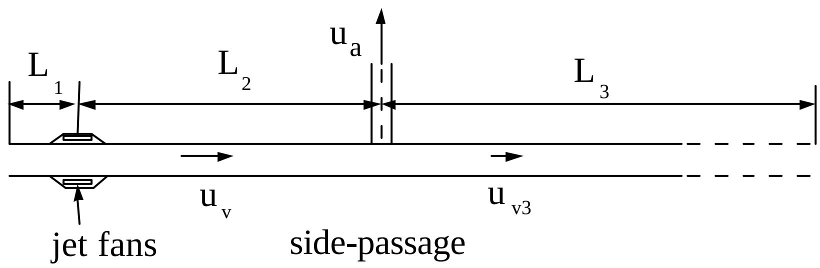

Fig. 7: Tunnel with side-passage.

The two different cases considered here are illustrated in Fig. 8.

1. The jet fan starts operating in a quiescent tunnel environment. The time histories of u_v, u_{v3} and u_a are plotted as solid lines. The velocity u_a of the flow diverted through the side passage increases quickly for reasons of mass inertia in the tunnel segment L_3, as already explained in section B.

2. When the jet fan starts operating, the train has left the tunnel, but the residual flow induced by the piston effect is still present ($t = 0$: $u_v = u_{v3} = 3\ m/s$ in Fig. 8). (In order to simplify the analysis, the same direction has been chosen for the residual flow and the flow generated by the jet fan.) The decrease of u_v and u_{v3} is illustrated by the dashed lines and the velocity in the side passage by the dash-dotted line. It can be observed that the flow rate in the side passage increases much more slowlier than in the first case without residual flow. This can be explained by the fact that the blockage effect of segment L_3 due to mass inertia is not relevant in this case.

It can be concluded that the time intervals $t_{90\%}$ required to reach 90% of the full ventilation power in the cross-passage connecting two single-track tubes (see Fig. 6 in section B) have to be augmented considerably when residual air flow is present. The values for $t_{90\%}$ given in Fig. 6(b) should be considered as lower bounds valid for an initially quiescent tunnel atmosphere. The conditions for an effective use of jet fans can be identified only after a careful analysis of the planned ventilation scenario.

Remark

Influences, which are not completely understood, or meteorologic pressure differences between the tunnel portals have not been taken into account. They could reduce the effectiveness of the jet fans, so that a power reserve must be recommended.

Note that compressibility effects have been neglected in the present study. This simplification is motivated by the low Mach numbers of the flow. The present results are quite accurate when compared to calculations taking compressibility effects into account, even when the rapid transients of the present application are considered.

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Fig. 8: Time history of the velocities u_v, u_{v3} and u_a
in the sections $L_1 + L_2$, L_3 and the side-passage, respectively.
Continuous lines: no residual velocity due to traffic (case 1).
Dashed and dash-dotted lines: residual velocity due to traffic (case 2).

4. CONCLUSIONS

The present analysis deals with a tunnel system consisting of two long single-track tubes, which are connected by cross-passages used for escape and rescue in case of a tunnel fire. The installation of jet fans in the portal regions supporting the emergency ventilation in the cross-passages close to the portals, is an option discussed here. The present analysis shows that the jet fans are only effective under special conditions.

- When trains are present in the tunnel, the traffic-induced flow dominates over the flow generated by jet fans, so that jet fans are not effective. This situation can generally be encountered in long railway tunnels.
- In medium-sized tunnels, trains can leave the tunnel, but there may still be some residual traffic induced flow, when the jet fans start operating. In this case jet fans can contribute to the emergency ventilation after a time delay, when the traffic-induced flow has decreased.
- Jet fans are quite effective in an initially quiescent tunnel environment. Only short time intervals are required to reach full ventilation power in the cross-passages. In particular, a short-circuit flow through the cross-passages close to the portals is quickly established.

It can be concluded that the benefit of jet fans installed close to the tunnel portals is limited in the presence of traffic induced flow. The corresponding ventilation scenarios have to be analysed carefully before considering the installation or use of jet fans. In the light of these results, the more costly alternative of an emergency ventilation by jet fans installed in the cross-passages themselves could be envisaged.

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$u_{v3}, u_v, u_a \;\; [m/s]$ $u_{v3}, u_v, u_a \;\; [m/s]$

$u_{v3},\ u_v,\ u_a \;\; [m/s]$ $u_{v3},\ u_v,\ u_a \;\; [m/s]$

$t[s]$ $t[s]$ $t[s]$ $t[s]$

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$u_{v3},\ u_v,\ u_a \;\; [m/s]$ $u_{v3},\ u_v,\ u_a \;\; [m/s]$

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PROVISIONS AND MEASURES TO IMPROVE FIRE RESISTANCE OF TUNNEL STRUCTURES FROM THE POINT OF VIEW OF AN ACCREDITED TEST INSTITUTE

Helmut PEHERSTORFER, Arthur A. EISENBEISS,
Thomas TRAUNER,
IBS – Institute For Technical Fire Protection And Safety Research Ltd.
State Accredited Testing And Supervising Institute

ABSTRACT

Safety requirements in tunnels sometimes require a specification for fire resistance which cannot be fulfilled by concrete as built but has to be coated by protective layers.
Time of fire resistance as a feature of concrete structure is strongly influenced by the chosen design fire. A comparison of different resistance periods as a function of the selected design fires (e.g. the ISO 834, the RWS curve and fire curves calculated from fire szenarios in particular tunnel geometries) are presented.
This paper describes furthermore an overview about coatings and linings including concrete containing additives like fibrilised polypropylene fibers. Specific focus is placed upon the applicability of linings in existing tunnels regarding the improved performance against impact of temperature load.
Experimental results about the temperature distribution as a function of depth within the concrete are given. Emphasis is put on the temperature as a function of time at the place of reinforcement for various thickness of the covering concrete layer.

Key words: Fire Loads, Fire Tests

The stepped-up occurrence of serious and even fatal fire accidents in traffic tunnels in Europe in recent years, has led to an increasing focus on safety aspects in tunnels. The extent of the damage caused to the concrete in the event of fire can be attributed to several damage mechanisms in the case of conventional concrete. The individual damage patterns are superimposed in most cases and can be split up into the following categories:

- vapour formations
- chemical transformations
- reinforcement failure
- thermal length alteration

Water acts in concrete in many different ways, but the harmful influences predominate. Water´s transition from liquid to gas at 100 °C is associated with a big energy intake. Apart from the energy intake during the transition phase from liquid to gas, there is a massive increase in volume, which is responsible for concrete parts flaking.

The rapid temperature increase causes spalling of the top layers of concrete with corresponding high humidity thereby setting free the first layer of reinforcement or removing the layer by layer of not enforced concrete. The temperature gradient moving into the concrete reduces step by step the strength and the distortion characteristics of the concrete and steel structure.

Less damage is to be anticipated from a small fire with a low energy build-up and a corresponding high porosity than in the case of a major fire involving compact concrete. The demand for a concrete with high strength and compactness, which seems justified for constructional reasons, in order to arrive a sufficient durability, emerges to be adverse in terms of fire resistance.

Fire Loads

As far as the assumed fire incident is concerned, so far very different fire load curves, which are used for tests, have been defined throughout Europe. In this connection, the duration of the individual phases and the absolute level of the temperatures arrived and depend on the nature of the combustible materials used. With regard to the temperature-time curves, this relates to the development of a fire and can be anticipated e.g. in dwellings or in commercial premises. This general curve course forms the basis for the fire load curve according to ISO 834 together with the "heating up phase".

The considerably higher fire durations, amounting in some cases to more than 50 h, which were registered during the tunnel fire accidents in the last years, can be attributed to the flash-over point and the burning of different vehicles, which occurred at various times.

In order to dimension protective measures to counter fire loads, time-temperature curves are assumed, which in some cases, vary considerably from one another. Fires involving hydrocarbons, which are largely prevalent when a vehicle catches fire, are insufficiently represented by the course of the curve for the standard temperature curve – ETK. The heating up phase is reduced to a few min, once the maximum temperature is achieved. The other curves commonly used in Europe take this rapid increase into consideration.

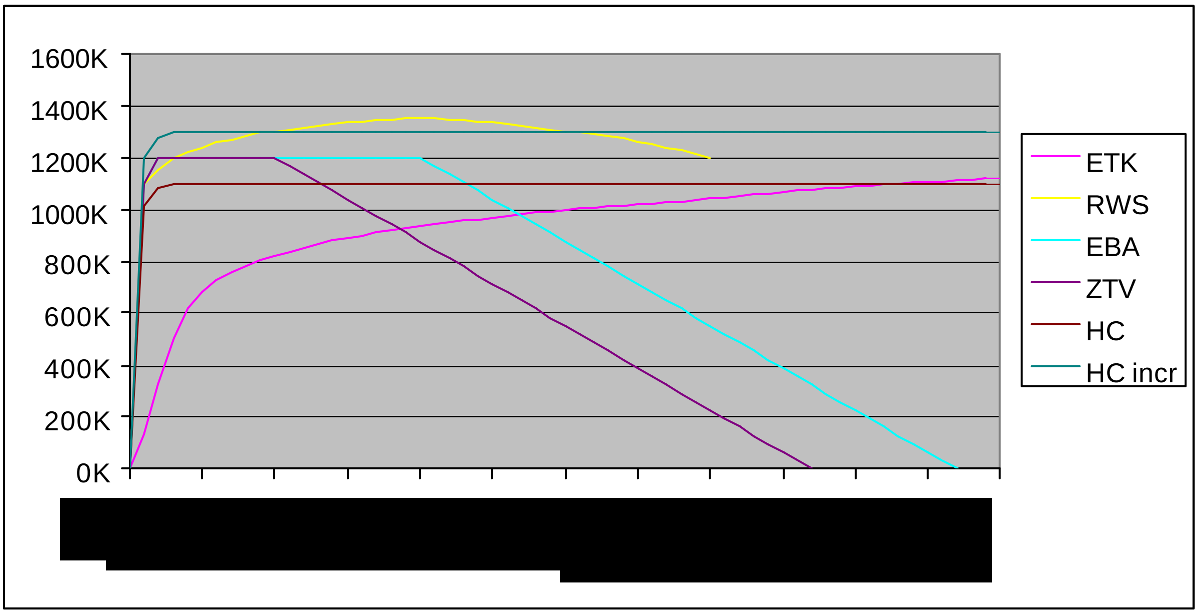

Figure 1: Temperature-time curves

The highest demands are placed in the Netherlands by the Rijkswaterstaat (RWS). The curve in question is based on a fuel tanker on fire in a tunnel. The exposed position of the Netherlands regarding tunnels in groundwater and with a large part of the surface of the country below sea-level has led to very high safety requirements governing the possible destruction of buildings, damage to which could have catastrophic results for the entire country.

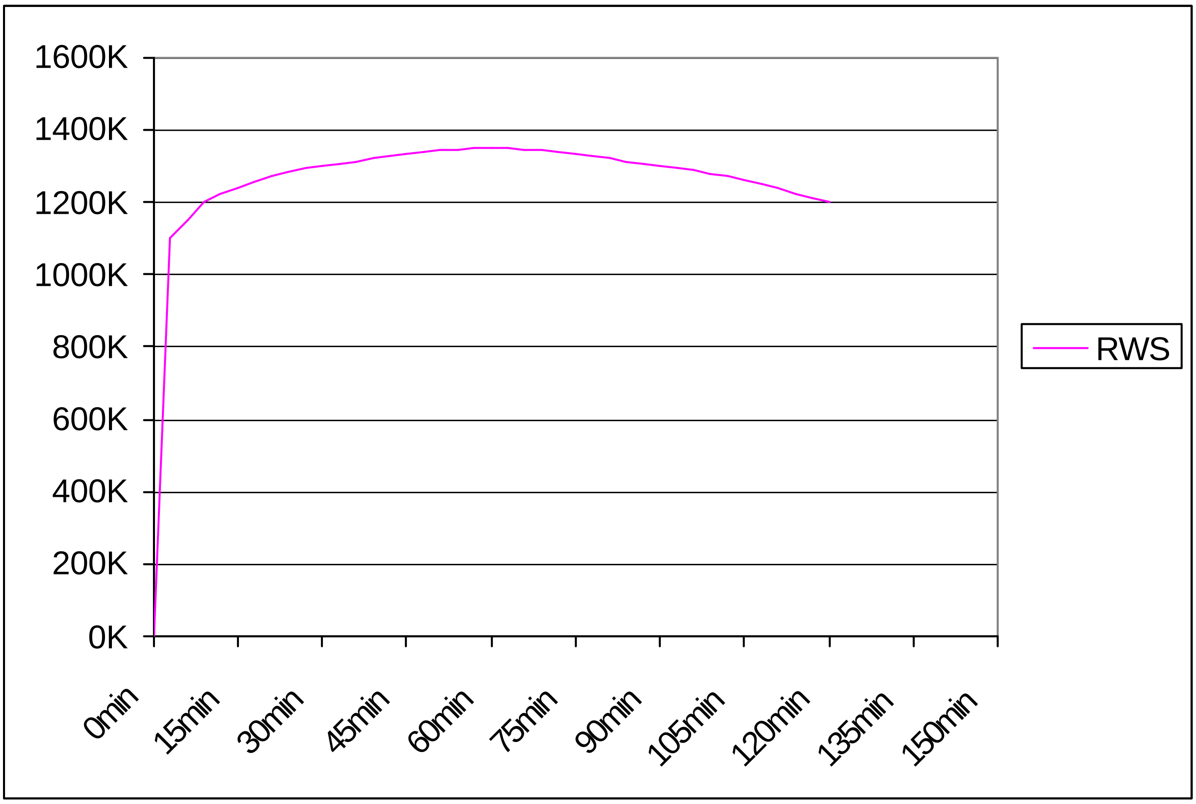

Figure 2: Temperature-time curve Rijkswaterstaat

Testing methods

There are only a few places throughout Europe where tunnel linings are tested. For clarification of occuring questions referring to the architectural fire safety the "Österreichische Straßenforschung" commissioned a research program for fire resistance of various concrete mixtures.

The objective is to reduce the spalling by additives of synthetic fibres and fibremixtures. Further objective is to study the behaviour of mono stranded wire in case of a thermal load. This requires an estimation about the influence of the essential parameters (e.g. surface stress at the hot top layer, humidity, mineralogical composition of the addition, the classes of concrete resistance). As less heat load at the reinforcement shall be achieved in order to save the cross sectional load capacity as long as possible. Alternatively protective layers like panel linings, coverings, etc. which can be on still existing construction are investigated.

From the today's point of view the test program includes 40 big sized plates of concrete which shall be exposed to the following heat loads:

Heat load according to RWS – curve
Heat load according to object specific fire curves
Heat load according to ISO 831

Size of concrete samples:

- 180 cm x 140 cm x 50 cm containing additional reinforcement in form of a net, thermo-couples placed in various depths
- Various tension conditions at the hot side
- samples with various humidity content due to different storage conditions
- Various compositions of concrete and synthetic fibre additives
- Stress-controlling reinforcement in different depth of the samples

Results

During fire tests carried out in the past at traditional conventional concrete, intensive spalling even in the initial phase has been observed.

Concrete devices containing particular additives have shown a totally different behaviour when exposed to the temperature load. Not any surface damages could be found by visual inspection after the test. The measured temperature values decrease in form of a steep gradient with increasing concrete depth. The temperature within the concrete raises with a time delay, even after stop of the temperature load. As deeper in the sample as later the maximum temperature value will be achieved.

Fire tests with fire board linings

Fire board linings have a protective effect by isolating properties against temperature load. It should be remarked, that the fire board linings are well suited to be installed in tunnels because they are designed to withstand and/or absorb bending stress, dynamic suction- and pressure forces caused by pressure- and suction-effects as a consequence of ongoing traffic.

Fire board linings must not be removed from the supporting concrete elements under high temperature conditions during a fire.

Fire board linings which have been tested in our Institute could prove appropriate behaviour in this point of view during the whole fire test.

Up to now a thickness requirement of 70mm was treated as state of the art. From today's point of view it should be noted that nowadays, thanks to innovation, the thickness could be reduced to half of this value.

Fire resistance of construction products for the use in tunnels

All construction products used as tunnel equipment (e.g. fire resistant doors, closed service galleries for cables, etc.) which offer the class of fire resistance F 90 ("brandbeständig") do fulfill 90 min of resistance if the ISO temperature load is applied. They do NOT resist 90 min if higher project specific temperature loads are applied or they fulfill resistance for a shorter time interval.

These lack of fire resistance has to be considered for fire barrier components as well. Their properties shall block the transfer of temperature and smoke, in particular to ensure a save escape of people in the first 30 min. Especially for the safety of people these components must fulfill the requirements for the whole of the specified time of resistance.
Consequently those components have to be tested and have to prove their fire resistance properties for a temperature load which is realistic to be expected in the tunnel.

Conclusion

The real fire risk and the real temperature load resulting from the risk has to be the base for specification, design and approval procedure for construction parts.

In the initial phase of a fire the safe escape of persons present in the hazardous area is prior. The initial phase offering the possibility to escape is very limited in case of fires in a tunnel. Temperature exceeding 1000°C together with the smoke concentration provide conditions where the chance to survive is near zero. The surrounding walls in a tunnel together with the lack of heat escape in vertical direction lead to an intensive temperature increase in a few minutes.

Despite an innovative and successful progress in the field of construction parts numerous questions are still waiting for an answer. These questions have to be answered to meet the tunnel-specific safety objectives.

Beside the solution of technical questions the same intensive work has to be invested in test standards, classification standards and product standards in order to meet the reality best.

VENTILATION OF ROAD TUNNELS THE NEW SWISS DIRECTIVE

F. Zumsteg and U. Steinemann
US+FZ Beratende Ingenieure

A. Hofer
Swiss Federal Roads Authority

1. ABSTRACT

Due to the tunnel fires on the one hand and the reduction of vehicle emissions on the other hand the design of tunnel ventilation systems is nowadays determined by safety reasons. Several new features of the new Swiss directive have led to changes in conception and design of the ventilation systems of planned tunnels, tunnels under construction and existing tunnels.

Main novelties in ventilation design in Switzerland are

- *Ventilation system definition: Transverse and reversible semi-transverse systems as formerly used will not be recommended any longer.*
- *Standardisation of system choice: The ventilation system has to be determined according to traffic type and volume, tunnel length and gradient and in some cases secondary influence factors have to be checked.*
- *Design fires: The buoyancy effect of the design fires is defined.*
- *Remote control dampers: In the case of fire controllable dampers are used to concentrate the extraction capacity to the location of the incident. Indications for position, shape and dimensions of the dampers are given.*
- *Redundancy: The redundancy of primary safety elements is defined.*
- *Escape routes: The maximal distance of escape routes for different tunnel types is defined.*

The higher complexity of the new systems requires primary attention to the maintenance of the most important elements such as dampers, incident detection and measuring systems.

2. INTRODUCTION

The work for the new Swiss directive for the choice of system, design and operation of road tunnel ventilation started in December 1998. The document replacing the report FEDRO (1983) will be released this year by the Swiss Federal Roads Authority. The fundamental ideas of the new directive must be applied today already. Due to the fatal tunnel fires on the one hand and the reduction of vehicle emissions on the other hand today safety reasons determine the design of tunnel. Several new features of the directive have led to changes in conception and design of the ventilation systems of planned tunnels, tunnels under construction and existing tunnels.

3. AIM

The aim of the directive is to standardise the design process of tunnel ventilations and consequently standardise the systems and equipment of the road tunnels. The directive is primarily designed for

- the tunnel owner offering an easy to use instrument for rough estimates
- the ventilation specialist to give him clear indications for the system choice and design
- the engineers of other domains indicating the necessary facts in the early conceptual stages

The requirements of the directive are mandatory for the design of all tunnels that are subsidised by the Swiss Federation. If possible and practical it should be applied also for all other tunnels in Switzerland. When renovating an existing tunnel, the standard defined in the directive has to be reached. Deviations from the requirements of the directive are admissible if they can be justified by project specific features.

4. CLASSIFICATION OF VENTILATION SYSTEMS

On a first level the ventilation systems are classified into three groups:

1 Natural ventilation
2 Ventilation systems without a smoke extraction duct and
3 Ventilation systems with a smoke extraction duct.

On a second level the systems with a mechanic ventilation are subdivided in

2a Longitudinal ventilation with jet fans and
2b Longitudinal ventilation with point extraction with or without jet fans
3a Systems without fresh air duct
3b Systems without fresh air duct

Furthermore combinations of the above mentioned systems are possible.

5. GENERAL CONCEPTUAL RULES

In general the following rules must be observed:

The extraction capacity must be concentrated onto the tunnel section near the incident by means of controllable dampers usually situated in the intermediate ceiling. If needed the openings for fresh air supply must be placed near the road surface. Reversible fresh air/exhaust air duct are no longer possible. The reason for this is the possible de-stratification of smoke by the fresh air blown in from the ceiling and the loss of time during the reversing process of the air in the duct and possibly of the ventilator or the dampers. Dampers for air extraction should only be used in the positions closed or fully open. Continuous air extraction through slightly opened dampers is not recommended.

6. CHOICE OF THE VENTILATION SYSTEM

The directive uses the classification of traffic according to PIARC (1999a) distinguishing

RV 1 uni-directional traffic with low frequency of congestion,
RV 2 uni-directional traffic with high frequency of congestion and
GV bi-directional traffic
(RV stands for 'Richtungsverkehr', GV for 'Gegenverkehr')

High frequency of traffic congestion is given if it occurs more often than once a week.

Together with the tunnel length the main group of ventilation system can be determined with Figure 1. If necessary influence factors of first or second order have to be applied to determine the relevant system. The indications are valid up to a slope of 5 %.

While for tunnel X (figure 1) with a length of 2.5 km a refined investigation has to be made to judge the necessity of a smoke extraction duct, Figure 1 indicates that for Tunnel Y and Z the smoke extraction duct is mandatory. To allocate a tunnel in the subdivision A, B or C the main influence criteria are used: the traffic volume per day and lane number, the number of HDV per day and lane number and the slope of the tunnel (extreme mean values over 800 m).

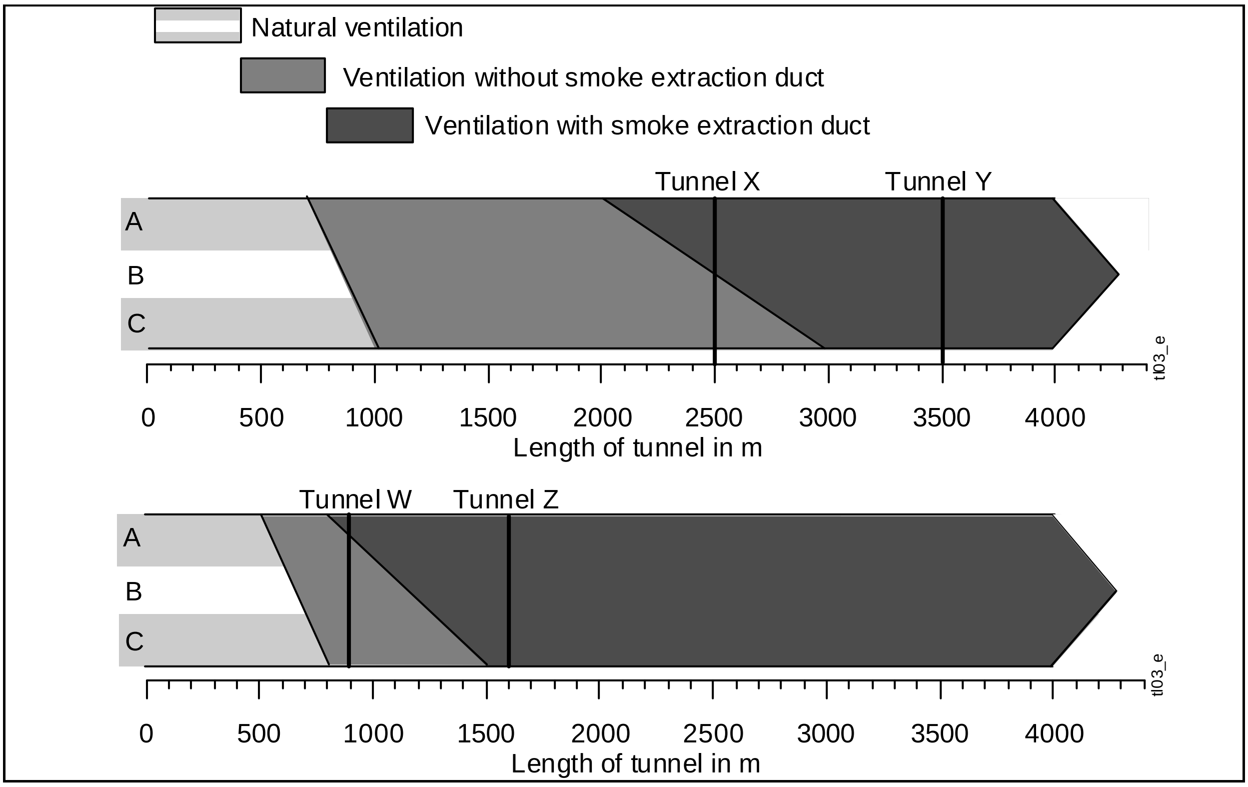

Figure 1: Classification of main groups of ventilation systems
above: RV 1, below: RV 2 and GV

If the main group is still not clear, further influence factors are proposed among them the length of escape routes. This indicates a weak interdependence between the choice ventilation system and the escape route length. In fact the authors of the directive regard ventilation and escape routes not as compensatory.

7. DESIGN OF THE VENTILATION SYSTEM

The directive defines the requirements and describes the design of the chosen ventilation system for normal traffic situations, incidents including fires and protection of the environment.

7.1 Design for normal traffic situations

For normal traffic situations, e.g. freely flowing traffic, congested traffic, blocked traffic and exceptionally bi-directional traffic, the approach described in PIARC (1995) is used. Some special features are:

- The end of the design period is 10 years after putting the tunnel into normal operation.
- Congested traffic is only to be considered if congestion is expected during more than 50 hours per year.
  A prognosis of such a value is usually very difficult. Therefore the directive in appendix 2 offers an estimation method on the basis of traffic character and traffic volume per day and lane.
- According to measurements of the driving speed of heavy duty vehicles on the San Bernardino route in 2001 the maximal speed values for HDV in slopes have been defined as

Slope [%]	-6	-4	-2	0	2	4	6
$V_{max,HDV}$ [km/h]	60	80	90	90	80	65	50

It is mentioned that on routes with a high percentage of trucks the values are lower.

- For the calculation of the fresh air requirement the limit values of 100 ppm CO and 0.005 m-1 for turbidity are given. These values are used for all kind of traffic schemes. Higher requirements as e.g. in PIARC (1995) are not regarded as necessary, since in the future all tunnels should be equipped with a traffic control system to prevent long exposition times in tunnels. For tunnels below an altitude of 800 m measuring devices for CO are no longer necessary.
- The directive quotes the NO_2 limit value of 1 ppm at an oxidation rate of 10 % according to PIARC (1999b). With the given limit values for CO and turbidity the NO_2 value will always be fulfilled and a special calculation for NO_2 is not regarded as necessary.
- In Appendix 3 of the directive the necessary values for the emission calculation of CO and turbidity are given in detailed form. Those values include contributions from surface friction and resuspension to the turbidity emission.
- To get a controllable system the minimum fresh air requirement in m^3/s is defined as 1.5 m/s times the tunnel cross section in m^2.

7.2 Design for a truck fire

7.2.1 Design fire

As is in several European countries the directive uses a fire load of 30 MW for the main design fire. This value refers to a loaded truck as cited in the Eureka trials (1998). A second design fire with 5 MW relating to a private car fire is a reminder for the ventilation designer to give attention to the fire scenarios with lower heat development but possibly high smoke production. For tunnels with high gradients the air flow and thus the smoke propagation can be fundamentally different. Even down-drafts of smoke are possible due to temperature differences between tunnel and environment.

An analysis of the detailed data of the Memorial trials (1995) led to the necessary interpretation of the label '30 MW' in order to calculate buoyancy forces by the fire:

ΔT_{fire}	65 K	final mean temperature rise over L_{heat}
L_{heat}	800 m	distance from fire with heat effect
$\Delta time_{heat}$	10 min	duration of linear rise of bulk temperature
η_{fire}	0.75	effectiveness of buoyancy

For non-homogenous slopes a refined temperature curve within L_{heat} can be necessary. The duration of the temperature rise is used for checking the instationary behaviour of the system. The buoyancy effectiveness is an empirical factor derived from the Memorial trials. An realistic combination of unfavourable meteorological conditions has to be regarded. It is the coincidence of a natural temperature difference between tunnel and environment of at least 5 K and the local 95 %-value of the pressure differences between portals due to barometric reasons and wind pressure.

7.2.2 Longitudinal ventilation systems

For the thrust of the jet fans in tunnels with longitudinal ventilation the following flow requirements are set:

Traffic mode (RV 1)

direction of traffic flow	downhill	uphill
buoyancy of fire	30 MW	no fire heat
requested minimal air flow	3 m/s downhill	3 m/s uphill

Traffic mode (RV 2)

direction of traffic flow	downhill	uphill	uphill
buoyancy of fire	30 MW	30 MW	no fire heat
requested minimal air flow	3 m/s downhill	1.5 m/s downhill	3 m/s uphill

Traffic mode (GV)

direction of traffic flow	uphill and downhill
buoyancy of fire	30 MW
requested minimal air flow	1.5 m/s downhill

The design should cover at least a reaction time of 3 minutes between the incident and the start of the jet fans and the traffic control respectively. The consequences of longer reaction times must be declared in the design report.

7.2.3 Ventilation systems with duct for smoke extraction

The report FEDRO (1983), which was the basis for the former ventilation design, started from the assumption that the smoke from a large fire remains stratified for a certain distance and time from the incident. The observations of the Ofenegg trials had led to such a conclusion. As a consequence most tunnels with smoke extraction were equipped with an intermediate ceiling with fixed openings over the whole length of the extraction segment. In newer tunnels the fixed size slot in the ceiling was throttled with a heat sensitive polymer enlarging the slot opening in the case of a near fire.

In the meantime experience from real tunnel fires and from the Memorial trials (1995) has shown that rarely a lasting stratification of smoke can be assumed. Taking into account a reaction time of detection and inertia of the system the new design for extracting smoke is no longer based on the idea of a fully transverse ventilation (fresh-air in on road level, smoke out from the roof) but mainly on the idea of influencing the longitudinal flow in the tunnel towards the fire. To that end controllable dampers between traffic space and smoke duct are necessary.

The main design demands to respect are:

- Smoke extraction must be performed with remotely controllable dampers.
- The dampers are to be placed in a distance of 100 m between each other.
  Since an erroneously open damper can cause grave consequences, maintenance of their function is a primary need. The given distance had been chosen under the aspects of maximal length between incident and damper, i.e. 50 m and the necessary size of damper (see below).
- At the incident 3 or 4 dampers must be opened, i.e. over a distance of 200 m to 300 m.
  This requirement results from a compromise between redundancy of dampers and exactness of the detection of the incident location. It is also taken into account that in real tunnel fires a certain length of the tunnel will be filled with smoke before the ventilation is effective.
- The outmost dampers should be installed 200 m to 300 m from the portals.
  Extraction close to portals is usually very inefficient. In addition this allows to place jet fans in this section.

- The free area of the fully open damper should result in a mean vertical speed of about 15 m/s with respect to air of ambient temperature. If the volume flow of extraction is higher than the requested minimum, the vertical flow component can be increased up to 20 m/s.
  The limit of the vertical speed is set for the case of a stratified smoke layer under the ceiling. With very high local speeds the percentage of fresh air in the extracted gas is higher.
- The minimal extraction flow rate $V_{extraction}$ for a tunnel with cross section A_T over the distance of the opened dampers and related to ambient air is
  $V_{extraction} = A_T \cdot 3 + V_{fresh\_air}$
  Decisive for the value was that in most tunnel geometries the so-called critical air velocity to force the smoke to one side of the incident is about 2.5 m/s. Applied to bi-directional tunnels the smoke spreading can not be avoided. The fresh air flow from either side might allows though a stratification at the initial phase of a fire.
- The requirements for the longitudinal flow on either side of the incident are as follows:

Traffic mode	**Traffic situation at time of incident**	**airflow toward location of incident**	**tunnel section**
RV 1	Freely flowing	≥ 3 m/s ≥ 0 m/s	congested branch emptied branch
RV 2	Freely flowing	≥ 3 m/s ≥ 0 m/s	congested branch emptied branch
	Congestion	≥ 1.5 m/s	both sides of incident
GV	Freely flowing or congestion	≥ 1.5 m/s	both sides of incident

  To meet these requirements for all possible incident locations in a tunnel, either a high extraction volume flow or a combination with jet fans is necessary. The thrust of the jet fans balances the pressures in the two tunnel branches on either side of the incident.
- In a double tube tunnel, the above stated requirements are valid for both tubes individually and it must be possible to operate the extraction in both tubes simultaneously and independently. The practice has been adopted that the ducts of the two tubes are connectable to get an even higher extraction volume flow at the incident.
- The design should cover at least a reaction time of 4 minutes between the incident and the full function of the smoke extraction and the traffic control respectively. The consequences of longer reaction times must be declared in the design report.

7.3 Behaviour of the system

For the relevant scenarios, the behaviour of the tunnel system within the first 20 minutes from the incident must be estimated. The result can be decisive for increasing the capacity of the ventilation system.

7.4 Redundancy requirements

For the main ventilation components of safety, redundancy requirements are set:

- Jet fans — After the failure of a group of jet fans the thrust remaining must be at least 90 % of the required value.
- Extraction ventilators — After the failure of a ventilator the remaining extraction flow rate must be at least 65 % of the required value.

The directive contains further redundancy requirements for dampers, flow measurements, incident detection and plausibility of automated function checks.

7.5 Environmental aspects

The necessity to design the ventilation system to reduce the outflow of tunnel air through the portals must be determined by a separate environmental study according to Swiss law. Since first design assumptions are usually performed long before those studies are accomplished, the directive names values for the NO_x portal load over which such systems usually are necessary.

Environmental situation	NO_x portal loads usually asking for measures
city centre	> 10 t/year
residential	> 20 t/year
industrial	> 30 t/year
rural	> 40 t/year

8. ESCAPE ROUTES

Only routes directly to the open are regarded as escape routes. Safety rooms without connection to the open are no alternative to escape routes. The escape routes should be placed equidistantly.

For uni-directional tunnel with two parallel tubes the following requirements are set:

- The distance between cross-connections is defined as 300 m.
- Every third cross-connection must be dimensioned for the vehicles of safety personnel.

For bi-directional tunnels and uni-directional tunnels without a second parallel tube the minimal requirements are still under discussion. Main factors for the definition of the escape route length are tunnel slope, tunnel length and traffic volume specified as number of cars and heavy goods vehicles per time. In certain cases a parallel safety tunnel or a passable duct below the road could represent the most economic solution. Presently the 6.6 km long San Bernardino tunnel is equipped with a safety tunnel below the road.

9. EXEMPLES

At present a large number of ventilations of tunnels in operation, in construction or in the planning stage are checked and brought to the level of the new requirement.

Gotthard road tunnel (bi-directional, 16.6 km)

About 18 months ago, the project to replace the fixed openings in the intermediate ceiling with controllable dampers was started. At the time of the tunnel fire in October 2001, a damper prototype had been installed. Today all 180 dampers are mounted and an intermediate ventilation system is in operation. Among all checked road tunnels in Switzerland, including San Bernardino, Gotthard is the only tunnel that has to be operated in fully transverse mode during normal traffic situation. In this mode the dampers have to be put into a intermediate position with very small opening angles (4° to 8°).

The tunnel passes the main alpine ridge, and barometric pressure differences between the portals up to 200 Pa must be considered. Due to the tunnel length and the very large installed fresh air capacity, jet fans to stop the longitudinal flow are not necessary.

Aeschertunnel (uni-directional, 2.2 km)

The Aeschertunnel as part of the new highway circle around Zurich is under construction. About half of the tunnel length is already excavated. Due to the fact that the risk of congestion is clearly in the range RV2 (figure 1), the tunnel ventilation system had to be changed lately. In the originally longitudinally ventilated double-tube tunnel, intermediate ceilings were added with two cross-connections between the ducts. With a slope up to 3 %, it was necessary to increase the jet fan thrust.

Gotschnatunnel (bi-directional, 4.2 km)

With an average slope of almost 5 % the buoyancy by a natural temperature difference of 10 K is about the same as the buoyancy developed by a 30 MW fire. To meet the requirements of the directive (see above chapter 7.2.3), the fully transverse ventilation system with a minimal extraction capacity of 210 m^3/s had to be completed with controllable dampers and jet fans. Due to the given tunnel width, 20 jet fans of rotor size 630 mm will be mounted pairwise toward the upper end of the tunnel.

10. CONCLUSIONS

The Swiss directive sets a new national standard for the ventilation of road tunnels. While a few years ago the demand during normal traffic situations dominated the design, today the requirements for the fire case is determining the size of the systems. Extensive trials in the past years in the scale 1:1 led to new findings that were included in the design principles. With the higher quality of ventilations in an emergency case the systems became more complex and maintenance of the systems will require highest priority in order to avoid malfunction with possibly fatal consequences.

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AIRFLOW GENERATION IN A TUNNEL USING A SACCARDO VENTILATION SYSTEM AGAINST THE BUOYANCY EFFECT PRODUCED BY A FIRE

J D Castro[a] , C W Pope[a] and R D Matthews[b]

[a]Mott MacDonald Ltd, St Anne House, 20-26 Wellesley Road, Croydon, CR9 2UL, UK
[b]Centre for Tunnel Aerodynamic Research, South Bank University and Impulse Ventilation Systems Ltd UK

ABSTRACT

It is generally difficult to provide ventilation shafts for tunnels which pass under water or high mountains. An alternative is to ventilate the tunnel using the Saccardo system with impulse fans located at the portals. Tunnels that pass under water descend to a low point and there is concern over the capability of a Saccardo system to provide adequate levels of ventilation control in the case of a fire occurring in an inclined section of tunnel. This paper considers the problem in relation to a train fire occurring in a single track rail tunnel 3 km long. In order to investigate the effect of Saccardo ventilation nozzles on the flow generated by buoyancy from the fire, a computational fluid dynamics (CFD) model was used. The results indicate that a practical Saccardo system can be developed to provide effective smoke control against the effect of buoyancy in a fire situation. Moreover, the predictions indicate that fan "start up" may be achieved against an established buoyancy driven flow by the fire. The time taken to clear the air behind the fire is dependent on the response time of the fans.
Key words: Saccardo nozzles, fire, smoke control, CFD

1. INTRODUCTION

The design of rail tunnels demands that adequate ventilation systems are installed in order to ensure effective control of smoke during a fire incident. The Saccardo system (Ref 1) is a very convenient means of ventilating a tunnel under emergency conditions where the provision of a conventional shafts based ventilation system is difficult. In this paper, consideration is given to the question of whether a Saccardo impulse fan ventilation system has the ability to control the heat and smoke from a train fire in an inclined tunnel, where buoyancy forces are an important factor.

The rail tunnel under consideration is 3 km long with a Saccardo ventilation installation located at the entry portal. The tunnel falls on a gradient of 2.5% to the mid-point and then ascends at 2.5% to the exit. The injection nozzle is positioned in a cut and cover section 44 m from the bored section of the tunnel and directed towards the exit portal. The entrance at the tunnel has been designed as a cut and cover section with the intent of encouraging the development of a forced flow through the tunnel by the diffusion pressure of the Saccardo nozzle.

Three different scenarios were considered in an ascending order of operating difficulty for the ventilation system to establish a robust flow over the train. The first simulation was for cold flow conditions (no train fire) to predict the proportion of ventilation air entering the tunnel. The second simulation was undertaken for the Saccardo fan switched on at the same time as a fire breaks out on the train. Finally, a simulation was undertaken for the ventilation system initiated after a buoyancy driven flow had been established in the tunnel by the fire.

A train 400 m long with a 7 MW fire at the leading end is positioned 600 m from the entry portal. A diagram of the train and tunnel configuration is given in Figure 1. The critical flow velocity for the case under consideration was determined from a one dimensional flow analysis to be 1.5 ms^{-1}.

In order to investigate the effect of Saccardo type ventilation nozzles on the propagation of smoke from a train fire within the tunnel, the problem was analyzed using a simplified CFD model. A description of the model and the predicted results are given in the sections which follow.

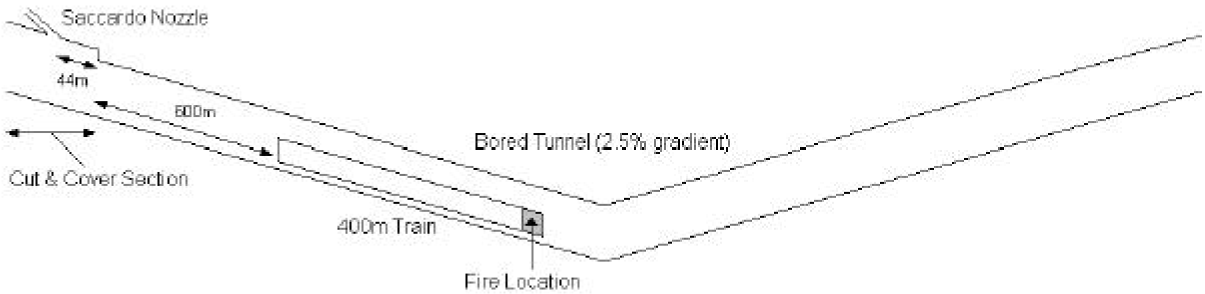


Figure 1: Diagram of Rail Tunnel Configuration (Scaled Vertically to Aid Viewing)

2. COMPUTATIONAL FLUID DYNAMICS MODEL OF TUNNEL

A CFD model was developed in order to perform three-dimensional simulations of the movement of heat and smoke from the fire.

In order to investigate the basic characteristics of the problem, a simple rectangular blockage was used to represent the train, the front of which was located 1000m from the mouth of the bored tunnel. A diagram showing the geometrical arrangement is given in Figure 2. To enable the CFD calculations to be performed within a short period of time, a half-model of the tunnel was constructed, a plane of symmetry being imposed along the centre-line of the tunnel.

In order to perform the simulations, the CFX code from AEA Technology was used. The code solves the fluid mechanics equations using the method of finite volumes. To represent the effects of turbulence, the standard k-ε model was employed. The flow was treated as weakly compressible, the density given by the equation of state. Time steps of 5 s were chosen, with a suitable number of iterations for each time step in order to ensure adequate convergence. A close-up view of the computational mesh is shown in the lower half of Figure 2. Time constraints prevented any assessment of the effect of grid resolution on the results. This should, however, form a key element of any future in-depth study.

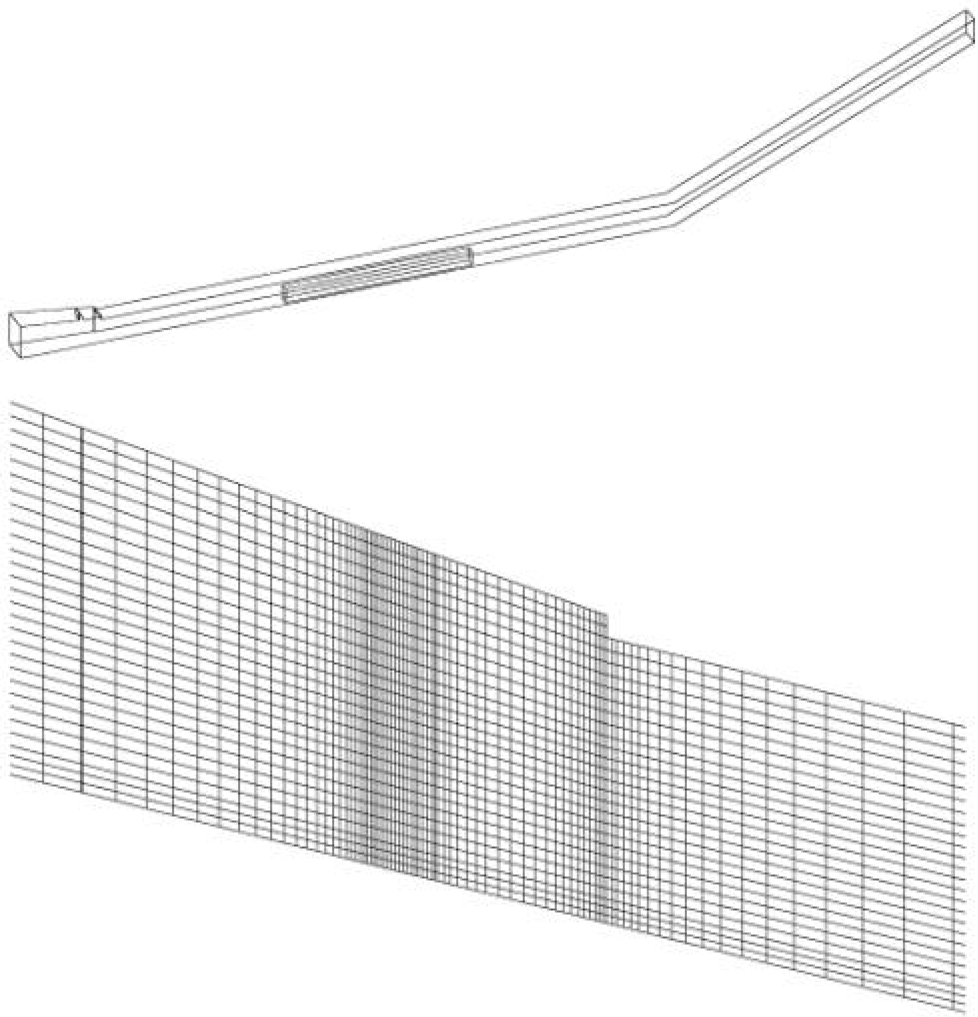


Figure 2: View of CFD model and close-up of mesh at boundary between Cut & Cover section and Bored Tunnel (both scaled to aid viewing)

The 7 MW fire was represented as a volumetric source of heat, located at the end of the train farthest from the tunnel portal. The heat was specified as a constant source in the enthalpy equation and the volume of the source was updated at each time step to ensure reasonable temperatures at the source. No account was taken of radiation, hence the results will err on the conservative side with respect to the propagation of heat and smoke towards the tunnel exit. Smoke from the fire was represented by adding a source of passive scalar. A scalar concentration of 1% has been adopted as an acceptable limit with regards to obscuration and visibility but the actual mass concentration of soot will depend on the properties of the fuel being burnt. The 1% value is considered a suitable indicator here, since it is only required in this study to evaluate the effectiveness of the Saccardo nozzle in establishing a flow of fresh, smoke-free air over the train.

The Saccardo nozzle was represented by adding an additional block to the roof of the tunnel. This is required to properly capture the flow from the fan down into the cut-and-cover section of the tunnel.
The area of the nozzle inlet was 4 m^2, with a volumetric flow from the fan of 120 m^3/s. A turbulence intensity of 5% was specified at the fan inlet, with the hydraulic diameter of the inlet used as the dissipation length scale.

3. SIMULATIONS PERFORMED

Cold Flow Case

The first simulation undertaken was a cold flow simulation (no fire source) with the Saccardo fan in operation. This was undertaken to assess the capability of the Saccardo system in establishing a strong enough tunnel flow in the absence of a fire. The average velocity predicted in the bored tunnel was 2.7 ms^{-1}, indicating a flow of 96 m^3s^{-1} from the Saccardo nozzle through the tunnel and 24 m^3s^{-1} out of the south portal. The friction factor, f, applied on the walls of the tunnel was taken to be 0.007.

A one-dimensional unsteady tunnel flow program (Ref 2, based on the method of characteristics) was also used to undertake simulations of the ventilation system. The results from this analysis indicate a steady cold flow air velocity of 2.3 ms^{-1}, rather than 2.7 ms^{-1} as predicted in the CFD analysis. The difference can be related to the use of a momentum transfer coefficient in the 1-D network studies, the CFD analysis giving higher diffusion pressures in the region of the Saccardo nozzle. The 1-D simulations are naturally unable to take into account any three-dimensional variation in the flow field.

Plots showing the predicted velocity field in the vicinity of the Saccardo nozzle and over the train are given in Figure 3.

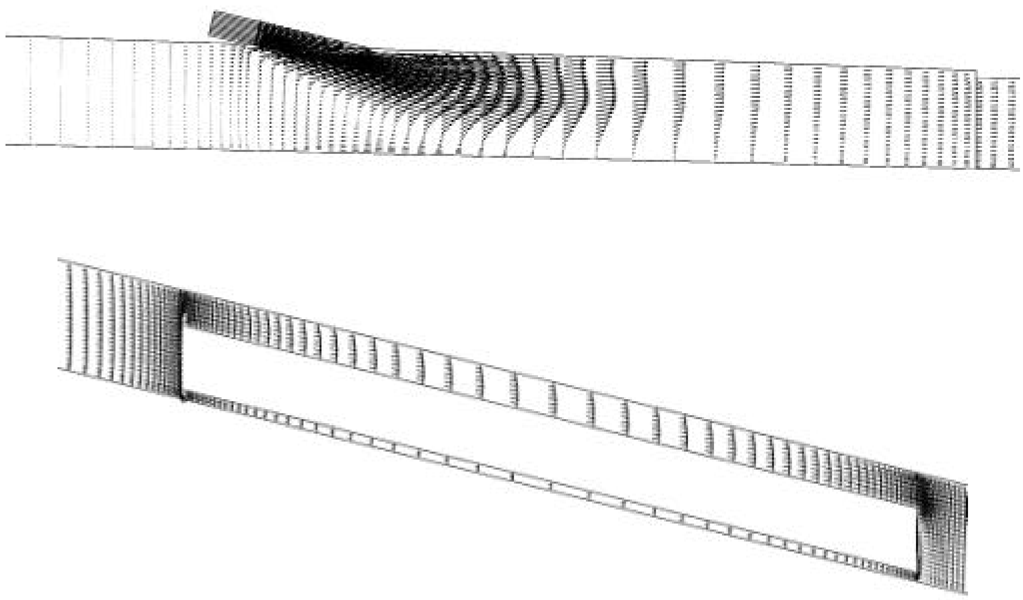
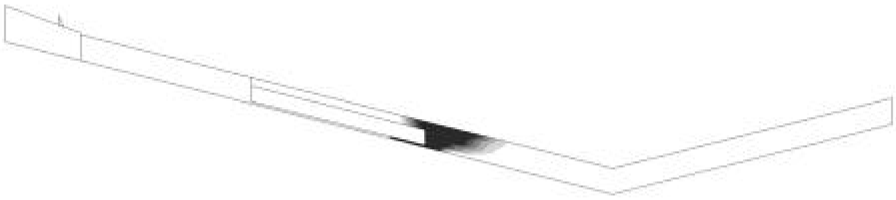


Figure 3: Predicted Flow in Region of Saccardo Nozzle and over Train

The circulation of air immediately behind the Saccardo inlet stream is clearly apparent. The CFD simulation predicts a more or less uniform flow velocity at the boundary between the Cut and Cover and Bored sections of tunnel. The profile becomes fully developed by the time it reaches the front of the train.

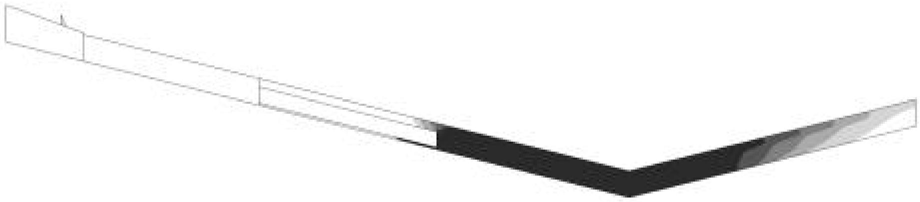
7 MW Fire, Saccardo Fan activated at time zero

The first fire simulation undertaken was for the case of the Saccardo fan activated at the same time as when the fire breaks out, i.e. at time zero. No back-layering from the fire is predicted. The flow velocity down the bored tunnel towards the train reaches its steady-state value by 7.5 minutes. Figure 4 illustrates the results of the simulation:



1 minute

3 minutes



5 minutes

7.5 minutes

Figure 4: Predicted Smoke Layer at 1, 3, 5 and 7.5 minutes

7 MW Fire, Saccardo Fan activated at 10 minutes

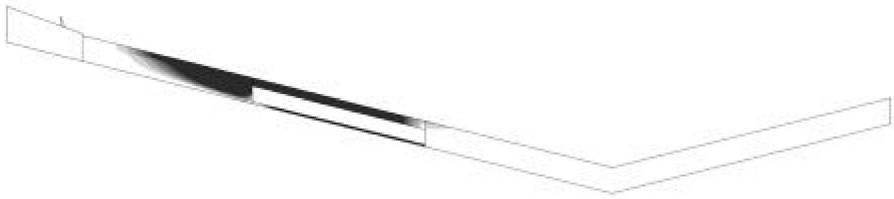
In this simulation, no ventilation is applied for 10 minutes. During this time, a buoyancy driven flow is established in which smoke and hot gas from the fire reaches the exit. By 10 minutes, virtually steady state conditions are attained, the smoke layer having reached the exit and subsequently venting out to atmosphere.

At 10 minutes, the Saccardo fan is switched on to work against the effect of buoyancy and reverse the flow. The CFD simulation predicts that it takes a further 10 minutes to establish a steady flow in the opposite direction, with a column of clean air between the fan and location of the fire. Thus fan "start up" may be achieved against an established buoyancy driven flow, although it takes a while to achieve the desired result. It is expected that an earlier start up time would result in a more rapid clearing of the air behind the fire. However time constraints prevented a more thorough examination at this stage.

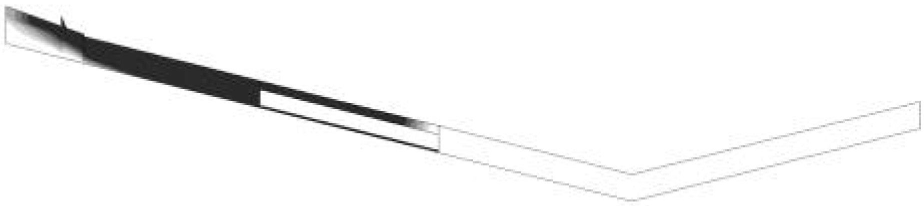
Plots of smoke concentration during the scenario are illustrated in Figure 5. The CFD simulation predicts the movement of the smoke layer past the location of the Saccardo nozzle by 7.5 minutes. By 10 minutes, virtually the entire cross-section of the tunnel upstream of the fire is affected by smoke. The Saccardo fan flow takes a couple of minutes to begin fully clearing the smoke layer in the bored tunnel. Five minutes after the fan is switched on, nearly the entire length of bored tunnel upstream of the train is clear of smoke. A steady flow of smoke out of the north end of the tunnel is established by 20 minutes.

On examination of the results of the standard k-ε model, it is worthwhile noting the thickness of the smoke layer which is predicted by the model. Modifications to the flow equations are possible in order to account for the suppression of turbulence in the smoke layer, which would be expected to lead to a thinner and more well stratified layer.

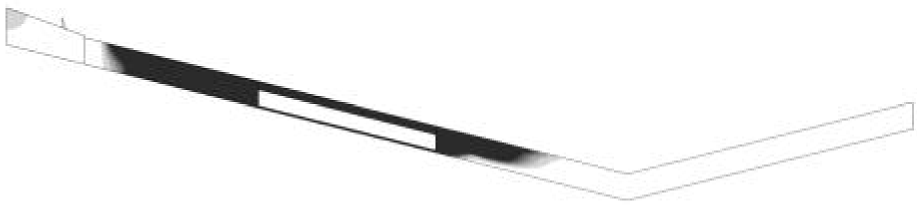
It would be worth re-running the model at a later stage to examine the effect of modifying the flow equations on the predicted results. Since a better stratified layer may be expected in practice, the Saccardo fan could take longer to drive the smoke back down the tunnel.



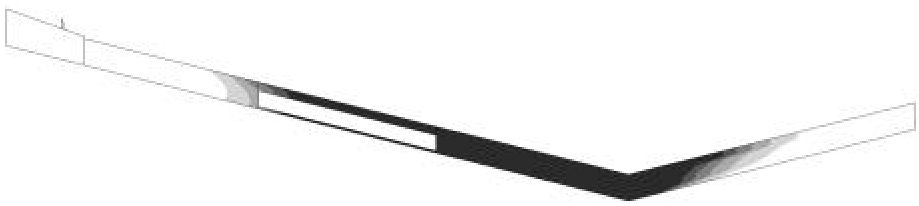
5 minutes



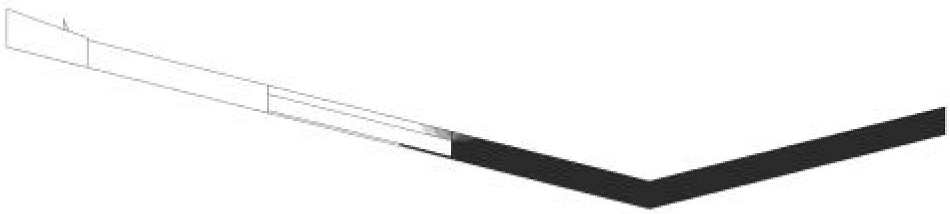
7.5 minutes



12.5 minutes



15 minutes



20 minutes

Figure 5: Predicted Smoke Layer at 5, 7.5, 12.5, 15 and 20 minutes
(Contours of 1% - 5%+ concentration)

4. CONCLUSIONS

Consideration has been given to the problem of generating a forced ventilation flow in a tunnel using a Saccardo system against an established buoyancy driven flow produced by a train fire. The predictions have shown that the system is capable of overcoming the buoyancy forces to produce a robust unidirectional flow directing heat and smoke away from the train. The study also demonstrates the potential usefulness in applying CFD techniques to the prediction of smoke movement in underground rail tunnels using impulse ventilation systems.

For future studies, it would be worth performing a grid-dependency analysis, as well as examining the effect of choice of turbulence model and differencing scheme on the results. Ideally full-scale experimental tests should be carried out to confirm or otherwise the general smoke behaviour predicted using CFD.

ACKNOWLEGMENTS

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VENTILATION CONCEPTS FOR BUENAVISTA ROAD TUNNEL

Wagner Harald, D2 Consult Linz / Austria
Pucher Karl, TU-Graz / Austria

ABSTRACT

The Buenavista Tunnel in located in the Eastern Cordilleras at the transition to the wide plains of Metha Province. Its length is 4.520 meters. It consists of one tube with two lanes for each direction. It also has two pedestrian lanes which are lateral arranged. The original ventilation concept has been part of the original design from 1986. It has been equipped with longitudinal ventilation using jet fans. The tunnel profile has been designed accordingly. Construction of the project has been done in two contracts, executed by different consortia. The first contract has been executed between 1995 and 1997, whereas approximately 20 % of the works have been completed. Final completion including ventilation and safety installations within the second contract is expected by approx. middle of 2002. Criteria of design between 1986 and today's requirements of the completed structure were changed dramatically. Traffic loads, increased safety requirements, environmental conditions and engine emissions are different than 20 years ago. The paper reports how these changes are considered in the course of the realization of this complex infrastructure project. Those ventilation concepts are explained, which finally led to the decision of the Ministry for the chosen hybrid solution using jet fans together with ventilation ducts in the roof equipped with ventilation dampers.

Key words: jet fan, damper, emissions, traffic load, fire life safety

1. LOCATION OF TUNNEL AND PASS ROAD

The Tunnel is located approx. 120 km East of Bogotá. It is the most important traffic link between the plains of Los Llanos with its widespread green land and the capital of Colombia with its population of approx. 8 Million. The existing road in the area of the tunnel is crossing over various hills near the city of Villavicencio.

The Bogotá-Villavicencio road is transferred within the frame of a concession contract to Coviandes, a special Consortium which is also responsible for maintenance and operation. The length of the tunnel is 4.5 km, thus representing the Eastern link between Bogotá and Villavicencio. The tunnel shortens the time in comparison with the existing road by approx. 15 minutes.

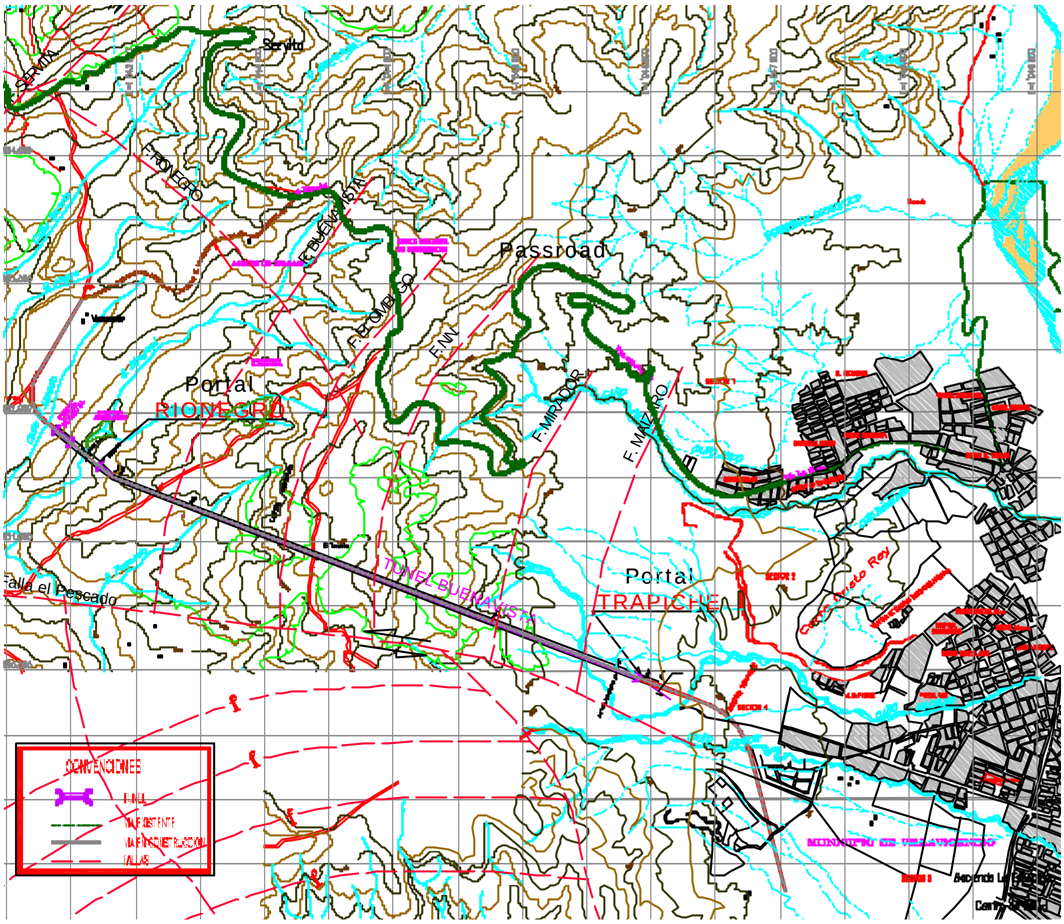

Figure 1 Location of the tunnel versus pass road

2. ORIGINAL TUNNELPROJECT WITH 2 TUBES

The original tunnel project has been developed between 1980 and 1985. There have been two parallel tubes each of them to be used unidirectional. Ventilation has been designed with longitudinal jet fans for each tube. The project has been considered to be well feasible under those conditions especially using lower traffic loads at that time.

3. DECISION FOR CONSTRUCTION IN 2 PHASES

The Ministry for Transport has decided in the following years to execute construction in 2 phases. In Phase 1 it was foreseen to construct one tube for bi-directional traffic.

4. MISSING ADOPTION OF VENTILATION CONCEPT IN PHASE 1 WITHOUT ADOPTION

It has been overlooked, that the ventilation concept has to be adopted to the changed phasing of construction. This includes construction of rescue tunnel which are needed in accordance with the Austrian Guidelines. Rescue tunnels or alternative parallel galleries should provide access at minimum 3 – 4 locations to the outside. Regardless of such rescue possibilities it is necessary for the fire case in the tunnel, that also for this configuration a special solution should be provided.

5. PROPOSAL OF HOWDEN WITH REVERSIBLE SEMI-TRANSVERSAL VENTILATION WITHOUT SHAFT WITHOUT ADOPTION

On the basis of the project as constructed with one tube for bi-directional use, the Howden company has submitted an improved proposal. This proposal represents a ventilation concept on the basis of a reversible fresh air semi-transversal ventilation without shaft. Fresh air demand as calculated by Howden is less in comparison with fresh air demand as calculated by the authors of this paper. However, there is more than the fresh air demand on the basis of CO emissions as calculated by Ingetec company.

The Howden proposal needs a concrete ceiling for the whole length of the tunnel separating the space for the vehicles from the roof of the tunnel, whereas there is a cross section of approx. 7 m² available for fresh air supply. The height of the traffic area has been 4,3 m, whereas 4,7 m are required. There are 2 ventilation sections starting at the very portal and dividing the whole tunnel into two half tunnels. Under normal conditions the required fresh air will be pressed through opening equipped with dampers and arranged in the ceiling above the traffic space. Bad air will be mixed with fresh air in the traffic section for pushing through the portals to the outside of the tunnel.

In the case of fire the fresh air channel is converted into a bad air channel. In the area of the fire the dampers will remain open in order to suck off the smoke. All other dampers in the ceiling outside of the area of the fire will be closed.

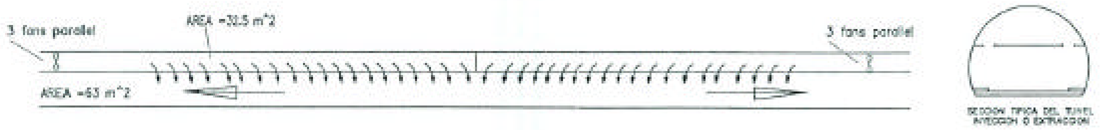

Figure 2 Semi-transversal ventilation scheme without shaft, System Howden

6. PROPOSAL D2 CONSULT / PROF. PUCHER WITH REVERSIBLE SEMI-TRANSVERSAL VENTILATION AND CEILING

This proposal has foreseen a reversible semi-transversal ventilation with ceiling and major bad air dampers. The rough calculation of fresh air demand, using the required height between carriage way and ceiling of 4,7 m results in a necessary channel cross section of 5 m² between roof of the tunnel and ceiling, using the existing profile geometry. Two variants have been in closer consideration.

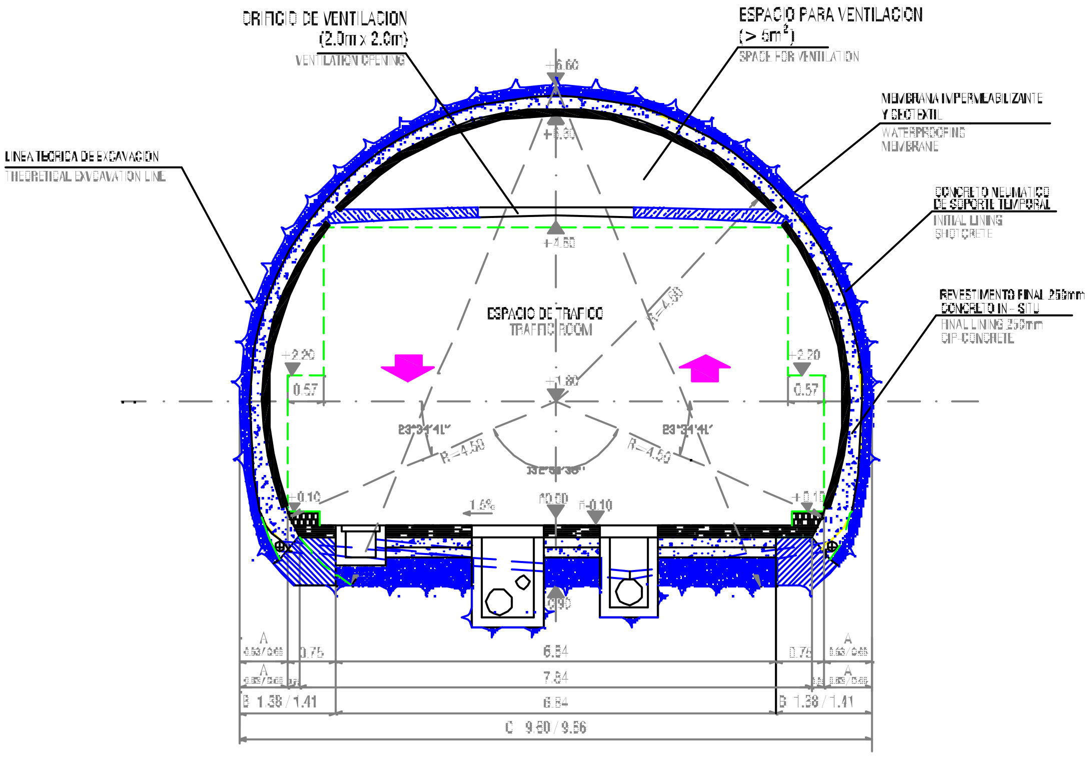

Figure 3 Tunnel cross section with ceiling for semi-transversal ventilation,
System UT DIS/EDL - D2 CONSULT

Variant 1 has foreseen a shaft with four ventilation sections. The shaft should be located approx. in the middle of the tunnel. There should have been two quarterly sections each at both sides of the shaft for supply of fresh air.

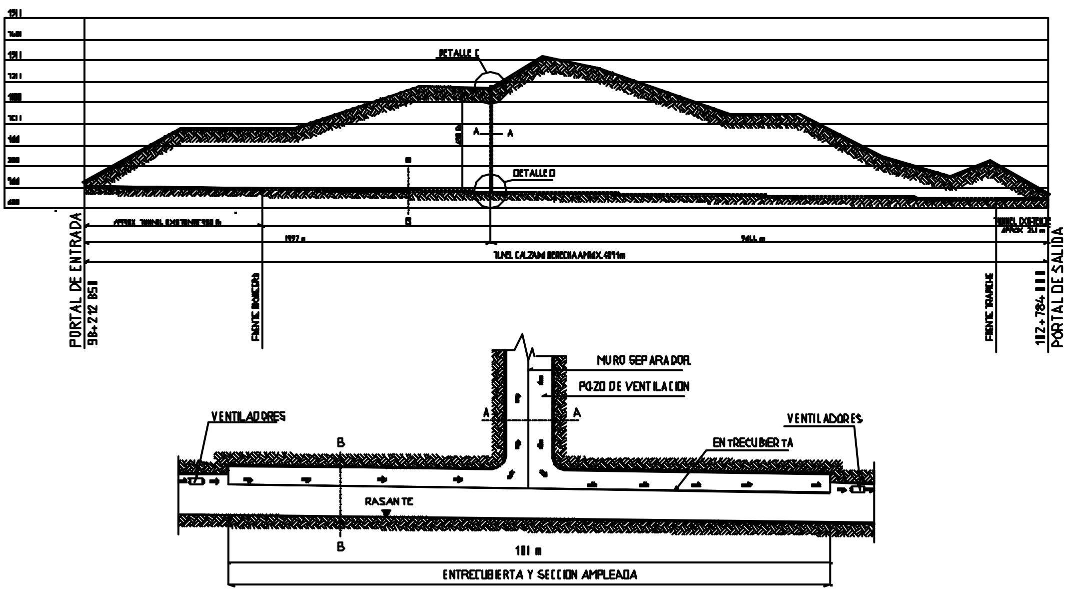

Figure 4 Scheme with longitudinal ventilation and shaft,
System UT DIS/EDL - D2 CONSULT

Variant 2 has foreseen construction of one (or two) parallel gallery reaching from the eastern portal to approx. one third (or two quarters) of the tunnel. Ventilation sections 1 and 4 should be supplied from the portal respectively from the parallel gallery.

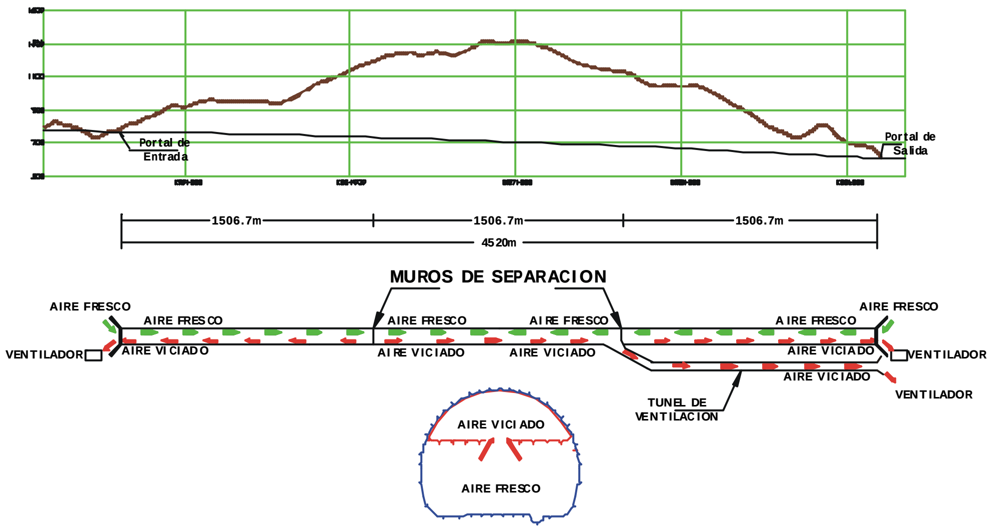

Figure 5.1 Scheme for semi-transversal ventilation with one gallery

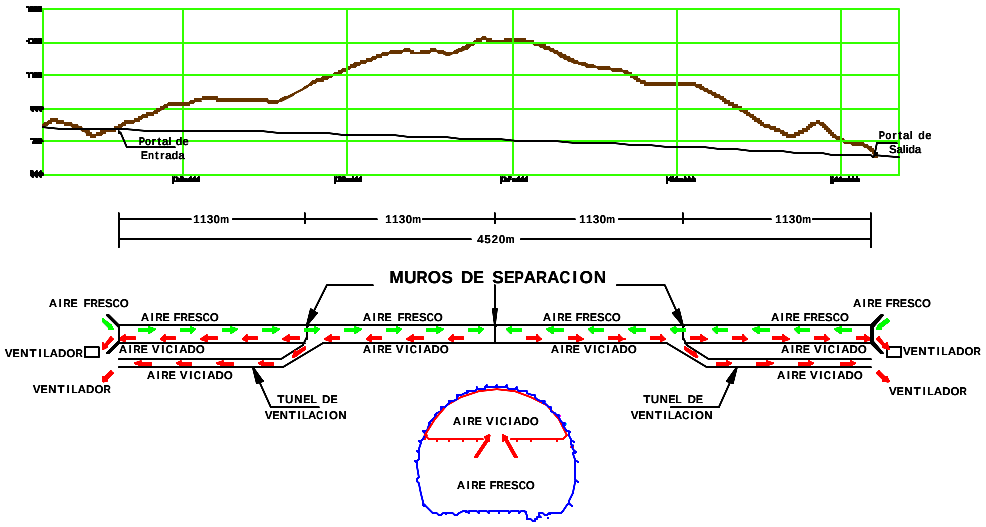

Figure 5.2 Scheme for semi-transversal ventilation with two galleries

Both proposals could not be realized as they have been rejected for reasons of time and cost.

8. INGETEC PROPOSAL WITH LONGITUDINAL VENTILATION AND ADDITIONAL SUCK OFF TUBE

Finally the Ministry has decided for the ventilation concept of Ingetec company. This ventilation concept provides tunnel ventilation with longitudinal jet fans, whereas traffic load estimate in normal conditions is assuming less traffic than estimated by the authors. If traffic load is increasing (e.g. during Semana Santa = Holy Week) the tunnel will be used in one direction only, whereas the traffic in the other direction will use the existing pass road.

It has to be stated, that in case of a tunnel fire this cannot be controlled in accordance with existing Standards and Guidelines unless the second tube will be constructed. Furthermore it is presumed today, that the second tube will be constructed until the year 2007 with subsequent use of both tubes in one direction only.

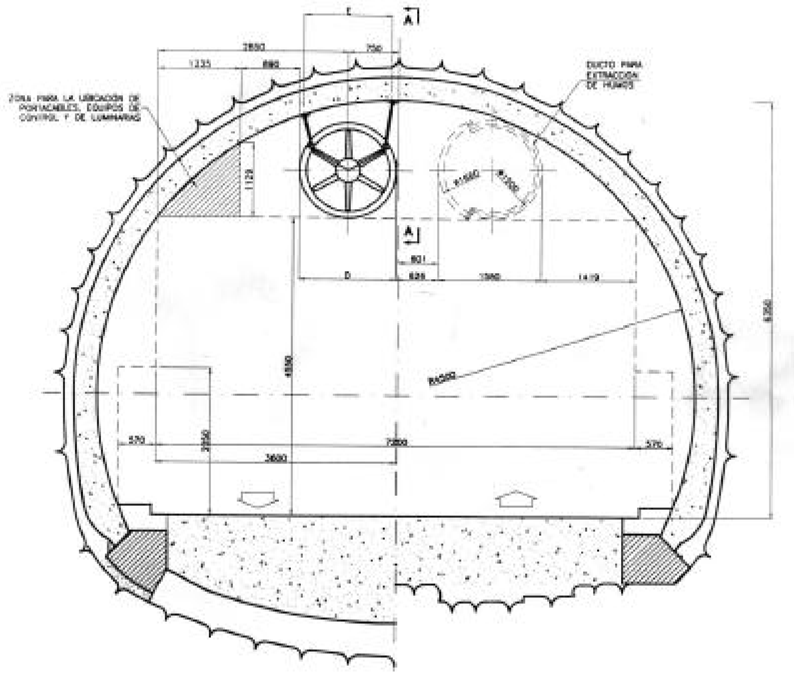

Figure 6 Longitudinal ventilation and suck off tube, System Ingetec

9. FRESH AIR DEMAND CALCULATION ACCORDING TO PROF. PUCHER

When calcualting fresh air demand it is to be considered, that truck and vehicle emissions in Colombia are higher than in Austria. Exhaust tubes of trucks of light to medium heavy types big and black exhaust is almost always evident. Heavy trucks mostly imported from the USA do show less emissions. Calculation of necessary fresh air is impossible in accordance with Austrian Guideline RVS 9.261 and PIARC Requirements 1995 / 1991.

Calculation in accordance to PIARC 1987, standard D (no effective emission control) corresponds only with emission situation of Colombia.

Following table shows calculated fresh air (summary of uphill and downhill lane) per second and kilometre for the Buenavista Tunnel, located in 700 m above sea level and having an inclination of ± 2.6 %. Truck portion is approx. 25 % from total traffic load of approx. 900 vehicles per hour. Fresh air demand maximum results from visibility emission at 40 km/h of speed.

q_{CO} (Basic emission CO) $m^3(h/veh.)^{-1}$	q_T (Basic emission visib.) $m^2(h/t/veh.)^{-1}$	Necessary Fresh Air $m^3(s/km)^{-1}$
1.5	25	153
1	20	120
0.7	16	90

These values correspond with fresh air demand as installed during the 1980's in tunnels. In accordance with RVS 9.261 as valid in Austria the specific fresh air volume would result in approx. 35 $m^3(s/km)^{-1}$.

9.1 Calculation of ventilation in normal conditions

When designing the ventilation fresh air volume has been used in order to provide necessary thrust of jet fan ventilator (internal diameter Di = 1250 mm, capacity 52 kW for each ventilator). In normal conditions the number of necessary jet fan ventilators amounts to approx. 25 with a total capacity P_{tot} ~ 1300 kW.

9.2 Tunnel operation under conditions of fire

In order to suck off the smoke in case of fire there are two tubes with an internal diameter of 1.4 m arranged in the roof of the tunnel, each of them leading from the middle of the tunnel to the portal. In certain distances there should be controllable dampers arranged on the tube in order to be opened in case of fire. Smoke should be sucked off via respective dampers in the tube. Smoke should be moved with a strong ventilator, located at the portal to be blown out into the atmosphere.

When sucking off smoke with a relative small tube and respective ventilator, there are problems of material as well as problems of aerodynamic and thermal aspects. With increasing suck off volume these problems are increasing as well.

9.3 Material and cost problems

- When using stainless steel in accordance with Austrian Guidelines the cost for such steel tubes are extremely high
- Very high ventilation capacity will be required (approx. 15.000 kW)

9.4 Aerodynamic problems

- Because of relative high speed of air in a rather small tube there are high pressure losses expected (ΔP = 20.000 N/m² - 100.000 N/m²)
- Because of high under-pressure there are high problems of tightness resulting in false air at closed dampers

9.5 Thermal problems

- Necessary heat resistance in case of a fire
- Expansion problems because of temperature differences in normal and fire conditions

10. CONCLUSIONS

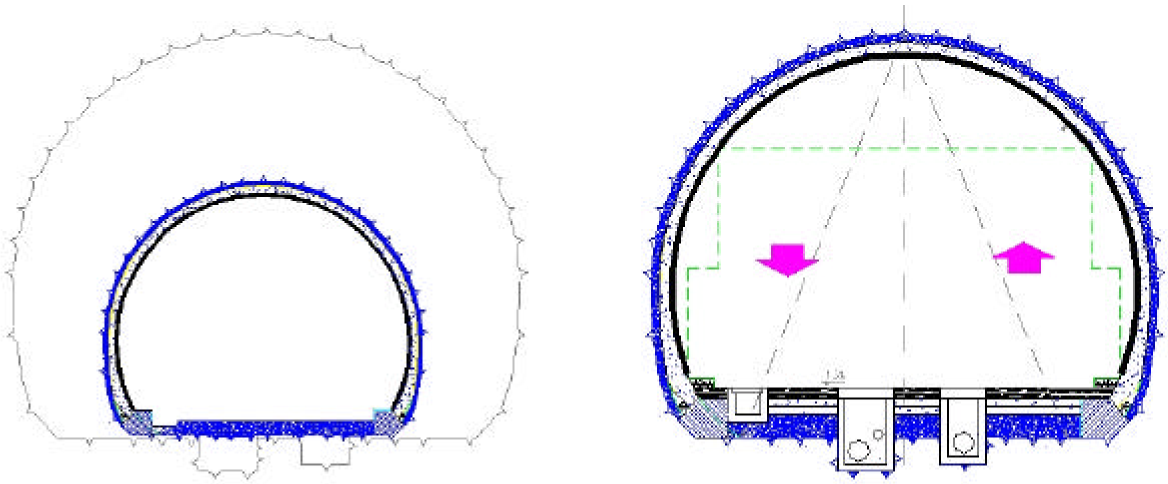

Figure 7 Existing tunnel cross section (with ventilation gallery suitable for future construction of second tunnel as proposed by UT DIS/EDL-D2 CONSULT)

From all prospectives it is evident that the Ingetec ventilation concept with the suck off tube in the tunnel roof cannot be considered as being technically sound in the case of fire. Final cost are considered to be in the same range as the semi-transversal concept proposed by UT DIS/EDL-D2 CONSULT. It is recommended not to realize this solution and instead start immediately with the construction of the second tunnel. With this, one would return to the original concept with two tunnels and sound safety system, whereas both tubes should be operated uni-directional and should be equipped with longitudinal ventilation.

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THE TÚNEL LA LÍNEA - A CHALLENGE FOR VENTILATION AND SAFETY

Mario Glessig, Gerhard Plank, Geoconsult, Salzburg, Austria,
Karl Pucher, Technische Universität Graz, Institut für VKM und Thermodynamik, Graz, Austria

ABSTRACT

The Túnel la Línea in Colombia with its length of 8.6 km will be the longest road tunnel on the American continent. Due to the large number of trucks that will use this tunnel and the exceptional elevation (2500 m above sea level), the Túnel la Línea represents a challenge for the design of tunnel ventilation and safety installations.

The design concept for the Túnel la Línea comprises one tunnel tube for bi-directional traffic and a parallel rescue tunnel. The tunnel will be equipped with a fully-tranversal ventilation system (with two ventilation shafts) in order to provide the highest level of safety in case of a tunnel fire. Other ventilation systems produce a higher air velocity in the tunnel during regular tunnel operation and would therefore delay the detection of the fire and allow the smoke gases to spread rapidly along the tunnel.

*The calculation for the fresh air demand was based on the recommendations of PIARC from 1987. In order to guarantee that the permissible maximum values for carbon monoxide and diesel soot concentration are not exceeded, a fresh air volume of approx. 170 m3/(s*km) will be required for the Túnel la Línea. An exhaust air extraction capacity of at least 120 m3/s at the end of each ventilation section would be available in case of a tunnel fire.*

With a fully-tranversal ventilation system, fire detectors all along the tunnel, a fire-fighting pressure pipe with hydrants every 125 m, emergency call niches every 250 m, a closed-circuit TV system and emergency exits to the parallel rescue tunnel every 500 m, the Túnel la Línea will be provided with a state-of-the-art safety concept.

Key words: Transversal ventilation system, rescue tunnel, tunnel fire, fresh air demand, safety concept

1 INTRODUCTION

The Túnel la Línea Project is located in the Cordillera Central mountain range of Colombia and consists of an 8.6 km long road tunnel and a parallel rescue tunnel. Construction is scheduled to start during the second half of 2002. Once completed, it will be the longest road tunnel on the American continent.

The Túnel la Línea is part of the road project Ibagué - Armenia, with the purpose to improve the existing road connection between Bogotá, Colombia's capital with a population of around seven million people, and Buenaventura, Colombia's main port on the Pacific coast and gateway for Colombia's rapidly growing trade with the Far East. Because of its importance for the country's economy, the road is mainly used by heavy trucks, many of them with 6 axes and a total weight of 52 tons. The existing road is crossing the mountain range at an elevation of approx. 3200 m above sea level. The Túnel la Línea will be located at an elevation of approx. 2500 m and will reduce the average driving time for trucks by more than 40 minutes.

2 TUNNEL DESIGN CONCEPT

The basic design for the Túnel la Línea comprises one tunnel tube for bi-directional traffic, two ventilation shafts, two ventilation caverns near the bottoms of these shafts as well as a parallel rescue tunnel (min. diameter 4.70 m). The horizontal alignment of the tunnel is slightly curved in an S-shape and has a minimum radius of 3000 m. The vertical alignment shows a constant gradient between the portals of approx. 1 %.

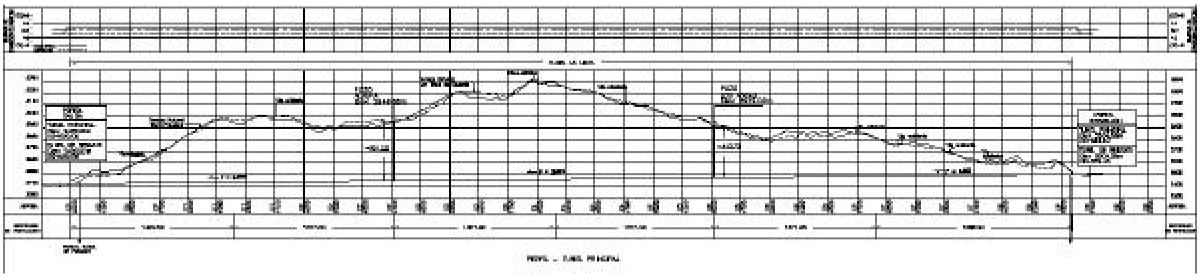

Figure 1: Túnel La Linea - Longitudinal Section

According to the basic design, the main tunnel comprises the following features:

- two traffic lanes with a width of 4.00 m each, and with a clear height of 4.70 m
- safety walkways (width 0.85 m) at either tunnel side wall
- a fully-transversal ventilation system with both ventilation ducts above the roadway, with fresh air jets every 6 m and exhaust air extraction openings every 96 m
- axial ventilators at both portals and at the ventilation caverns adjacent to the shafts
- emergency exits to a parallel rescue tunnel every 500 m
- niches for emergency stops every 1000 m at both side walls of the tunnel
- two U-turn possibilities at the locations of the ventilation caverns (approx. at the third points of the tunnel length)
- emergency call facilities every 250 m
- a fire-fighting water pressure pipe along the entire length of the tunnel with hydrants every 125 m, supplied by two water storage tanks (one at either portal)
- fire detection sensors along the entire length of the tunnel
- a closed-circuit TV monitoring system
- a radio communication system
- cable ducts underneath both safety walkways
- permanent lighting including an emergency lighting system
- a tunnel control centre at the East Portal (Portal Bermellón)
- a portal building at the West Portal (Portal Galícia)
- a primary (temporary) lining consisting of shotcrete, wire mesh, steel ribs and rock bolts and a secondary (permanent) lining consisting of cast in-situ concrete
- a waterproofing system between the two linings that prevents ground water from entering the tunnel
- two separate drainage systems, one for (clean) ground water and one for (contaminated) road surface liquids

- a storage tank for contaminated liquids from the road drainage (at the West Portal)

Since the Project Túnel la Línea will be awarded as a Design & Build Contract, the detailed design will be carried out by the Contractor. Changes of the basic design with regard to the excavation method, the ventilation system and the safety concept are permitted within the limits defined in the tender documents.

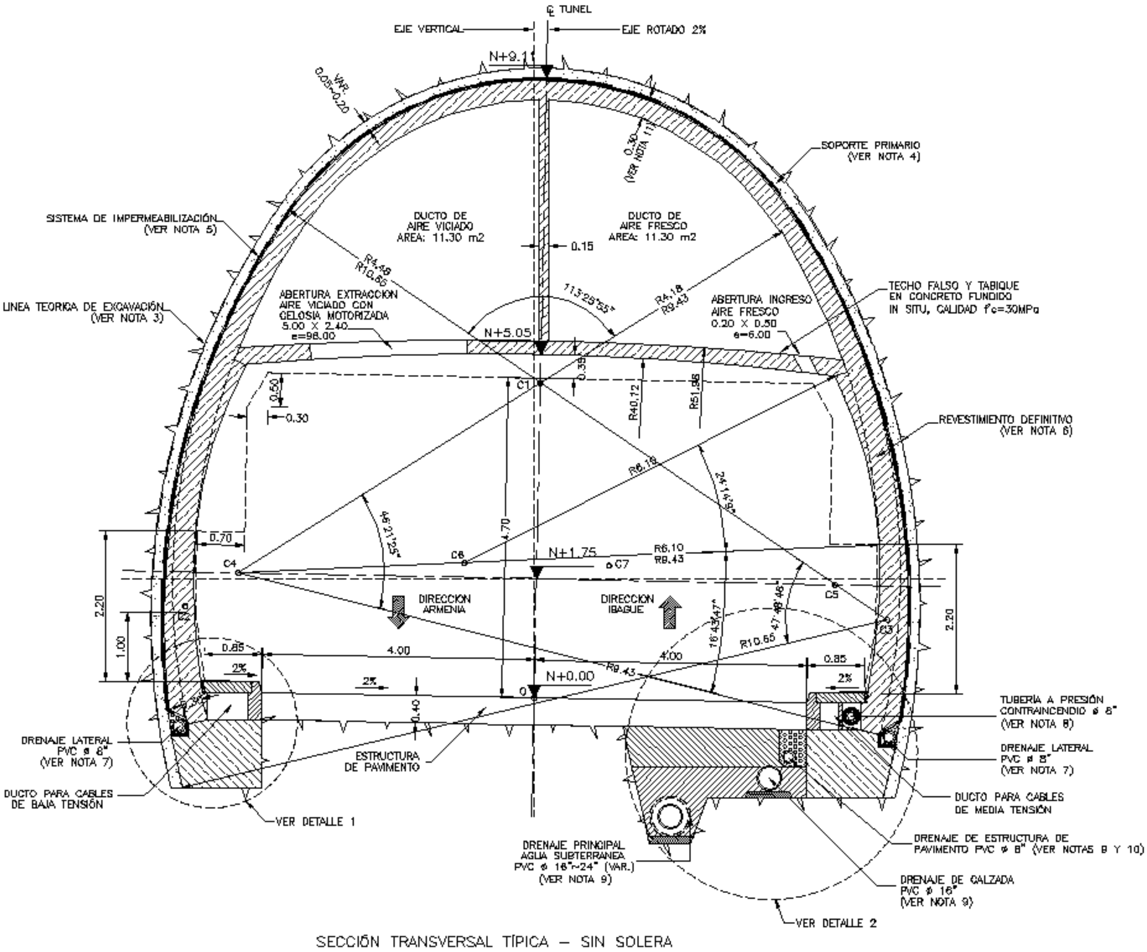

Figure 2: Túnel La Linea - Tunnel Cross Section

3 VENTILATION SYSTEM

3.1 General

At the Túnel la Línea, trucks and buses count for as much as 70 % of the total traffic volume. This traffic mix, together with the high elevation of the tunnel, will result in a considerable fresh air demand for tunnel ventilation.

The Túnel la Línea will require two ventilation shafts with depths between 450 and 500 m. Both shafts will supply fresh air and extract exhaust air from the tunnel tube. These shafts will be located as close as possible to the third points of the tunnel length in order to achieve optimum conditions for the operation of the tunnel ventilation system.

3.2 Traffic Data

According to existing traffic data, the expected traffic volume is 4126 vehicles / day for the year 2007. The corresponding traffic peak per hour, which is crucial for the ventilation design, is equal to

10 % of that value and therefore 412 vehicles / hour. Although traffic volume is expected to increase to more than 7000 vehicles / day in the year 2027, the total emission quantities will be less at that time, due to the improvements in vehicle technology.
Traffic for the year 2007 is expected to consist of 63 % HGVs (Heavy Good Vehicles), 30 % passenger cars and 7 % buses.
Based on existing traffic data, the average weight of the diesel-powered vehicles (M_G) was calculated with $M_G = 21.22$ t.

3.3 Vehicle Emissions

Various gases such as nitrogen (N_2), carbon dioxide (CO_2), steam (H_2O) and to some degree oxygen (O_2) are emitted by a combustion engine. These gases are, on the whole, not poisonous. Additionally, a number of harmful substances is emitted which can be classified in three categories: products of incomplete combustion, products of over-complete combustion and products from additives and impurities. Especially carbon monoxide and soot are dangerous in road tunnels:

- Carbon monoxide can have a poisonous effect on human beings if it is inhaled in higher concentration or for longer periods. CO is primarily emitted by gasoline engines.
- Soot in higher concentrations impairs the visibility and makes it difficult or even impossible to recognise any obstacles on the roadway. The danger of accidents in the tunnels increases. Soot is primarily emitted by diesel engines.

It is therefore necessary to provide fresh air in longer tunnels to lower the concentration of CO as well as to improve the visibility.
The average emissions of the various types of vehicles are very important. From traffic studies carried out by the local authorities in Colombia it could be concluded that the emissions of the majority of vehicles can be compared with the vehicle emissions existing in Austria around 20 years ago. Therefore, the basic value of the CO emission was assumed with 0.7 m^3/h, veh and the basic value of the diesel soot emission with 16 m^2/h, t. These values had been used in Austria prior to the introduction of the catalysator for the gasoline engines and the implementation of (new) strict emission laws for diesel engines.
The NO_x - emissions of a vehicle strongly depend on the performance efficiency of the engines. Only with extremely high performance efficiencies of the vehicle engines, a substantial NO_x - emission has to be expected. In comparison with the quantity of fresh air required for the dilution of soot emission, the quantity of fresh air required for the dilution of the NO_x - emission is always smaller. Even in the new Austrian Guidelines (RVS 9.262), a calculation of the NO_x - emissions is not required.

3.4 Allowable CO-Concentration in Tunnels

Haemoglobin (Hb) is the blood component that transports the vital oxygen through the human body. Only part of the haemoglobin in the blood joins oxygen (O_2Hb), the rest (a small percentage) is unsaturated (Hbu) and does not transport oxygen.
When the air contains CO, the haemoglobin joins the CO to carboxy haemoglobin (COHb) instead of producing O_2Hb, due to the greater affinity between carbon monoxide and haemoglobin. As a result, the amount of haemoglobin transporting oxygen (O_2Hb) is reduced.
The allowable CO-value has been fixed at 150 ppm (parts per million) for tunnels with normal traffic. This value also corresponds to the specifications provided by PIARC [1] (Permanent International Association of Road Congresses). In case of dense, slow-moving traffic the allowable CO-concentration is 250ppm.

3.5 Allowable Turbidity in Tunnels

The soot produced by diesel engines decreases the visibility in a tunnel, making it difficult or impossible to see objects on the roadway in time. The Institute of Combustion Engines and Thermodynamics at the Technical University Graz has carried out research works regarding the effect of soot from diesel engines on visibility. Numerous tests have shown that the allowable extinction coefficient K (indicating the reduction of the intensity of light when passing through a medium containing soot) in fresh air demand calculations should be around 0.007 to 0.008 [1/m]. In some cases the K-value can be slightly higher and was therefore set to K = 0.010 for the Túnel la Línea. Apart from impaired visibility, a certain amount of turbidity (k=0.014) should not be exceeded for health reasons. A tunnel should be closed if this value is reached until visibility improves.

3.6 Fresh Air Calculation

The fresh air demand (m^3/s, km, lane) was calculated in accordance with PIARC [1], using the following assumptions:
Basic value of CO emission [m^3/h, veh.]............................ $q^{\circ}_{CO} = 0.7\ m^3/h$ PCU
Max. permissible CO concentration [ppm CO .... CO_{lim}= 150 ppm
Basic value of diesel soot emission [m^2/h,t......................... $q^{\circ}_{T} = 16\ m^2/h$, t
Mean vehicle weight [t... m = 21 t / truck
Admissible diesel soot concentration................................ K_{lim} = 0.010 (1/m)
Fresh air demand has been calculated per kilometre of tunnel and for each lane separately. The calculations were performed using the computer program LUME 6c.

A minimum driving speed of 30 km/h was assumed for the downhill lane and of 0 km/h for the uphill lane. The maximum driving speed was determined according to following equation:

$$V_{max} = \frac{80 - 5s}{1 + 0.25s}$$ [2] s (%) inclination

<u>Normal Tunnel Operation</u>
With the high percentage of HGVs and buses for the Túnel la Línea, soot emission becomes the only decisive factor for the fresh air demand. Although at a speed of 0 km/h the dilution of carbon monoxide (both for the uphill and for the downhill lane) requires more fresh air than the dilution of the diesel soot, it has to be considered that vehicle engines have to be turned off once the traffic flow has stopped. Therefore, the fresh air demand for this case is not relevant for the design. Furthermore it is known that CO-emissions will decrease significantly in the near future. The elevation of the tunnel was considered by using the corresponding altitude factor according to PIARC [1]. For an elevation of 2500 m, this factor is more than 3 times the basis value applicable at sea level.
For the calculation of the fresh air demand for the uphill lane, where sluggish traffic flow and traffic stops cannot be excluded, the air demand for a driving speed range between v = 0 and v = 60 km/h (approx.) has to be considered (HGVs cannot reach a higher speed in average). The fresh air volume required for the uphill lane was calculated to be $V_B = 100.6\ m^3/(s*km)$. The traffic in the downhill lane will flow unhindered. Sluggish traffic flow ($v \leq 30$ km/h) and traffic stops can be excluded. Consequently, only the driving speed range above 30 km/h has to be considered. The fresh air volume required for the downhill lane was calculated with $V_T = 67.4\ m^3/(s*km)$. This results in a total fresh air demand V for the Túnel la Línea of: $V = V_B + V_T = 100.6 + 67.4 = 168.0\ m^3/(s*km) \sim 170 m^3/(s*km)$

Fire in the Tunnel

In case of a fire in a tunnel with a transversal ventilation system, the operation mode of the ventilation is changed from normal to fire mode. In the fire mode, no fresh air will be blown into the tunnel at the respective ventilation section; smoke gases will be extracted. The crucial factor is the smoke gas volume that can be extracted per second. According to Austrian Standards, it must be possible to extract 120 m^3/s of exhaust air at the end of each ventilation section in case of a fire.

A rough calculation showed that the ventilation system for the Túnel La Línea can fulfil this requirement.

3.7 Dimensions and Power Consumption

The Túnel la Línea will have six ventilation sections. Two of them will be ventilated from the two portals, the other four sections from the two shafts. The lengths of the ventilation sections are between 1400 m and 1700 m. With regard to a minimisation of the excavation cross section of the tunnel, the air flow velocities for fresh air and for exhaust air have been limited to 25.5 m/s, resulting in a cross section for the ventilation ducts of 11.3 m^2. While the maximum longitudinal air flow velocity inside the fresh and exhaust air ducts reaches these high values only in the vicinity of the ventilators, this is not the case for the shafts. There, the longitudinal air flow velocity remains constant for the entire shaft length and was therefore limited to approx. 18 m/s, resulting in an inner shaft diameter of 8.5 m.

The detailed design for the ventilator stations at the portals and at the caverns is not available at this stage. However, a preliminary estimate shows a required total power for the axial ventilators of approx. 5500 kW. A first estimation of the inner diameter of the axial ventilators for the portal stations and for the sections ventilated from the shafts results in a fan diameter D_i = 3350 mm.

3.8 Operation of theVentilation in Case of Fire

At the moment when a fire occurs in a tunnel with a transversal ventilation system, it can be assumed that the ventilation system is operating with full power and that the fresh air ventilators and the exhaust air ventilators are working at the same performance level. As a consequence, the longitudinal air flow would be insignificant. The smoke gases would rise almost vertically towards the tunnel ceiling. The ceiling has to be equipped with a fire detection system that can detect and localise the fire very quickly (within 10 to 20 seconds). Immediately after the fire has been detected, a fire ventilation program must start automatically. This program (fire program for the ventilation system, informing fire brigade and ambulance, closing of the tunnel for the traffic, etc.) will be developed during the detailed design.

In case of a fire in a tunnel, it is essential to switch off the fresh air supply immediately in that ventilation section and to switch the exhaust air extraction to full power at the same time. Every 96 m large openings (size approx. 12 m^2) with regulators will be installed at the exhaust air ventilation duct. During normal operation, the regulators are adjusted in a way that the same quantity of exhaust air will be extracted through each of the openings. Immediately after detection of a fire, the exhaust air extraction opening next to the fire in direction of the smoke flow will be fully opened by the regulators. All other exhaust air extraction openings of that ventilation section will be closed by the regulators. This will avoid a longitudinal airflow and achieve a concentrated extraction of the smoke in the immediate fire area. As a result, the smoke cannot spread to the rest of the ventilation section, thus enabling tunnel users to escape without difficulties into the rescue tunnel. Together with the start of the fire program, the jet fans (approx. 8 units), which will be installed inside the rescue tunnel, have to produce an overpressure relative to the main tunnel. This way, smoke cannot enter the rescue tunnel while people are escaping into the rescue tunnel. Instead, there will be a slight airflow from the rescue tunnel into the main tunnel, so that even with open connection doors, smoke will be kept from entering the rescue tunnel.

4 GENERAL TUNNEL SAFETY CONCEPT

A safety concept for a tunnel shall guarantee the safe evacuation of passengers in case of a major accident, e.g. when a large-scale fire occurs in the tunnel. It requires therefore a reliable monitoring system, a safe escape route for passengers, an access road for rescue vehicles, and an efficient and flexible ventilation system.

Safety concepts with safety niches at the tunnel walls where passengers could seek protection from the gases and the heat resulting from large-scale tunnel fires have not proven to be reliable enough. Escape tunnels (transversal to the main tunnel) leading from the main tunnel to the outside are not suitable for the Túnel La Línea due to the topographical conditions of the project area.

The technically best solution for a road tunnel safety concept is of course two separate tunnel tubes with unidirectional traffic in either tunnel tube. This reduces the risk of accidents in the first place and, by constructing cross passages at a regular spacing, provides excellent escape routes for passengers and access routes for emergency vehicles. A longitudinal ventilation system would be sufficient in that case because of the unidirectional traffic. For long tunnels, a concept with two tunnel tubes can usually not be constructed for cost reasons.

Almost all the advantages of the second tunnel tube with regard to safety in case of a tunnel fire can also be achieved with the construction of a much smaller rescue tunnel parallel to the main tunnel. Besides its important temporary function as a pilot tunnel during construction (geological investigation, pre-drainage), such a rescue tunnel will serve as a permanent escape facility for passengers and as an access for rescue vehicles. The rescue tunnel will be equipped with an emergency ventilation and lighting system and will be located at a horizontal distance of 40 - 60 m from the main tunnel, so that it could be enlarged to a second tunnel tube at a later stage, if required.

5 CONCLUSION

The safety concept proposed for the Túnel la Línea comprises a fully-transversal ventilation system, fire detection sensors and a fire-fighting water pressure pipe along the entire length of the tunnel with hydrants every 125 m, emergency call niches every 250 m, a closed-circuit TV monitoring system, and a parallel rescue tunnel with cross passages (emergency exits) at a maximum spacing of 500 m. For a tunnel with bi-directional traffic, this safety concept provides the highest possible level of safety for the tunnel users also in case of a major tunnel fire.

6 REFERENCES

[1] PIARC Committee on Road Tunnels, Brussels 1987

[2] Third International Symposium on the Aerodynamic and Ventilation of Vehicle Tunnels (Sheffield, England, March 1979, page 249)

LONGITUDINAL AIR VELOCITY CONTROL IN A ROAD TUNNEL DURING A FIRE EVENT

R. Borchiellini, V. Ferro, V. Giaretto
Energy Department – Politecnico di Torino – Italy

ABSTRACT

Ventilation equipment is used during a fire event in a tunnel with bi-directional traffic and a transverse ventilation system to obtain two main aims: a) an air velocity lower than 1.5 m/s to make the smoke extraction near the fire position easier using open fire extraction dumpers; b) to limit diffusion of the combustion products along the tunnel to allow the fire brigades to operate.

To obtain these aims, a great number of choices can be made by the ventilation manager (i.e. the position and the amount of fresh air that is supplied, the number and the operating point of the extraction fans and the number of open dumpers in the fire zone). Furthermore, the impact of these choices on the air velocity and on smoke diffusion along the tunnel is influenced by the boundary conditions of the system: the outside temperature and pressure, including wind effects.

The complex ventilation network (main tube and ventilation ducts) of the Frejus tunnel is modelled in this paper using the graph theory. The possibilities of achieving the main aims has been investigated, studying a large number of situations. Each situation has been defined taking into account the following parameters: the outside weather conditions, fire position, operating extraction fans, wind effects at the tunnel portals and the amount and position of the supplied fresh air.

The obtained results show the air velocity and temperature distribution along the tunnel. The knowledge of the air velocity distribution allows one to verify whether the requirements concerning combustion product diffusion have been satisfied.

Finally, the large number of obtained results has been analysed to outline general rules for the management of ventilation when a fire accident occurs.

Key words: fire event, transverse ventilation, bi-directional traffic, graph theory, thermo-fluid-dynamics analysis

1. INTRODUCTION

The management of a fire event with special emphasis on the role of the ventilation system, is a very important topic can be seen by the large number of papers that have been published and by the large number of experimental tests that have been carried out (PIARC, 1999, Lacroix et al., 1994, EUREKA, 1995).

A particular case concerning this topic is the case of the transverse ventilation system without jet fans in a bi-directional tunnel; this is the case of the here studied Frejus tunnel.

During a fire event, the action of the ventilation system is aimed at obtaining some main goals, that is to avoid backlayering, to obtain a longitudinal air velocity of less than 1.5 m/s in order to allow smoke stratification and to keep the smoke in the zone of the open fire dumpers.

A large set of experimental tests and analytical studies have been developed to outline the best operative procedures that should be followed by the operator of the ventilation system in the case of fire; the work here illustrated belongs to this set of activities.

This work is part of wider investigation that has been promoted conjunctly by SITAF and SFTRF (the companies which operate the Frejus tunnel); the plan of the activity after this investigation, which has been developed in steady-state conditions, includes simulation in transient conditions. The steady state hypothesis has been chosen in order to have the opportunity of performing a huge number of simulations; this is the case when the settings of the ventilation system have to be found to obtain the complete removal of the smoke and to allow fresh air out to go of the portals, which means that a nil velocity point exists inside the tunnel.

Although one-dimensional steady-state hypotheses are used, the system is too complex for manual calculation, therefore a computer must be used to solve the equations; an easy way to describe the system to the computer is to represent this as a network. A partial sketch of the network that was used is shown in Figure 1; the part here shown corresponds to a segment about 400 m long. The complete network is more than thirty times the network shown in Figure 1.

The study of the behaviour of the thermo-fluid-dynamic system is here modelled using the graph theory in which the system is represented by edges connected to nodes. The obtained numerical results define the flow, pressure and the temperature distribution along the tunnel and the ventilation ducts. The model is fully described in Ferro et al. (1991) e Ferro et al. (1992).

The graph-theory is very useful to give a mathematical representation of the system but in order to completely describe the system behaviour it is necessary to describe the physical phenomena that take place inside each edge of the network. The here considered system is not isothermal therefore the energy and the momentum equations should be used together. For this coupled problem, the model approach is that of considering the two equations one at a time, linked by the air state equation.

The network model (main tube, ventilation ducts and shafts) has been applied to solve a large variety of different situations that can occur during fire events; the implemented network takes into account all the fire dumpers and ventilation ducts and models the fresh air outlets (5 m step) as a continuous fissure along the main tube.

The network set-up has been executed using the results of the experimental measurement campaign developed for the Frejus tunnel in order to verify the efficiency of each exhaust station (SETEC, 2000). From these data it has been possible to calibrate the network, assigning at each ventilation station, the single resistance loss coefficient values that allow to obtain the maximum likelihood between the calculated and measured air flow rate. The resulting relative shift ranges between ±5%.

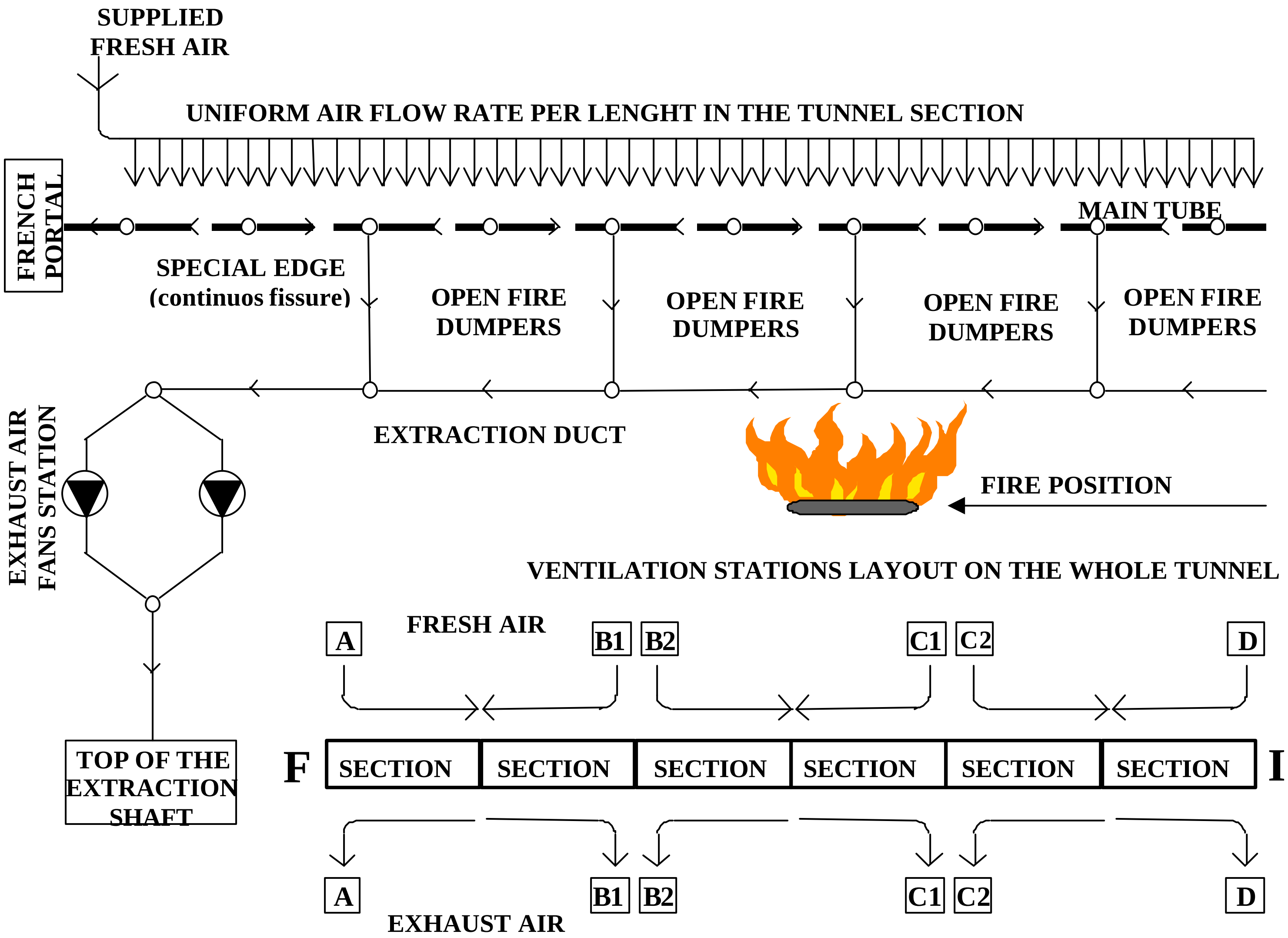

Figure 1 Sketch of network used to model the ventilation system and the main tube.

2. THE STUDIED CASES

As is well known, the Frejus tunnel presents the following main characteristics:
- main tube length 12868 m;
- main tunnel cross-section area 46.5 m^2;
- main tunnel cross-section perimeter 28.8 m;
- difference in level between the Italian (1297 m a.s.l.) and French (1228 m a.s.l.) portals;
- transversal ventilation (2570 fresh air outlets);
- six ventilation stations (two at the portals and two double stations underground, located approximately at 4300 m from the ends, connected to two ventilation shafts) connected to six tunnel section;
- number of fire dumpers (1 m^2 each) 98.

The parameters taken into account for designing the set of cases are the following:
- outside weather conditions (air temperature, barometric pressure, wind effects on tunnel portals);
- fire position along the tunnel;
- operating extraction fans;
- amount and position of the supplied fresh air.

The outside weather conditions were chosen taking available historical data collected over different periods of the year into considerations. Three sets of outside weather conditions, corresponding to, the summer, the winter and the others seasons here indicated as middle season were considered in paticular. The adopted outside weather conditions at the portals and at the top of the ventilation shafts are reported in Table 1

The wind effect was only considered at the tunnel portals one at a time, assigning an overpressure that ranged between 50 and 100 Pa.

Outside point	Summer		Middle season		Winter	
	Barometric press. (Pa)	Temperature (°C)	Barometric press. (Pa)	Temperature (°C)	Barometric press. (Pa)	Temperature (°C)
French portal	88572.00	16.3	87422.00	4.8	86272.00	-5.5
Shaft B	80496.00	11.4	79346.00	-0.1	78196.00	-10.4
Shaft A	88572	16.3	87010.41	4.6	86065.27	-5.6
Italian portal	87867.00	19.3	86717.00	8.0	85567.00	-1.2
Shaft C	83134.00	16.3	81984.00	5.0	80834.00	-4.2
Shaft D	87816.11	19.3	86340.4	7.8	85567	-1.2

Table 1 Outside weather conditions

Eighteen different fire positions were considered along the tunnel, that is, three positions for each tunnel section. The fire event was taken into account by setting the temperature distribution of the combustion products around the place of the fire (Eureka, 1995), as shown in Figure 2.

The number of open dumpers in the fire zone, the choice of the operating extraction fans, the amount and the position of the supplied fresh air, represent the only operating way of controlling the smoke motion in the main tube. A great number of different situations were analysed to find a link between the operating criteria of the ventilation system and the smoke diffusion along the tunnel. The set of cases includes about six hundred instances which could occur so as to develop a parametric study of the tunnel behaviour while varying the previous mentioned variables (outside weather conditions, wind effects, amount and position of the supplied fresh air, etc.). A few of the more representative studied cases are illustrated in the next paragraph.

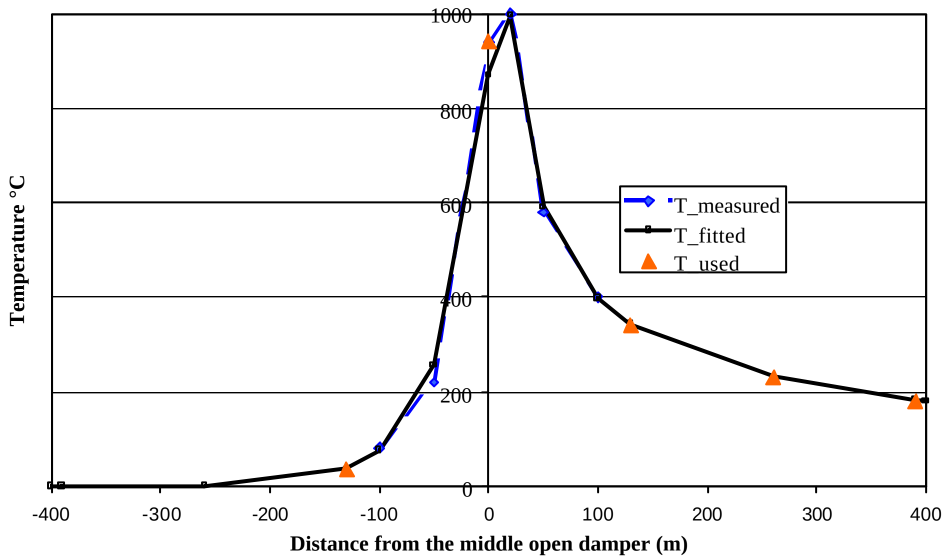

Figure 2 Temperature profile used for fire simulation

3. ANALYSIS RESULTS

The performed analysis can be split into two main parts. In the first one the fresh air is only introduced into the tunnel section where the fire event occurs; the smoke motion was calculated, when seven fire dumpers were open near the place of the fire for each outside weather condition, with or without wind effects, and varying the fire position along the tunnel. Independently of the external conditions and fire position, the tunnel behaviour was observed, in this part of the analysis, when the following common actions had been accomplished in the tunnel section where the fire occurred: extraction of the smoke using the maximum power of the station and supplying fresh air at 20% of the maximum power of the station (about 51 m^3/s for any ventilation station). In the second part, the amounts and the positions of the introduced fresh air, necessary for reaching the main aims, were carefully investigated to try to find some general rules for the ventilation management.

Some typical situations are here illustrated as an example of the first part of the analysis. Referring to the climatic period identified as the middle season, when the fire accident occurs at the beginning of the tunnel ventilation section denominated S4 (see Figure 1), the air velocity along the main tube is shown in Figure 3-a for the case without any wind effect at the portals. Figure 3-b and Figure 3-c shown the results when a wind pressure of 50 Pa is applied to the French or Italian portals, respectively. Figure 3-a shows that the main purposes are verified, in order to control the smoke diffusion and limit the air velocity in the fire zone up to 1.5 m/s. On the contrary, when the wind acts at the French portal (Figure 3-b), smoke diffusion is avoided, but the air velocity in the fire zone is greater than the assigned limit. When the wind acts at the Italian portal (Figure 3-c), neither of the main aims are achieved. The temperature profile for the three cases is illustrated in Figure 4.

An examination of all the studied situations in the first analysis, allows one to make the following remarks. All the considered variables are able to influence the smoke diffusion in the tunnel, in particular the outside weather conditions and the wind effect at the portals. More precisely, greater impact is due to the stack effect along the tube, which depends on the external and internal temperature and pressure conditions. The results of this part of the analysis are concisely summarised in Figure 5. The cases, when the smoke diffusion and smoke velocity in the fire zone are controlled, are outlined through their relative frequencies for each external examined condition, as a function of the differences in the effective pressure between the portals (stack effect).

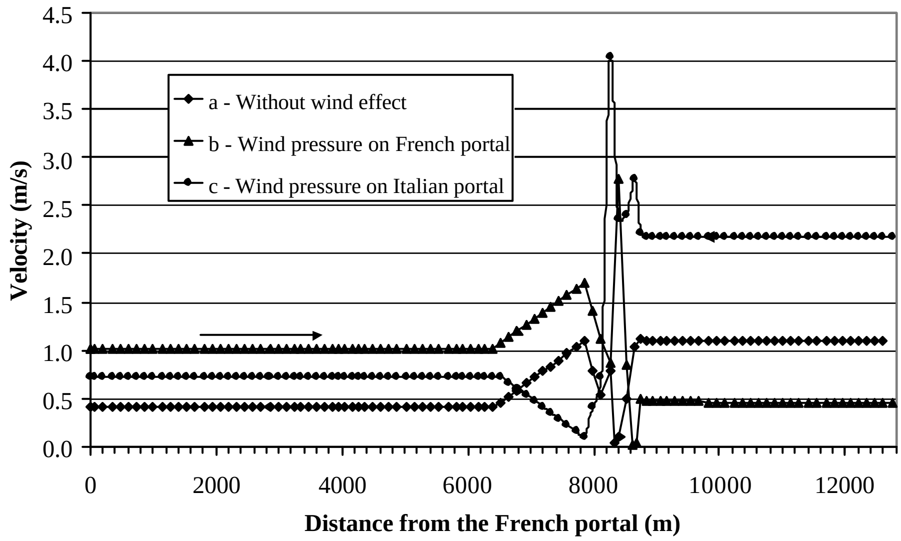

Figure 3 Velocity profile for the example cases

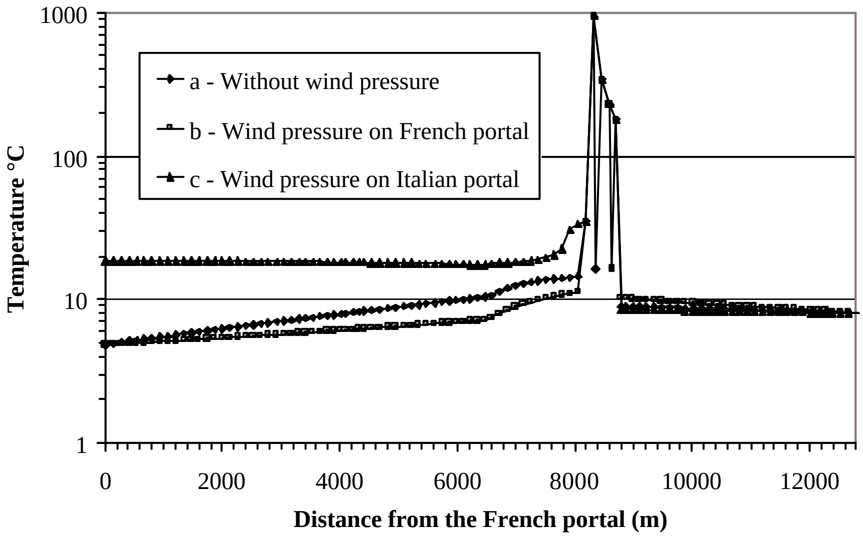

Figure 4 Temperature profile for the example cases

As can clearly be seen in Figure 5, when the stack effect ranges between a few tens of pascal from France to Italy it is possible, in some cases, to control the smoke diffusion and smoke velocity in the fire zone. On the contrary, when the stack effect is greater than a few tens of pascal or the effective pressure differences between the portals are negative (wind pressure on the Italian portal), it is practically impossible to control the smoke diffusion along the tunnel with the assigned ventilation criteria. A similar behaviour was also obtained, for the same external conditions and fire positions in the tunnel, when the fresh air is supplied to all the tunnel sections at the same flow rate for each station.

The obtained results for the middle season are summarised in Figures 6, 7 and 8. Each figure shows a histogram split into six parts, each of which refers to the relative tunnel section. Each of these parts represents the studied situation in which the fire accident occurs exactly in that tunnel section. Each of these reports three bars. The middle one (negative values) represents the flow rate extracted by the seven open fire dumpers in the fire zone. The right and left bars represent the entire supplied fresh air flow rate, with respect to the fire position, in the right and left sides of the tunnel, respectively.

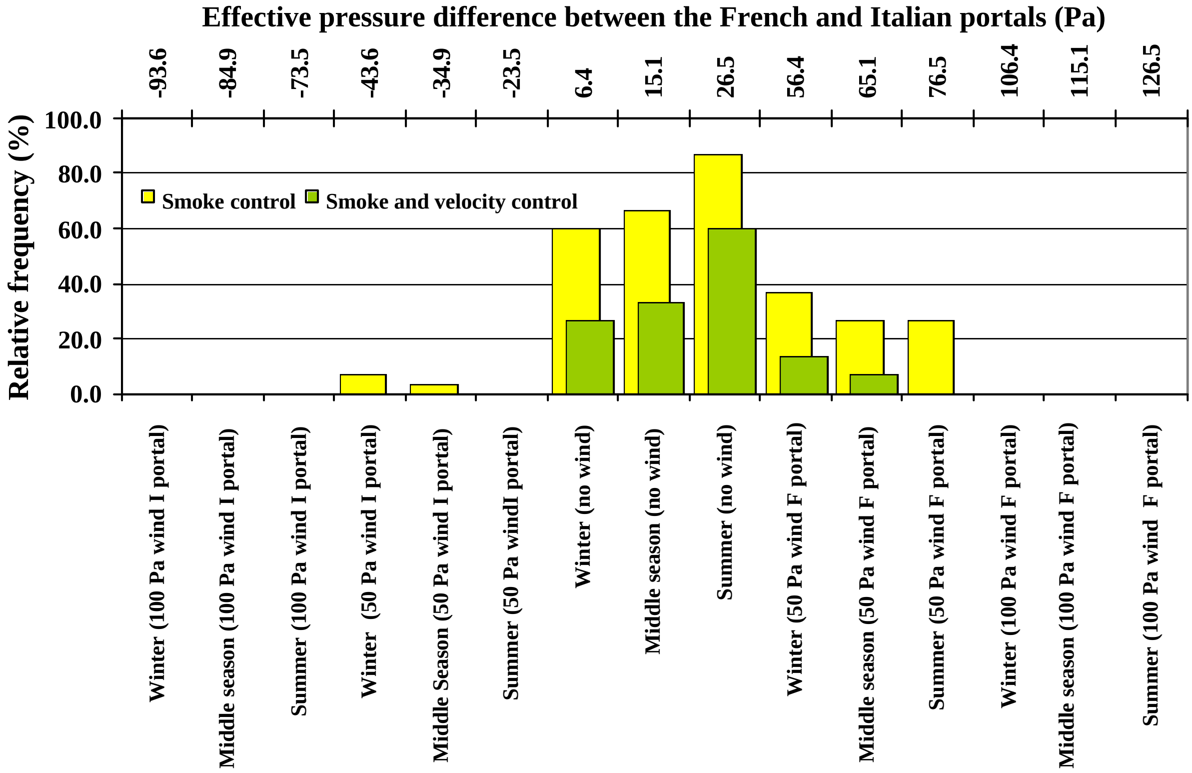

Figure 5 – Summary of the results of the first part of the analysis

More precisely, the right side of the tunnel represents the part that extends from the place of the fire to the Italian portal, while the left one is the part of the tunnel that extends from the place of the fire to the French portal.

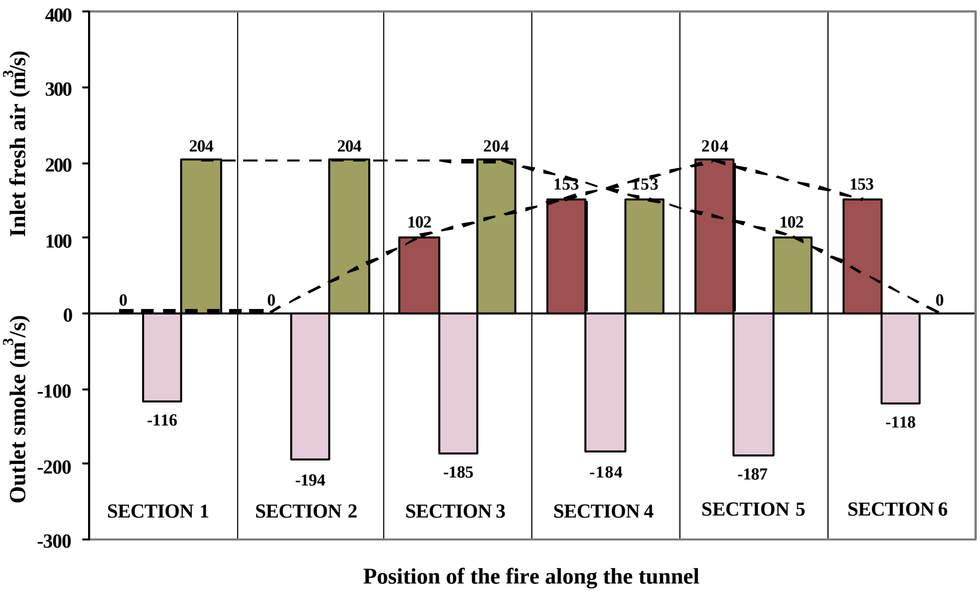

Figure 6 - Extracted smoke and supplied fresh air. Case without wind pressure

Figure 6, which refers to external conditions without wind pressure at the portals, shows a quasi anti-symmetrical trend of the fresh air amount supplied to the right and left of the fire. This quasi anti-symmetrical trend is due to the stack effect along the main tube which acts in the France to Italy direction. When the fire is located near the French portal, fresh air is supplied to right part of the tunnel, on the contrary, when the fire is located near to the Italian portal, fresh air is supplied to the left part. When the fire is positioned in the central part of the tunnel, a perfect symmetrical amount of fresh air is supplied to the right and the left sides. In the cases in which the wind acts at the French portal, with respect to the previous situation, the required amount of fresh air at the right side of the tunnel increases, and decreases at the left side only when the fire is located near the Italian portal. Figure 7 shows this situation for wind pressure of 50 Pa at the French portal. These highlight how necessary is to counteract the effects of the wind by suitably varying the amount of supplied fresh air in order to achieve the main aims.

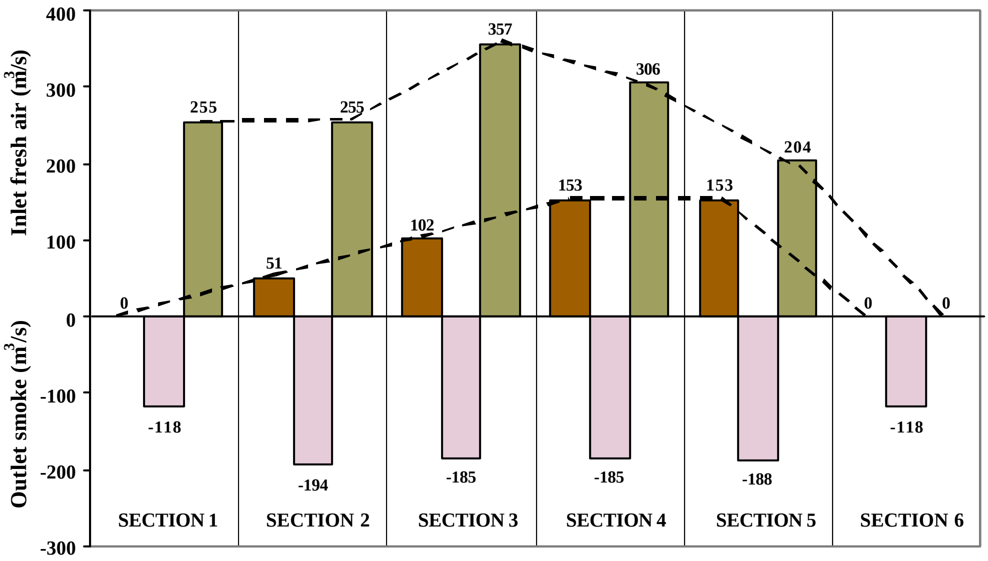

Figure 7 - Extracted smoke and supplied fresh air. Wind pressure on French portal (50 Pa)

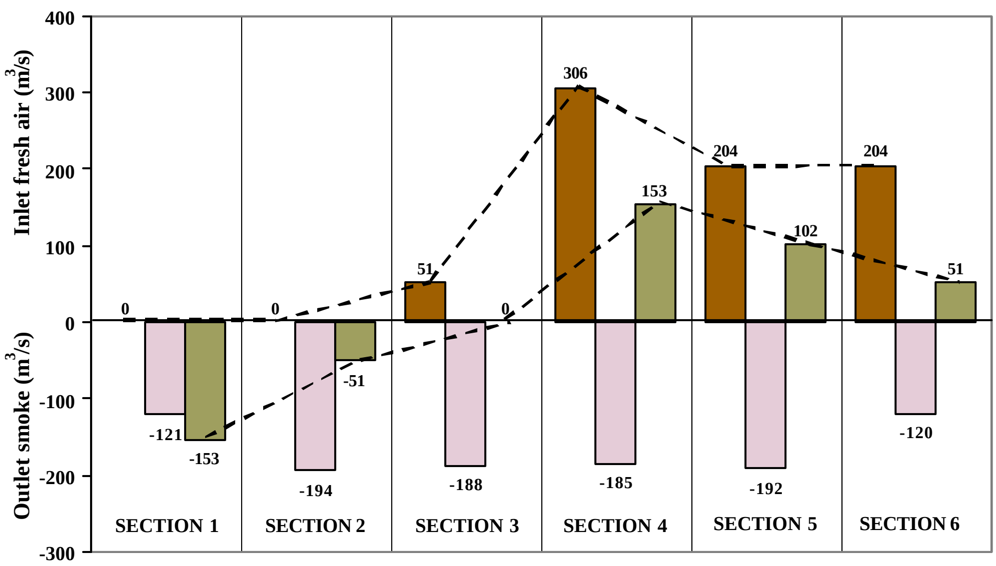

Figure 8- Extracted smoke and supplied fresh air. Wind pressure on Italian portal (50 Pa)

In the cases where the wind acts at the Italian portal, in order to stop the wind action, when the fire is positioned near the French portal it is in fact also necessary to extract air near the Italian portal as can be seen in Figure 8 from the negative values of the fresh air amount on the right side of the tunnel (right bars). In this situation, when the fire accident occurs near the Italian portal, the amount of fresh air supplied to the left side increases significantly with respect to the previous cases.

4. CONCLUSION

More than 900 different fire event situations were simulated and analysed. The obtained set of results allows one to know the behaviour of the complex tunnel-ventilation system for a huge number of different situations but which does not constitute an exhaustive set although it includes many possible and/or probable situations.
The variable used here to summarise the results and the system behaviour are the extracted flow rate and the longitudinal air velocity along the tunnel. The used parameters are the fire position, the fresh air flow rate, the barometric pressure, the weather conditions and the wind action at the tunnel portals.
The analysis results allows one to discover that the extracted flow rate is weakly influenced by the previous parameters while a strong influence of these parameters can be obtained by the longitudinal air velocity.
The performed simulations have shown that at least one configuration of the ventilation system always exists that allows one to achieve the goals defined in the introduction of this paper.
The results require to be confirmed by a further planned transient analysis in order to use them to define new rules for the operation of the ventilation system in the case of fire.

5. ACKNOWLEDGEMENT

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A NEW SYSTEM TO REDUCE THE VELOCITY OF THE AIR FLOW IN THE CASE OF FIRE

Dietmar Öttl[1], Peter Sturm[1], Raimund Almbauer[1], Wolfgang Öttl[2], Alfred Thurner[2], Günter Seitlinger[2]
[1]Institute for Internal Combustion Engines and Thermodynamics, Graz University of Technology, Austria
[2]Enfortech, Mariapfarr, Austria

ABSTRACT
The highest threat for people involved in a tunnel fire is the propagating toxic smoke from the burning vehicles. Hence, it is imperative to slow down the velocity inside the tunnel as fast as possible in case of fire to enable people to flee from the smoke. For that purpose, a new system has been tested in the 5400 m long Katschberg tunnel (Austria), which consists of a new developed synthetic material in form of curtains. Such were mounted on both sides of the tunnel wall, and each closed half over the tunnel cross-section. All in all six curtains were installed subsequently at 75 m distances in between in the middle of the Katschberg tunnel. The shape of the curtains is such, that people can easily run through them, and even that larger vehicles (e.g. fire brigade) can pass through. The new material is heat resistant up to approximately 750°C, which is significantly more than comparable equipment to slow down the velocity inside a tunnel (i.e. jet fans). The experiments revealed that the new system is able to slow down the velocity very effectively. For instance, a flow of 5.0 m/s could be decreased to 1.1 m/s with six curtains being closed. In combination with an existing semi-transverse or full-transverse ventilation system, where the smoke can be sucked off locally, another advantage is yielded. Downstream of the opening, where the smoke is sucked off, the flow can be turned around after closing the curtains at the upstream side. In other words, the smoke, which has already covered a certain tunnel section during the first phase of a fire incident, i.e. before the fire detection, is also turned around and sucked off within a few minutes dependent on the initial velocity inside the tunnel and the time it takes for fire detection.

Key words: curtain, tunnel fire, smoke, Katschberg tunnel

1. INTRODUCTION

Whenever it comes to an accident in a tunnel with fire breaking out, the most danger for people inside the tunnel results from the smoke production. Not only its toxicity but also the strongly reduced visibility minimizes the possibility to escape. Further, smoke complicates the fire fighting or even makes it impossible. Hence, systems which help to maintain the air inside a tunnel as clear as possible in case of fire are highly desirable.

As a consequence of the tunnel accidences in the Mont-Blanc tunnel and the Tauerntunnel, the national guide line for tunnel ventilation demands for an increased suck off air of 120 m³/s for semi- or full-transverse ventilated tunnels. As became apparent from several fire tests e.g. in Norway during the FIRETUN project, 120 m³/s is enough to extract smoke produced by a fire incident of two busses without dangerous goods (PIARC, 1999). However, the amount of air, which is polluted by the smoke depends also linearly on the flow speed inside the tunnel. The higher the flow speeds inside tunnel, the greater the amount of polluted air by the smoke. For e.g. a flow speed of 3 m/s and a cross-sectional area of e.g. 50 m², 150 m³/s are polluted by the convective and turbulent transport of smoke, even if only a passenger car is burning. One may conclude, that not only for security or fire fighting reasons the velocity has to be kept small in case of a fire, but also to maintain the extraction of smoke by the ventilation system.

2. SYSTEM DESCRIPTION

The systems consists of several curtains made of a newly developed synthetic material based on PTFE (=Polytetrafluorethylen) has been developed, which is heat resistant up to some 750 °C. It should be mentioned, that jet fans mounted on the ceiling are heat resistant up to 450 °C for a maximum of 1 hour. Jet fans would be the alternative system to slow down the velocity inside the tunnel in case of fire.
Nevertheless, the concept is in general to close the curtains at those sites, where there is no fire or smoke. The latter is important for cases, where there is still a stable smoke stratification in the initial phase of the fire incident. This is most probably the case, when flow speeds are below 3 m/s. To avoid the destruction of the stratification by closing the curtains, only those curtains need to be closed, which are in a smoke free zone.
From that point of view and having in mind, that it does not mind, where the curtains are being installed in order to reduce the velocity, curtains should be installed mainly at the entrances sections of a tunnel. One may then distinguish between two different fire scenarios:

- A fire in somewhere in the middle of a tunnel, at least a 150 m away from the curtains at the upwind side.
- A fire close to or in between the curtains at the upwind side.

In case one, the following simple procedure may be performed (figure 1): On bases of the measured initial flow direction inside the tunnel, the curtains at the upwind side are being closed after the fire detection. Parallel, if a tunnel is equipped with a semi-transverse or full-transverse ventilation system, the air in the vicinity of the fire can be sucked off locally. Since the velocity inside the tunnel will reduce rather quickly after closing the curtains, backlayering of smoke will occur. To avoid propagation of the smoke along the ceiling at the upstream side, the air should also be sucked off at the upwind side and not only at the downwind side of the fire. Since the amount of air sucked off, can only be provided from the downwind side (at the upwind side are the closed curtains located), the flow direction in the tunnel will be turned around at the downwind side of the fire. This has the advantage, that the smoke, which has initially diluted the downwind sections of the fire, is more or less slowly being sucked off (dependent on the amount of air being sucked off). The time it needs, that the tunnel is again free of smoke, except in the very vicinity of the fire, may be estimated with a few minutes, largely depending on the initial flow speed and the time it takes to detect the fire.

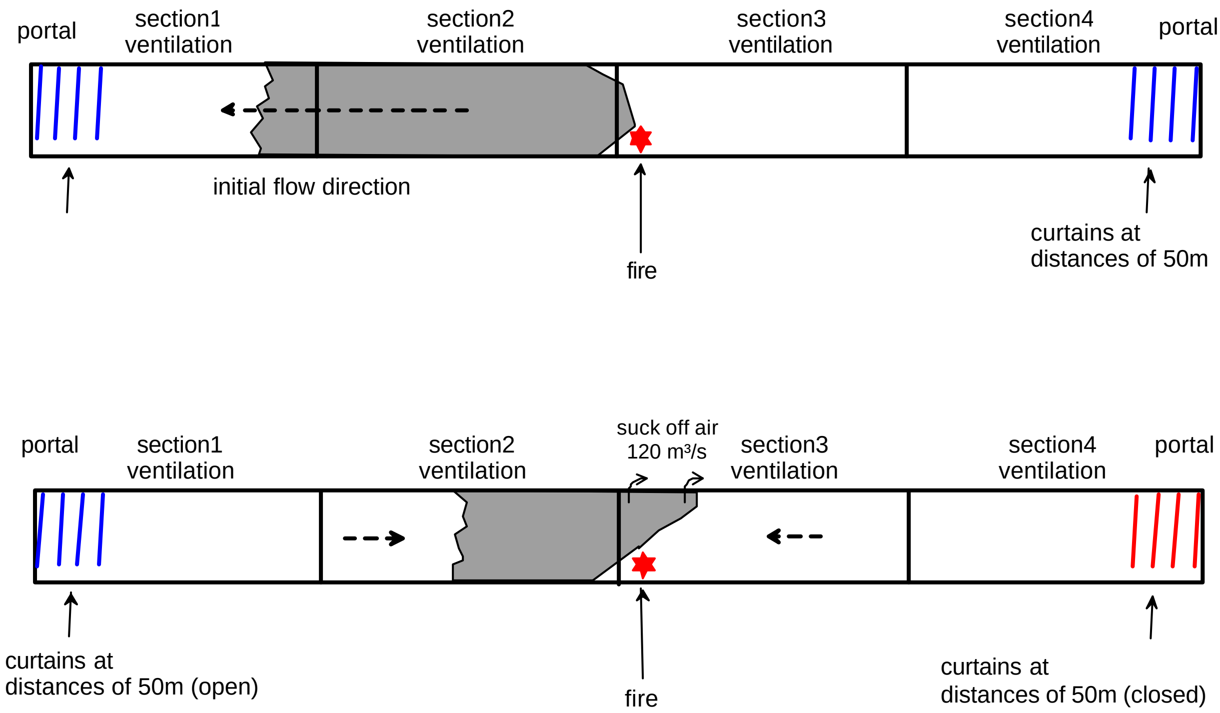

Figure 1. Fire scenario with curtains being installed at the entrance sections of a tunnel, where the fire is at least 150 m away from the curtains at the upwind side (top: smoke propagation before the fire detection; bottom: curtains at the upwind side closed and air is sucked off in the vicinity of the fire).

The second case (figure 2), where the fire is close to or in between the curtains at the upwind side is more difficult to handle, because those curtains need not be closed. As already mentioned the reason is, that for lower flow speeds (<3 m/s) a stratification of the smoke is very likely, which need not be destroyed. If the curtains would be closed, smoke would immediately be mixed down, and people trapped in between the curtains would get in high danger. Hence, only the curtains at the downwind side must be closed in order to reduce the velocity and thus, the smoke propagation. Since the system is primarily thought for longer tunnels, the smoke will not dilute the whole tunnel until the fire is detected. In order to get the tunnel free of smoke, air should be sucked off in the vicinity of the fire as before (for semi- or full-transverse ventilated tunnels). Due to the location of the fire close to the portal and the fact, that at the opposite portal the curtains are being closed, fresh air may only be supplied from the right side (see figure 2). This would result in a stagnation of the smoke at the downwind side, which is not favourable for fire fighting reasons. Hence, it will be necessary to provide fresh air by the ventilation system in case of a full-transverse ventilation system.

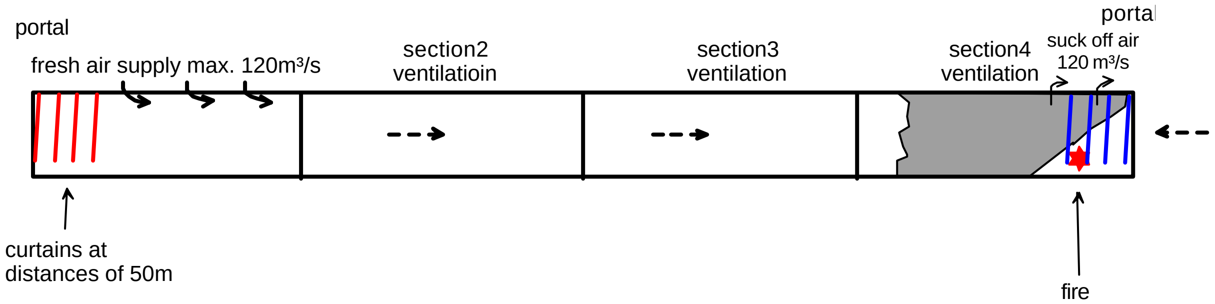

Figure 2. Fire scenario with curtains being installed at the entrance sections of a tunnel, where the fire is close to or in between the curtains at the upwind side (top: smoke propagation before the fire detection; bottom: curtains at the upwind side closed and air is sucked off in the vicinity of the fire).

In case of longitudinal ventilated or natural ventilated tunnel systems, the curtains may solely help to reduce the velocity to enhance the chance for people to escape from the propagating smoke. It is not possible to get the tunnel free of smoke after a certain time. If the latter is necessary for fire fighting purposes, mobile ventilation systems may be required (for natural ventilated tunnels) by the fire brigades to blow out the smoke after having checked, if people are still inside the tunnel.

Keeping an eye on the driving behaviour in case of fire and when such are being closed still reveal some difficulties, which may be encountered. The greatest danger may result from vehicles, which are actually driving in the surroundings of curtains, which are in the closing phase. It may happen, that drivers getting confused and cause additional accidents. Actually, there is no experience with the new system regarding that point of view, but it may regarded as one weak point of the curtains.

3. FIELD MEASUREMENTS

Field measurements have taken place in November 2001 in the Katschberg tunnel in Austria during revision work in the tunnel. The Katschberg tunnel is part of the Tauernautobahn, an important transit route between Germany and Italy. The tunnel is 5400 m long, is equipped with a full-transverse ventilation system, and has a bi-directional traffic flow. The cross-sectional area is about 50 m², and the two ventilation ducts (fresh air supply and suck off air) are on top of the tunnel separated by a ceiling and a middle wall.

It was not possible to install curtains at the entrance sections of the tunnel due to the ongoing construction work, so they had to be installed in the middle of the tunnel. The ventilation system consists of four sections, where each section can be controlled separately. New openings allow for a local suck off air in case of fire at any location in the tunnel. All in all six prototypes of curtains were installed. Three mobile ventilators (4400 N thrust) were placed near the northern portal to generate a well defined initial flow in the tunnel. An overview of the experimental set up is given in figure 3.

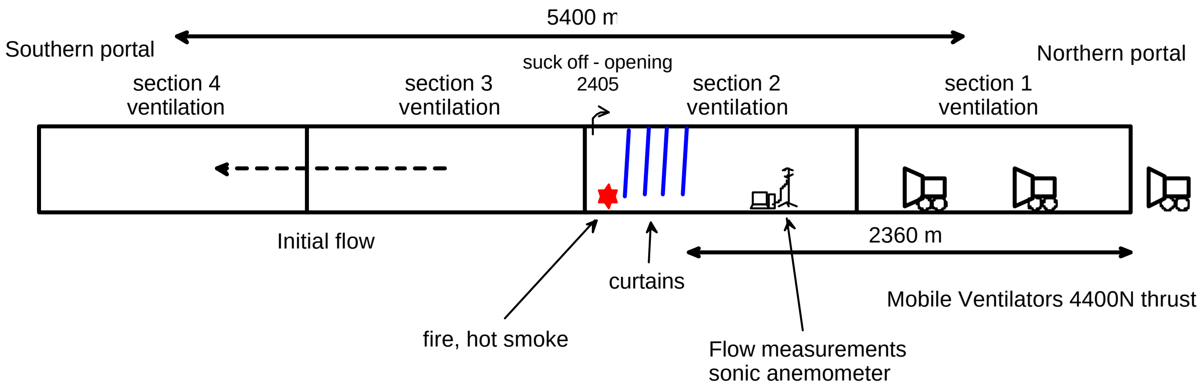

Figure 3. Overview about the experimental set up in the Katschberg tunnel.

The following experiments will be briefly discussed in this section:

- Measurements on how fast the velocity is reduced by closing the curtains.
- Measurements of the drag coefficient.
- Fire tests with and without curtains.

Figure 4 shows the longitudinal flow in the tunnel in dependence on the number of curtains being closed by hand. During that experiment, only the reduction of velocity was of interest and not the time it takes until a certain velocity was reached, because the curtains were all closed by hand, which took several minutes. The velocity could be reduced from 5.0 m/s down to 1.1 m/s.

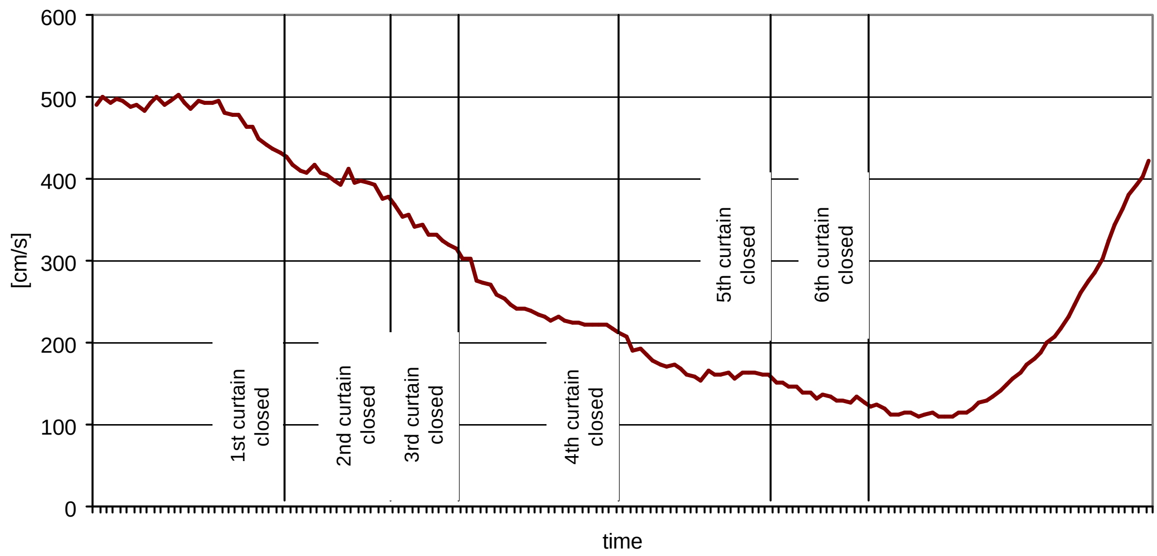

Figure 4. Measured longitudinal velocity in the Katschbergtunnel in dependence on the number of curtains closed by hand (the time dependency was not considered in this experiment, since it took some time to close the curtains).

By means of direct measurements of the force, which acts on the curtain by the flow, a velocity dependent drag coefficient was obtained in using:

$$c_d = \frac{2 \cdot F}{A \cdot r \cdot v^2}, \tag{1}$$

where F is the measured force, A is the cross-sectional area, r is the density of air, and v is the longitudinal velocity. Table 1 lists the measured values, which can be approximated roughly with:

$$c_d(v) = \begin{cases} 45 & v \le 1.3\,m/s \\ 120 \cdot e^{-0.7294v} & v > 1.3\,m/s \end{cases} \tag{2}$$

Table 1. Measured forces, and calculated drag coefficients with eq. (1) in dependence on the longitudinal velocity in the Katschberg tunnel.

Longitudinal velocity [m/s]	Force [N]	c_d-value [-]
1.1	1500	45
1.4	3550	63
2.8	4560	21
3.4	4613	15

As expected, the force increases with increasing velocity, but the drag coefficient decreases. An unusual behavior is noted for lower flow speeds, where the drag coefficient seems to decrease again. A reasonable explanation can not be given for it, but it might at least partly be due to uncertainties in the measurements.

Figure 5 shows the measured and calculated velocities north of the fire, south of the fire, and the amount of air sucked off by the opening 2405 during the first fire test in the Katschbergtunnel, where four curtains were closed after an assumed fire detection time of 90 seconds. 90 m³/s could be sucked off by the opening 2405 a few meters downwind of the fire. The initial longitudinal velocity in the tunnel was 3.0 m/s towards south. After closing 4 curtains and starting to suck off air at the closest opening 2405 downwind of the fire, the flow directions and speeds changed, such that north of the fire a southward flow of about 1.0 m/s developed, and south of the fire a northward flow of about 0.8 m/s developed. The latter causes the smoke, which has initially polluted the tunnel on the downwind side of the fire, to move back to the suck off opening. Within 20 seconds, the initial flow speed of 3.0 m/s was reduced down to 2.0 m/s, which would improve the escape chances of people.

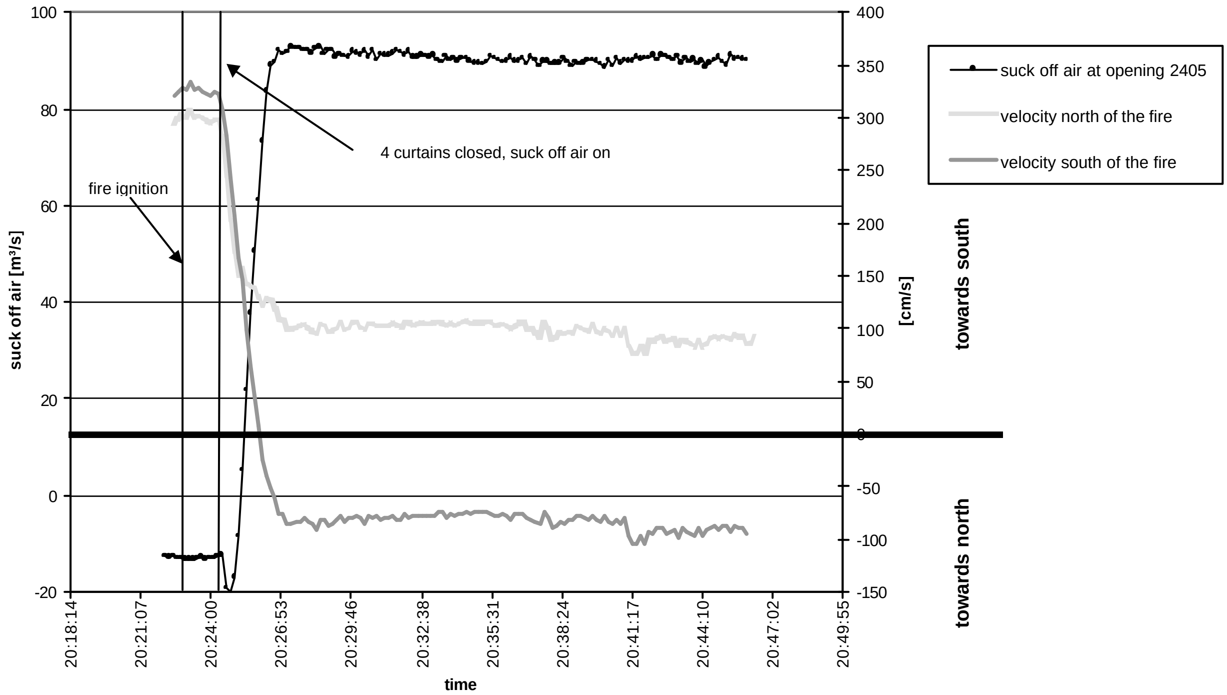

Figure 5. Measured and resulting velocities during a fire test in the Katschbergtunnel with four curtains being closed.

In a second test, the velocity was reduced by supplying fresh air in sections 3 and 4 of the ventilation system. The test revealed, that it takes several minutes until the velocity could be reduced and reversed south of the fire. At a certain distance (a few hundred meters) a region with calm winds developed as a result of the fresh air supply, where the fresh air diverts towards north and towards south. Smoke from the initial stage of the fire – before the fire was detected – is captured in that region and is a potential threat for people as well as a problem for fire fighters (figure 6). It is also difficult, and for higher initial flow speeds impossible, to reach such a steady-state flow as depicted in figure 6. If the fresh air supply is to strong, it may happen, that smoke is forced in the opposite direction towards regions, where people are supposed to be save.

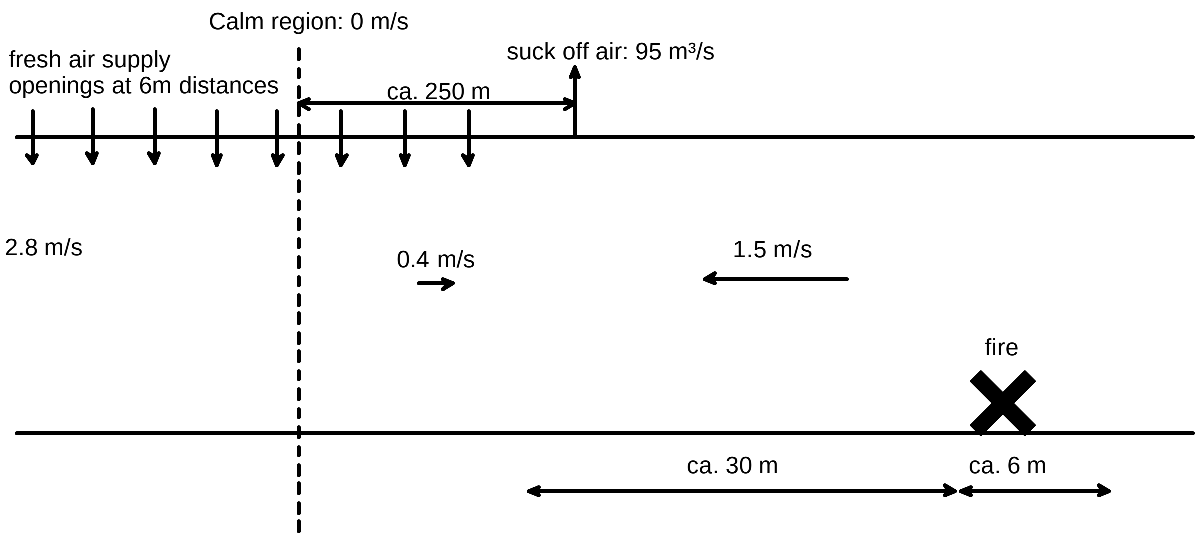

Figure 6. Velocities encountered for an experiment in the Katschbergtunnel, where the velocity was reduced by supplying fresh air in the sections 3 and 4 of the ventilation system.

4. NUMERICAL SIMULATIONS

Figure 7 shows the result of a numerical simulation by means of eq. (2) and the one-dimensional thrust equation for one test, where the velocity was reduced by closing one curtain. A rather good agreement could be obtained between the modelled and the observed velocity.

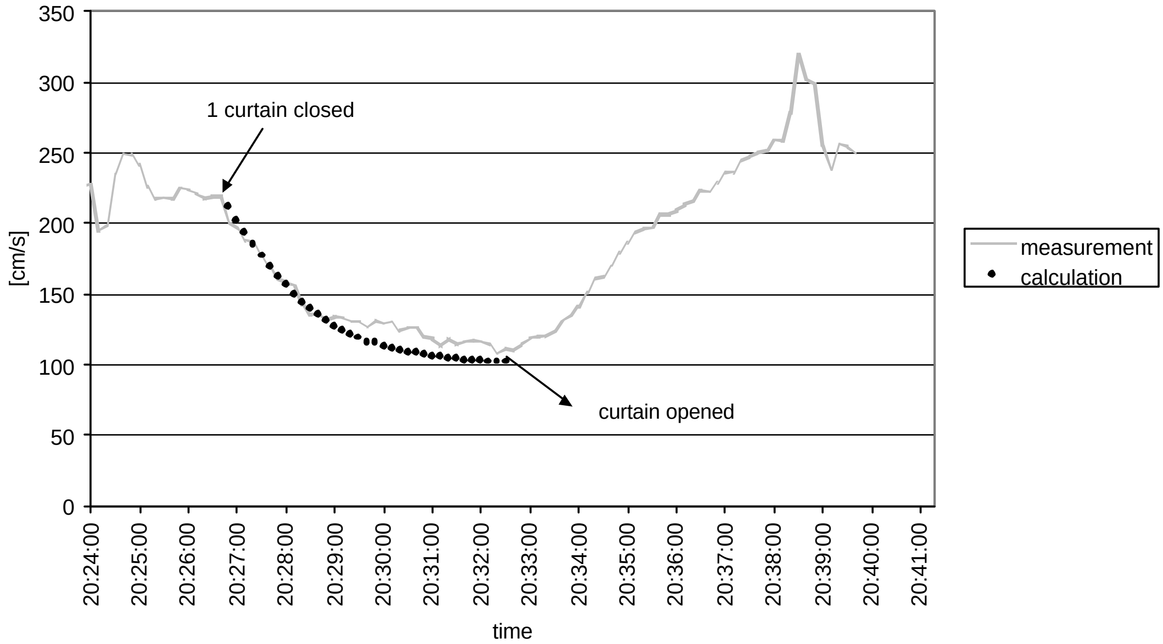

Figure 7. Comparison of modelled and observed velocity when closing one curtain in the Katschbergtunnel.

Further calculations for an initial flow speed in the Katschbergtunnel of 4.0 m/s and the assumption that 10 curtains are being closed, would result in a reduction of the velocity to 1.5 m/s in 30 seconds, and down to 0.7 m/s in around 60 seconds. The mean force introduced by the 10 curtains would be some 30 000 N. One may state jet fans could also be installed instead of curtains. In the case considered, about 40 conventional jet fans would be required to achieve the same total force as by the curtains. The fundamental disadvantages of jet fans are, that they require more space, an excellent regulation system to avoid that the smoke is forced in the other direction, and higher installation costs (power supply, individual cost of one jet fan).

5. CONCLUSIONS

The synthetic curtains tested in the Katschbergtunnel, Austria, proved to reduce the longitudinal velocity in the tunnel very effectively. Compared to jet fans, the curtains do not need a sophisticated regulation system, and are more cost-effective. The increasing risk for an accident due to closing curtains remains unresolved at the present stage, but is the main focus of the current research.

6. ACKNOWLEDGEMENT

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LITERATURE

PIARC, World road association (1999): Fire and smoke control in road tunnels.

THE NECESSITY OF FIRE TESTS USING THE PASSÜR TUNNEL AS AN EXAMPLE

Wolfgang Stroppa
TIWAG - Tiroler Wasserkraft AG
Eduard Wallnöfer Platz 2
A-6010 Innsbruck
Fax no.: +43 / (0)512 / 506-2778
E-mail: wolfgang.stroppa@tiwag.at

Sigmund Pfingstmann
ILF Beratende Ingenieure
ILF Consulting Engineers
Framsweg 16
A-6020 Innsbruck
Fax no.: +43/ (0)512 / 2412 – 200
E-mail: sigmund.pfingstmann@ibk.ilf.com

ABSTRACT

The Austrian design guideline RVS 9.261 "Tunnel Ventilation" requires the performance of fire tests prior to the opening of a new tunnel. These tests shall serve to verify the proper functioning and efficient interaction of the individual equipment components, especially the fire detection and the ventilation system.

Using the 1,855-m-long Passür tunnel as an example, the necessity of such fire tests shall be demonstrated, since malfunctions or defects in the ventilation control system may not always be detected by tests and simulations during start-up.

In a function test performed as part of the fire test, the design requirements for the ventilation control system were checked in accordance with the design guidelines for ventilation operation in case of a fire (fire program) drawn up during software development.

When starting the tunnel's fire program through the existing linear fire detection system, a number of problems inherent in the program sequence emerged.

In this paper, the project shall be presented from the ventilation engineer's perspective, listing the design requirements and comparing them to the fire test evaluation, a process which ultimately led to an adjustment of the ventilation control system.

Key words: Ventilation, ventilation control, fire test, fire response program

1. LOCATION

The Passür tunnel, which is located in the Province of Vorarlberg at an elevation of 1,300 m above sea level, forms part of the B197 federal road over the Arlberg pass, which passes by the Austrian ski resorts of Zürs and Lech. It is a 1,855-m-long road tunnel, which is operated in a two-way traffic or bi-directional mode. 1,152 m of this tunnel were constructed adopting mining methods, while the remaining 703 m were built in cut-and-cover. At a distance of 500 m to the west portal, the tunnel features an emergency exit.

The tunnel gradient ranges between 3 and 8 %. The tunnel ventilation is accomplished by a longitudinal ventilation system with 8 reversible jet fans, which have been arranged in pairs. Each fan has a thrust of 1,170 N and a power consumption of 37 kW.

Fig. 1: Jet fan arrangement in enclosed gallery

2. GENERAL

On 24.10.2000, a fire test was performed, which was to meet the following objectives:

- Verification of proper functioning of ventilation system and fire management program
- Monitoring of smoke and temperature development
- Collection of information regarding site accessibility for rescue teams.

3. TEST ARRANGEMENT

The fire tests were conducted in line with the RVS 9.261, Item 8, using 2 steel trays, each measuring 1 x 1 m. These trays were filled with 20 l of diesel, 5 l of petrol, and 10 l of water.

Fig. 2: Test arrangement

Underneath the fire trays and at the tunnel roof, thermal insulation was provided to protect the electrical installations against damage.

4. TEST PROGRAM

For the tests, two test sites were selected (Fig. 3), one in the area of the emergency exit, the other in the transition zone tunnel – gallery.

Test site no 1: at km 18.9+20.0 (approx. 50 m west of the emergency exit)
The fire alarm was automatically triggered by the sensor cable. Depending on the location of the fire, either the fire response program FRP No. 2 or the fire response program FRP No. 3 was to be activated.

Test site no 2: at km 18.3+60.0 (transition zone tunnel - gallery)
During the second fire test, the automatic ventilation system was deactivated, only using the natural ventilation resulting from the actually prevailing meteorological conditions.

Upon receipt of the alarm, the fire management program (FMP) shall automatically launch the adequate fire response program (FRP).
A change to a different program, subsequently initiated by the alarm of another sensor line, is not intended.

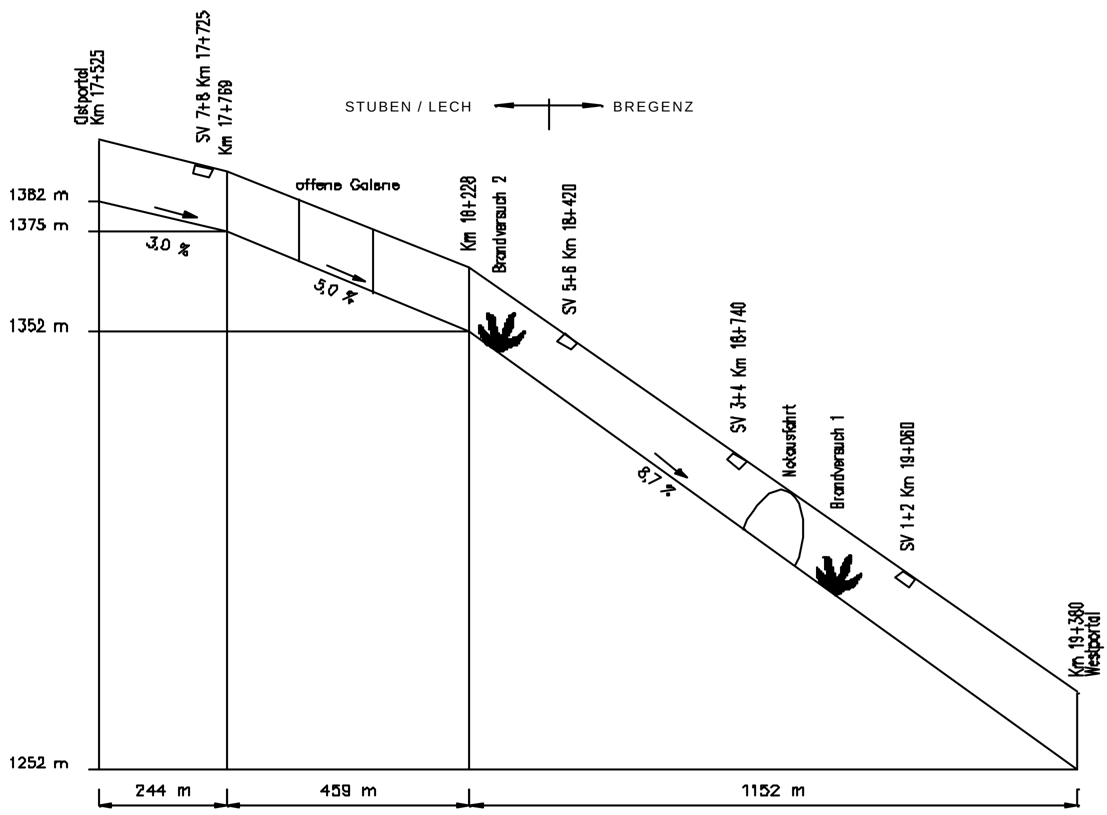

Fig. 3: Location of fire test sites in the longitudinal section

The tunnel is subdivided into 7 fire sections, each with an approximate length of 260 m.

5. MEASUREMENTS AND RECORDING

The following data were recorded:

a) Air velocity and direction inside the tunnel before and during the test
b) Temperature development close to the fire seat
c) Logging of all messages and alarms for the duration of the test in the tunnel control centre
d) Control of ventilation system
e) Video recording of fire development and smoke spread by means of existing cameras.

6. TEST SEQUENCE

Before the test was started, the local meteorological conditions produced an airflow of 0.7 m/s from west to east.
The smoke would – based upon the given parameters and depending on the prevailing flow direction as well as the actual fire seat – either have been conveyed to the east portal or to the west portal.

The following table for example lists the ventilation scenarios for FRP No. 2. The recommended ventilation configuration for an airflow of 0.7 m/s has been highlighted by a light grey background.

Table 1: Ventilation scenarios for FRP No. 2

pair of jet fan	1 + 2	3 + 4	5 + 6	7 + 8
air velocity m/s	direction of operation			
> +2.5	west	west	west	west
2.5 - 2.0	off	west	west	west
2.0 - 1.5	off	west	west	west
1.5 - 1.0	off	west	west	west
1.0 - 0.5	off	west	west	off
0.5 - 0.0	off	west	west	off
0.0 - 0.5	off	west	off	off
0.5 - 1.0	off	west	off	off
1.0 - 1.5	off	off	off	off
1.5 - 2.0	off	off	off	off
2.0 - 2.5	off	off	east	off
> -2.5	off	off	east	off

7. SEQUENCE OF EVENTS

At 21:07, the fire brigade set both steel trays on fire, which at 21:08:46 induced sensor line No. 2 (SL No. 2) of the sensor cable to produce an alarm.

Fig. 4: Ignition of fire at test site No. 1 (21:07)

FRP No. 2 was launched precisely 30 seconds after an alarm from sensor line No. 2 (SL No. 2) was received. This period shall offer the operating personnel a chance to eliminate any possible false alarms. 28 seconds later, an alarm of sensor line No. 3 (SL No. 3) was triggered.

Contrary to expectations, the ventilation control system subsequently activated FRP No. 3, yet without deactivating FRP No. 2.

This sequence of events was not only completely unscheduled but was actually to be prevented, since it led to a combination of both fire response programs and thus to an undefined situation.

Once the trays had been set on fire, the smoke slowly spread to the east portal. A short backlayering of smoke extending over approximately 10-15 m could be observed. The ventilation control – in line with FRP No. 2 – next activated jet fans Nos. 3+4 (JF Nos. 3+4) and jet fans Nos. 5+6 (JF Nos. 5+6) which were blowing in westerly direction.

Table 2: Log excerpt

Datenpunktbezeichnung	Quellzeit	Wert	INV	GA	SPO
#1	#3	#4	#5	#6	#7
PA_BS_ Sensorlinie.LA2............ ALARM	2000.10.24 21:08:46	1	0	0	1
PA_BS_ BMZ-Brandsummenalarm....... EIN..	2000.10.24 21:08:46	1	0	0	1
PA_BS_ Brandsummenalarm.MÜTEC.L20. EIN..	2000.10.24 21:08:46	1	0	0	1
PA_BS_ TR-Meßstelle.1............. EXT..	2000.10.24 21:08:51	2,28	0	0	1
PA_BS_ Ampel.Portal.Ost........... ROT..	2000.10.24 21:08:55	1	0	0	1
PA_BS_ Ampel.Portal.West ROT	2000.10.24 21:08:55	1	0	0	1
PA_BS_ Sensorlinie.LA3... ALARM	2000.10.24 21:09:14	1	0	0	1
PA_BS_ Löschwasseranforderung.. EIN	2000.10.24 21:09:16	1	0	0	1
PA_BS_ Lüftungsautomatik... EIN	2000.10.24 21:09:16	1	0	0	1

PA_BS_ Brandprogramm.2............ EIN..	2000.10.24 21:09:16	1	0	0	1
PA_BS_ TR-Meßstelle.1............. EXT..	2000.10.24 21:09:16	10,7	0	0	1
PA_BS_ TS-Meßstelle 1 Voralarm ... EXT..	2000.10.24 21:09:16	1	0	0	0
PA_BS_ TS-Meßstelle.AST.1......... WARN.	2000.10.24 21:09:16	1	0	0	0
PA_BS_ TS-Messung.AST.1........... ALARM	2000.10.24 21:09:16	1	0	0	1
PA_BS_ Strahlv.FST..Ri.O.......... EIN..	2000.10.24 21:09:17	1	0	0	1
PA_BS_ Strahlv.3....Ri.W.......... EIN..	2000.10.24 21:09:18	1	0	0	1
PA_BS_ Strahlv.4....Ri.W.......... EIN..	2000.10.24 21:09:30	1	0	0	1
PA_BS_ TR-Meßstelle.1............. EXT..	2000.10.24 21:09:41	14,8	0	0	1
PA_BS_ TS-Meßstelle 1 Alarm ...... EXT..	2000.10.24 21:09:41	1	0	0	0
PA_EN2 Strahlv.5....Ri.W.......... EIN..	2000.10.24 21:09:41	1	0	0	1
PA_BS_ Brandprogramm.3............ EIN..	2000.10.24 21:09:44	1	0	0	1
PA_EN2 Strahlv.6....Ri.W.......... EIN..	2000.10.24 21:09:54	1	0	0	1
PA_BS_ Strahlv.1....Ri.O.......... EIN..	2000.10.24 21:10:05	1	0	0	1
PA_BS_ Strahlv.2....Ri.O.......... EIN..	2000.10.24 21:10:18	1	0	0	1
PA_BS_ Luftströmung-Messung..+/-.. M/S..	2000.10.24 21:10:33	0,7	0	0	0
PA_BS_ Luftströmung.Ost-West...... EIN..	2000.10.24 21:10:33	1	0	0	1

FRP No. 3 put JF Nos. 1+2 into operation directing the airflow towards the east portal, while JF Nos. 3+4 and JF Nos. 5+6 directed the airflow towards the west portal – as intended by FRP No. 2. As a result of this setting, the jet fans now worked against each other, creating a swirling airflow and filling the entire tunnel cross-section with smoke.

The jet fans reversed the airflow from east to west and FRP No. 3 further enhanced this westerly flow. With both jet fans now blowing in westerly direction, an excessive number of jet fans was now activated and/or deactivated which led to a sinusoidal airflow curve illustrating the respective airflow acceleration and deceleration.

The recordings of video camera no. 5 clearly reveal that, after the ignition of the fire trays, the smoke spread approx. 150 m in easterly direction, to then – after JF Nos. 3+4, and JF Nos. 5+6 were in operation – be forced back in westerly direction to the emergency exit.

Once JF Nos. 5+6 were deactivated, the smoke was again blowing in easterly direction to emergency lay-by No. 2 (EL No. 2) – some 130 m east of the fire site.

JF Nos. 3-6 were then reversed in direction, blowing the smoke westwards to the emergency exit.

It was at this point in time that all jet fans were deactivated again. Yet shortly later JF Nos. 5+6 were activated again in easterly direction.

This chain of events induced the smoke to flow to EL No. 2 area and from there, after JF Nos. 3-6 were re-activated, to flow back in westerly direction.

The sharp increase in air velocity and the steep amplitude response curve reflecting the sinusoidal airflow curve (see Fig. 5), would – if the control system had been working properly – only have been half as steep and/or would have stabilized after a few minutes.

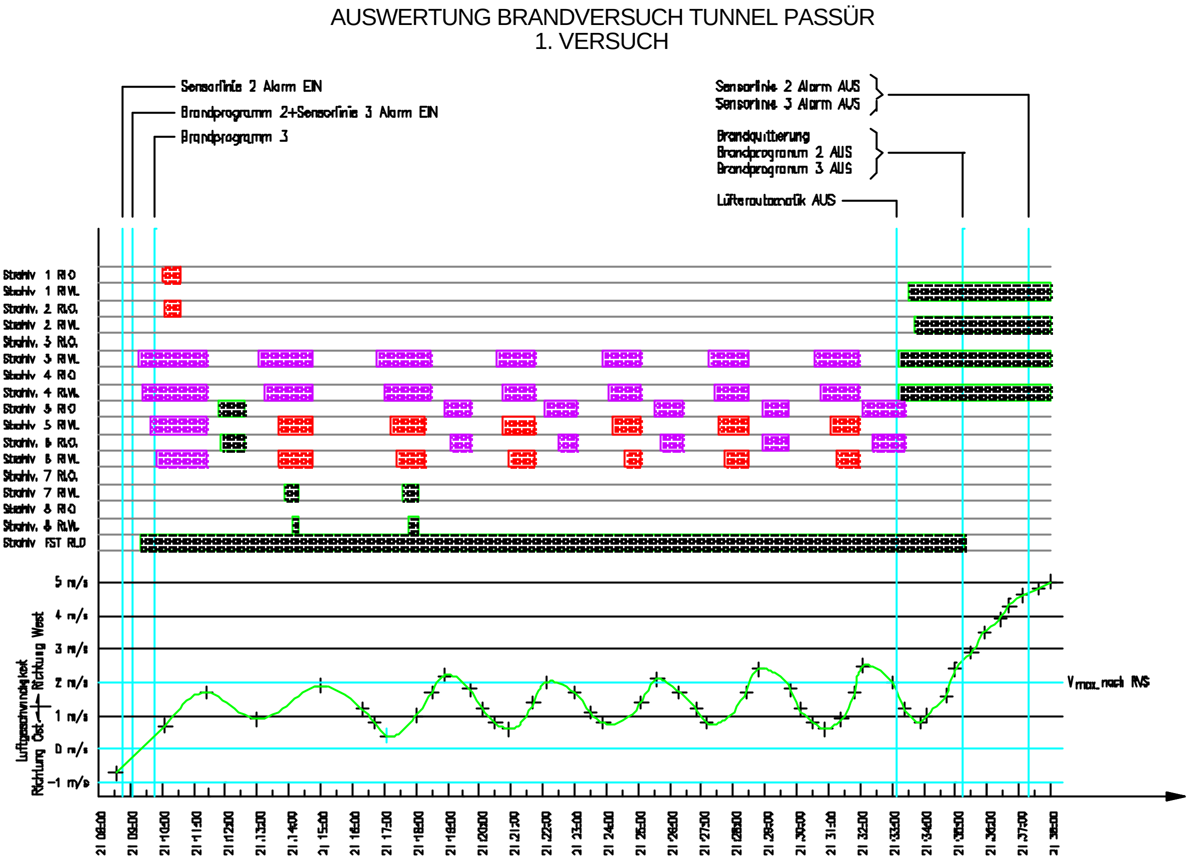

Fig. 5: Test evaluation in graphical form

8. TEMPERATURE EVALUATION

Fig. 6 illustrates the temperature development in the course of time. As the sensor above the seat of fire was covered up, the maximum value reached was 100 °C. The covering up of the sensor led to a delayed fire detection. The "bottleneck" in the diagram represents the covered sensor.

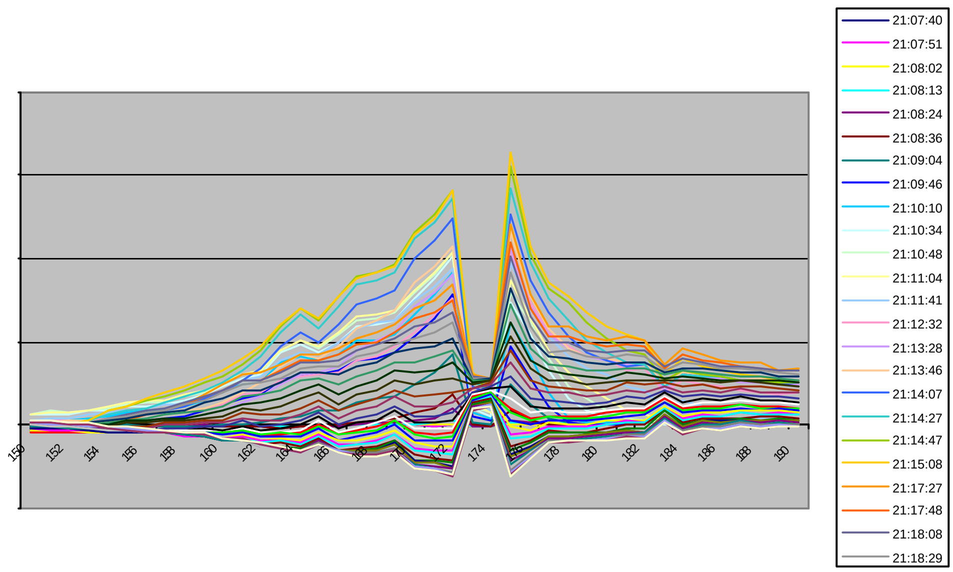

Fig. 6 Temperature development

9. DISCUSSION OF RESULTS

All fire management sequences were in full compliance with the design requirements except for the fact that more than one fire response program was activated at a time. For a proper ventilation system operation, it is to be ensured that only one fire response program is active. In automatic mode, a later change to another fire response program is inadmissible, i.e. the fire response program which was initially launched, is to remain active. If this requirement can not be met, the conditions for persons trying to escape from the tunnel will be anything but defined and the situation inside the tunnel is in fact likely to deteriorate.
An improvement would be a shortening of the measuring cycle time and – against this background – an adjustment of the jet fan response time.
It furthermore seems to be preferable if the individual jet fans were activated individually instead of being activated in pairs.
The test revealed that, at an airflow velocity of approx. 1-2 m/s, a laminar smoke layer extending over a length of 150-200 m may be maintained. This is also evident from the videos, in which an area of approx. 1.5 m above the road surface was found to be smoke-free.

10. CONCLUSION

The fire test confirmed that a perfectly functioning ventilation control is imperative for a safe escape from the tunnel and that any false operation may easily worsen the conditions inside the tunnel. If the fire test had not been conducted, one would not have discovered this malfunction in the control system, since the automatic response reaction induced by the rise in temperature could not have been simulated under normal operating conditions. The performance of fire tests is thus a valuable tool in analysing the tunnel control system and especially the ventilation control system.

FIELD TESTS AND NUMERICAL SIMULATIONS AS TOOLS FOR VENTILATION DESIGN AND TUNNEL SAFETY

Sturm P.J., Pretterhofer G., Rodler J.
Institute for Internal Combustion Engines and Thermodynamics
Graz University of Technology

ABSTRACT

Field test have always been used to check the functionality of equipment and operating procedures for traffic tunnels. Due to the improved performance of computers and numerical models the numerical simulation has become more and more important and reliable. This tool can be very effective as with a relatively small effort a huge number of simulations can be made, and situations simulated which can not be tested in real tunnels without the risk of damages of the tunnel and equipment. Nevertheless numerical tools are models for physical phenomena with a lot of boundary conditions which can not be simulated as a total. Therefore – and especially for test of safety equipment and safety procedures – field tests in tunnels gain again importance and can not be totally substituted by numerical simulations. The article focuses on the use of field tests and numerical simulations which can – in combination – help to improve the design of safety equipment and safety procedures.
Key words: tunnels, field tests, numerical simulation, ventilation, safety

1. BACKGROUND

The design of traffic tunnels is based on experience coupled with a great deal of knowledge about the physical processes. While many procedures are well known, there are always situations which call for extra testing and simulation. These are largely non standard situations in the "lifetime" of a tunnel, which may be at or almost beyond the limits of everyday operation. Mostly, emergency situations – such as tunnel fires - are concerned. In order to prevent such situations, to reduce the damage and/or to test equipment and operation procedures, it is necessary to perform tests under conditions as close as possible to the "real world". Numerical models may also be helpful as they allow for simulations of dangerous situations without risking any harm to the tunnel structure.

Field tests are useful for investigating the functionality of equipment used in tunnel operation, checking tunnel safety, and the effectiveness of operation and safety procedures. The drawback of field tests is the high cost they entail, which leads to restricted use. Numerical simulations can therefore be an alternative, particularly as methods have greatly improved in recent years. Once the necessary numerical grid (structure) is set up, modifications can easily be made and different scenarios considered without any excessive effort. In addition, a real tunnel is not needed, which allows for independence with respect to time and location of investigations. The drawback lies in the fact that a large number of physical phenomena have to be modeled, and a model has always restrictions. In addition, boundary conditions also have to be defined and simplifications be made.

2. FIELD TESTS

The following section will deal with field experiments used for validation and test purposes. Field tests serve various purposes, such as:

- Testing of new equipment
- Training of tunnel operators

- Checking operation procedures
- Checking ventilation under normal and emergency conditions
- Verification of parameters for ventilation design

2.1. Tunnel Ventilation

Tunnel ventilation has to fulfil two tasks. Under standard operation it has to provide fresh air and extract exhaust air, in order to ensure that air quality complies with the threshold levels given for tunnel operation (CO and visibility) and/or with those concerning environmental criteria (mainly NO_2). In emergency situations (fire) the ventilation has to be capable of extracting the smoke at a certain location and of preventing a propagation of smoke through the whole tunnel.

2.1.1 Operation Conditions

Ventilation systems are built to provide enough fresh air. They are designed on the bases of two parameters: first the expected amount of traffic through the tunnel, and second, the emission factor for the vehicle fleet expected to pass through the tunnel. In former days, such emission factors were derived from tunnel tests (e.g. Pischinger 1977). Since the 80's emission factors have been investigated on chassis dynamometers or on engine test beds, as they are needed for a growing number of topics in environmental issues. The driving behaviour, upon which such emission factors are based, is assumed to represent real world driving for a lot of different driving situations. Recently, tunnel studies have been used to validate emission factors instead of deriving them (Sturm 2001, John 1999). As a by-product, emission factors for tunnel ventilation design can be validated, too. The necessity for validation is shown in the following. Figure 1 depicts the calculated CO concentration versus the measured tunnel concentration for a period of a three days measurement in a tunnel. The slope coefficient is 0.93 and the coefficient of determination (r^2) 0.88, i.e. the calculated values fit the measured ones very good.

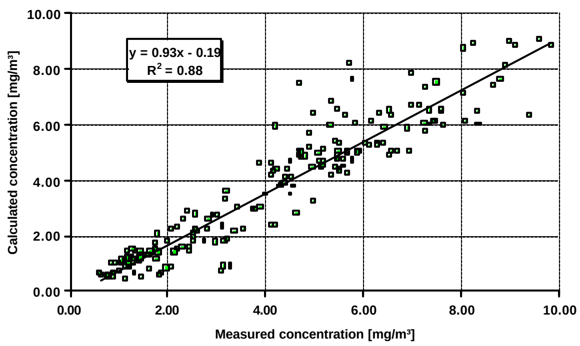

Figure 1: Measured CO vs. calculated CO-concentrations

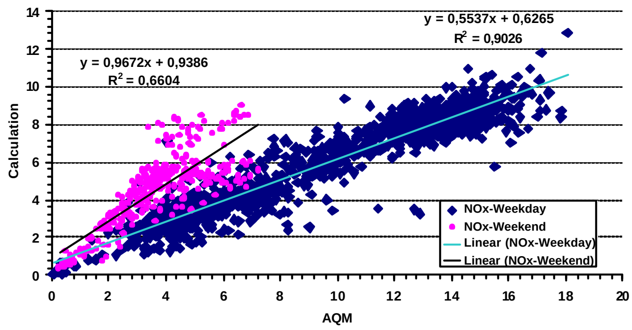

Figure 2: Measured vs. calculated NOx concentration

A totally different picture appears when NOx emissions are considered. The statistical analysis (Figure 2) shows that for weekends, the calculation and measurement fit well, while during working days the slope coefficient is only 0.59. This means that the calculation dramatically underestimates the observed values. Here the emission factors are definitely wrong.

When considering the PM emissions and hence the visibility, a similar situation arises. In tunnel ventilation design, fresh air demand is coupled in the calculation with the emission of exhaust particulate matter (PM) via an emission/light extinction correlation factor. However, in reality, exhaust PM is not the only one PM in the tunnel atmosphere. There is also a lot of non-exhaust PM (brake and tyre wear) as well as resuspended dust from the surface (dirt, lost goods, etc.). If measured concentrations are to be compared with calculated values two fundamental questions arise:

1) Do all size fractions of PM absorb light in the same way?
2) Which PM size fraction comes from which source?

Figure 3 shows data from a PM mass measurement over a period of eight days. Total suspended particulates (TSP) were measured over the whole period, while the PM10 fraction was monitored over the first 4 days and the PM2.5 fraction over the last four days. All the directly emitted emissions can be covered in the PM2.5 fraction, while the resuspended PM can mostly be found in the range above PM 2.5. The PM10 fraction counts for roughly 20 to 25 % of the TSP, while the PM2.5 fraction is in the range of 5 to 10 % of TSP. Statistical analysis of the calculated PM data versus the measured PM2.5 and PM10 data shows that in both cases an extreme underestimation is given by the calculation, since it reflects only the exhaust part of the PM. But how this influences visibility is not really known. The measurements also showed a strong connection between the TSP-PM2.5/PM10 fraction and the amount of HDV-traffic. During times with little HDV-traffic (e.g.. Sundays) almost all measured PM could be allocated to PM10.

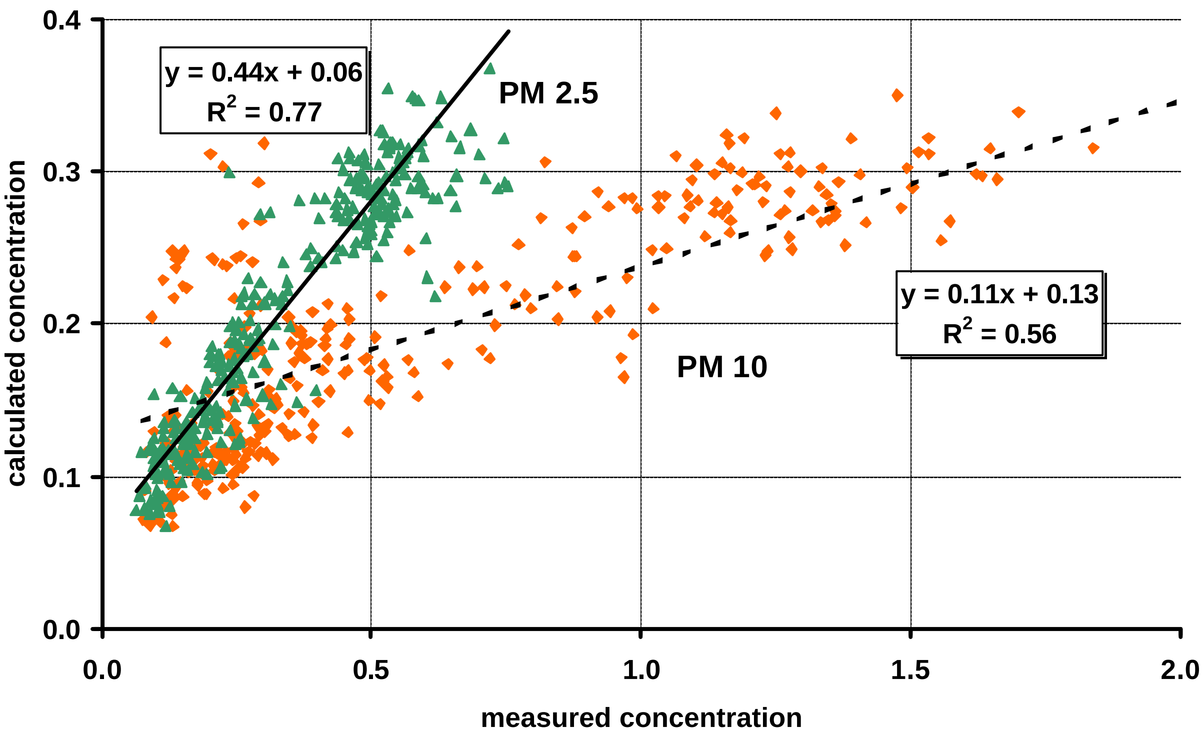

Figure 3: Particulate matter measurements for total suspended PM (TSP) and the PM2.5 and PM10 fraction.

The conclusion of these results is limited by the fact that:

a) Too little knowledge is existing about the correlation between light absorption and emission of higher PM sizes
b) The relation between TSP and PM2.5/PM10 may be different in each tunnel as it depends strongly on the proportion of HDV-traffic and resuspended PM.

Nevertheless, it is clear that the calculation of the fresh air amount does not take into account the biggest part of PM emissions (at least in mass), and this results in an underestimation of the visibility related fresh air amount.

2.1.2 Emergency Conditions (fire)

In the case of a fire, the purpose of the ventilation system is totally different to ist purposes under standard operation. Here, the extraction of the smoke laden air from the fire area and the restriction of its propagation inside the tunnel are absolutely essential. This can only be done together with other installations, such as dampers in the case of transverse and semi transverse ventilation systems. In anyway the functionality of such systems has to be proven in field tests, as each system has to be seen in connection to the whole tunnel. In addition, the location of the fire inside the tunnel may play an important role, when for example two ventilation sections are affected. Such field tests are essential in the training of tunnel operating personnel and fire brigades. The same is true for tests of new equipment. Everything has to be tested with respect to its functioning in a realistic tunnel situation.

3. NUMERICAL MODELLING

Numerical simulations have the big advantage that neither a tunnel nor equipment is needed to perform tests. Different scenarios can be played out without great effort and dangerous situations can be simulated without any damage to the tunnel structure. This explains why numerical simulations are often used for fire studies. Nevertheless, numerical models have drawbacks. These are mainly related to questions of accuracy and predictability of the results. There are two groups of problems. The first concerns the physical modelling of the flow field, and the second, the modelling of the fire and smoke distribution in the case of fire.

The numerical problems can be related to turbulence modelling in the region near the fire, conjugate heat transfer (the walls), modelling radiation, etc. Problems related to fire source include the heat release as a function of the development of the fire, smoke production as a function of burning material and the connection between smoke concentration and visibility.

Computational fluid dynamic (CFD) studies are an important tool for tunnel design, ventilation design and even for design of equipment. Nevertheless, models still have to be validated, parameters generated and boundary conditions measured. I.e. a lot of information is needed to perform a reliable CFD calculation, and most of this information has to be derived from field tests.

3.1. Numerical modelling in the framework of environmental assessment studies

In the following section, a field test used to validate a model for the dispersion at tunnel portals is discussed. There is a strong need for an air quality model which can deal with the special dispersion conditions at tunnel portals and, in addition, is suitable for environmental assessment studies. In this particular case, field tests with a tracer gas (SF6) were performed at a tunnel portal to develop and validate just such a dispersion model (Sturm 2002). Figure 4 shows the tunnel portal, and Figure 5, the calculated concentrations (dashed line) and the measured ones (underlined values).

Figure 4: Tunnel portal

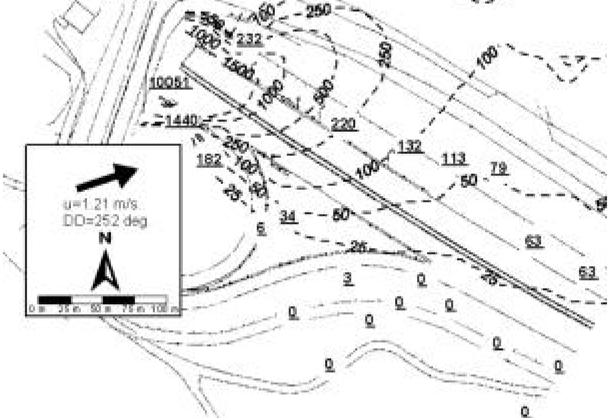

Figure 5: Measured and calculated concentration values

As seen in Figure 4 the tunnel portal is situated in a cut and cover section. Due to this fact the terrain has some influence on the dispersion conditions. The test case shown in Figure 5 depicts an interesting situation. The meteorological conditions cause a transport of polluted air from the exit portal to the inlet portal of the second tube. Clearly, models need to be designed which take such processes into account. In addition, this test shows very clearly how important a barrier wall in the centerline of the highway would be in order to prevent a recirculation of polluted air into the tunnel. This is especially the case in emergency situations, in which smoke laden air could block the second tube, too. Apart from this Figure 5 shows that the dispersion behaviour predicted by the model is quite acceptable.

3.2. Numerical modelling of in-tunnel situations

The following section contains a description of an extensive study combining field measurements and numerical modelling. The field measurements were used to derive parameters which themselves then served as input parameters for the numerical simulation. The case deals with so-called moveable curtains in case of fire in a tunnel (Öttl 2002). The curtains act to impede airflow and to build up a high resistance inside the tunnel. This forces a reduction of the longitudinal velocity, which is a prerequisite for an effective smoke extraction through dampers in the false ceiling of the tunnel. In this particular case, the resistance of the curtains (drag value) is dependent on the air velocity. These drag values were measured in a field test. Further tests were carried out in a 6 km long tunnel with a 2 MW diesel oil fire, with and without the use of the curtains.

Figure 6 shows how, using four curtains, the airflow decelerates, immediately after closing them (above) and 30 seconds later (below). The average speed decreases within these 30 seconds from 3.2 m/s to 2 m/s.

The tests were carried out such that 90 s after the fire ignition the alarm system was activated. This activation caused the curtains to be closed and the ventilation system to be switched to 100 % exhaust air in that section (~ 90 m^3/s). It took an additional 60 seconds until the exhaust air ventilation system was fully activated. During that time smoke had already travelled some 500 m downstream before any useful action against smoke propagation could be taken. Both cases show therefore almost the same effects concerning visibility (Figure 7). The only difference is to be found in the location of the fire, since in the case without curtains, a smoke stratification occurs, while in the case with curtains such layering is destroyed.

Figure 8 shows the same cases after 8 minutes. In the test without curtains a large area is blocked by smoke, while the test with curtains shows that it was already possible to extract a considerable amount of smoke through the dampers and the smoke laden air zone is considerably reduced. Equivalent results were found in the field experiment.

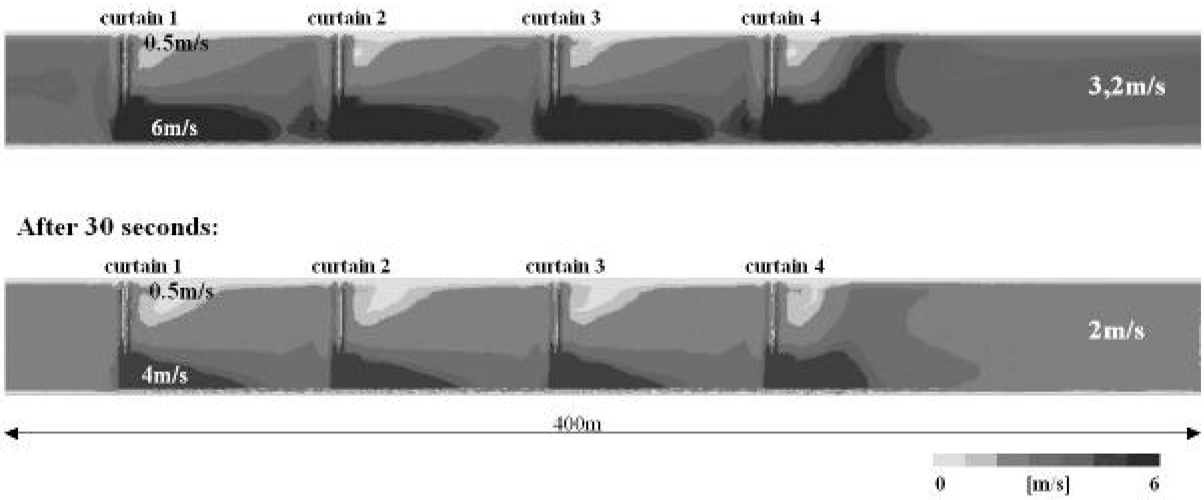

Figure 6: Velocity distribution after closing the curtains and 30 s later

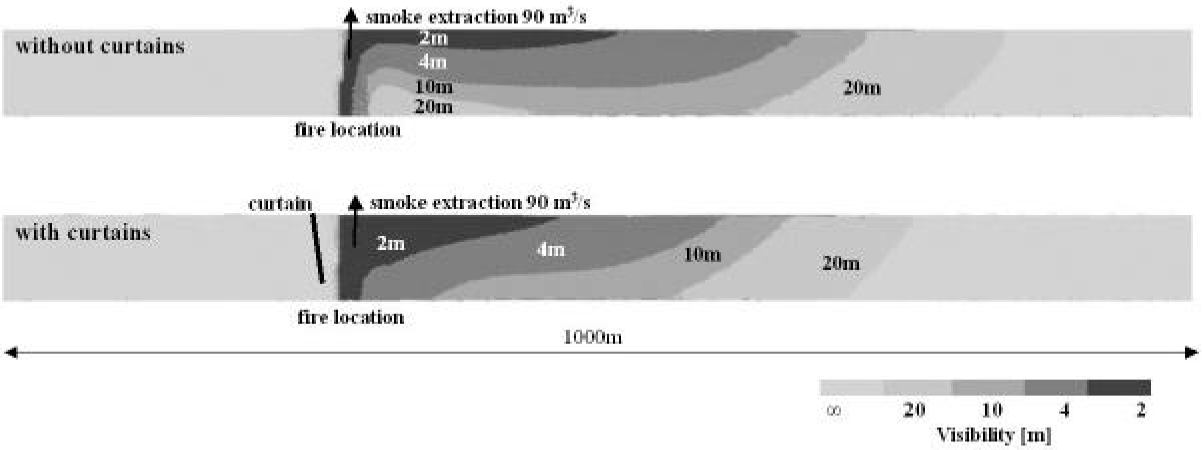

Figure 7: Simulated smoke propagation (visibility), three minutes after the start of the fire

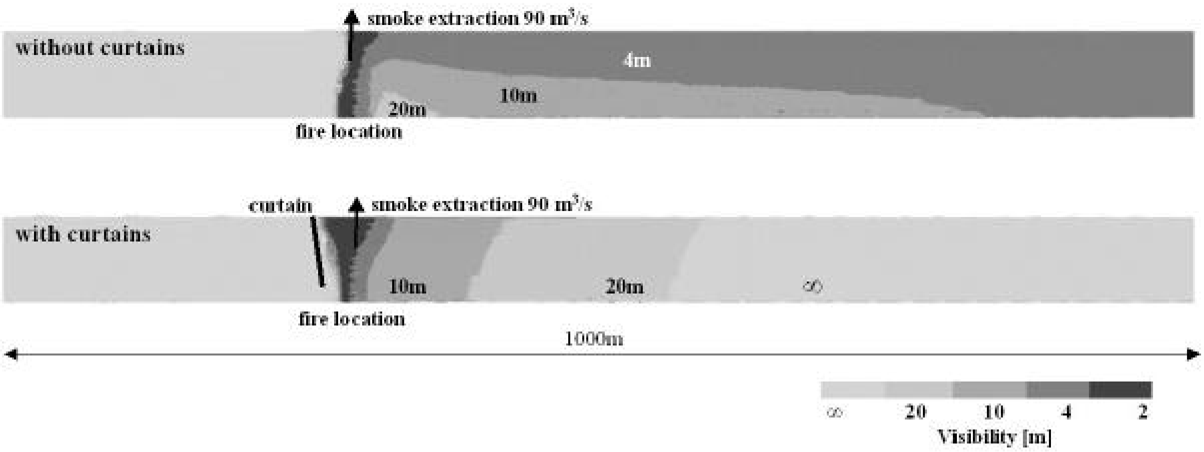

Figure 8: Simulated smoke propagation (visibility), eight minutes after the start of the fire

With the results gained from the tests and simulations it is now possible to perform simulations for different curtain set-ups, different tunnels (with or without slopes), and for different heat releases.

Another simulation is shown in Figure 9 and Figure 10. This case investigates a fire with 3 MW, in a 3300 m long tunnel with a grade of 50 percent. The simulation starts with a natural flow in the tunnel with a wind speed of 1.5 m/s on average and 10 m/s locally (in the region which is blocked by an obstacle). The ambient temperature is roughly 0°C, and 200 C at the ignition location of the fire. Two minutes after the ignition the temperature increases to more than 300°C in the biggest part of the tunnel, with much higher values in the fire region and some 100°C at the exit portal. The velocity increased in average to 10 m/s, with a strong vertical velocity distribution (up to 40 m/s at the ceiling and low velocities at the bottom) and very high velocities in the region of the heat release. An additional 15 minutes later the heat release is over and the average temperature goes down to 100 °C. The velocity at the exit reaches 20 m/s in average, but now with a almost uniform speed profile. Figure 9 shows the velocity distribution and Figure 10 the respective temperature profiles.

Such cases are ideal for numerical models as they allow for the testing of different measures aiming at reducing temperature and hence the buoyancy effects which again reduces the impact of the fire.

4. CONCLUSION

Field tests and numerical simulations are important tools in tunnel design and operation. They can help to develop and improve equipment as well as operation procedures, and they are essential in the training of tunnel operator staff and fire brigades. However, to achieve reliable results, the test facility and the simulation case have to be as close to the “real world” as possible.

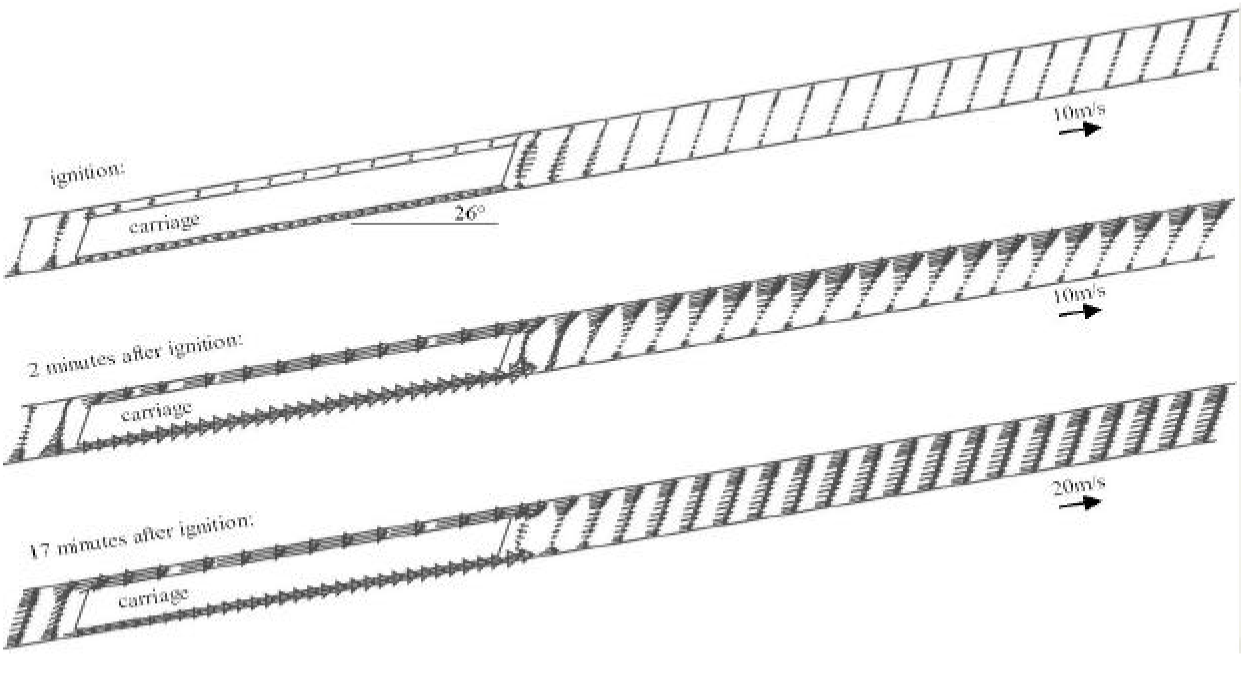

Figure 9: Flow field as a result of a tunnel fire (3300 m length, 50% gradient, 3 MW heat release)

Figure 10: Temperature distribution of a tunnel fire (3300 m length, 50% gradient, 3 MW heat release)

ACKNOWLEDGMENT

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TUNNEL FOR SAFE TRAFFIC

Robert Planinc, Institute for Civil Engineering, Zagreb, Croatia
Josip Pavetic, Ekovent d.o.o., Novo Cice, Croatia
Marko Planinc, Tribo Beton d.o.o., Zagreb, Croatia
Ivica Tisovec, Faculty for Safety Measures at Work, Zagreb, Croatia
Dubravka Bjegovic, University of Zagreb, Faculty of Civil Engineering, Croatia
Irina Stipanovic, University of Zagreb, Faculty of Civil Engineering, Croatia
Miodrag Drakulic, Marine Research & Special Technologies Institute, Zagreb, Croatia
Milan Carevic, Faculty for Safety Measures at Work, Zagreb, Croatia

ABSTRACT:

This work presents the project "TUNNEL FOR SAFE TRAFFIC" which is a result of two patent solutions. In this project, the safety elements in the tunnel include multifunctional prefabricated secondary lining "Tribo-Beton", 3K ventilation "Ekovent", fire extinguishing by water spray, video-surveillance and fire-alarm.
After primary tunnel lining is placed, the elements forming a self-supporting arch are installed by using a special symmetrical scaffold. This scaffold enables the handling and placement of precast elements, which also serve as a self-supporting formwork for filling fresh concrete into the space between the elements and the primary tunnel lining. After having installed the 200 m secondary lining, the installation of 3-K ventilation elements can start.
These precast elements will play a multiple role in tunnel construction and performance. Their special composite structure makes them fire and water-resistant. Their prefabricated nature keeps construction costs at an acceptable level; in addition, better quality of concrete is achieved in controllable factory conditions. The “SKEMOT-3" scaffold specifically intended for such construction enables continuous traffic even during the reconstruction of the tunnel, but, of course, with reasonable speed and traffic flow restrictions.

1 INTRODUCTION

Catastrophes caused by fires in several road tunnels in Europe in a very short period of time have radically changed the attitude towards fire protection systems. The effects of fires in tunnels highlighted two main problems: damage to the conventional secondary tunnel lining and the breakdown of the ventilation system supplying fresh air to the captured people. The spalling of the concrete in secondary tunnel lining prevented rescue teams and firemen from approaching the fire and people captured in the tunnel, [1-5]. Concrete changes its mechanical properties under high temperatures. According to the PIARC document (Chapter VII. 4.3.) [6] the concrete lining cracks and spalls already at the temperature of 200°C blocking, to a large extent, the firemen’s intervention on the pavement. The firemen, being equipped for a short stay at temperatures from 400 to 450° C (in a tunnel such temperatures can produce a radiation level of about 5 kW/m^2, which is the maximum tolerable value for firemen), are directly endangered by the spalling of concrete lining. Furthermore, usual fire extinguishing with water gushes stimulates the spalling of the concrete lining due to a sudden cooling of the concrete mass (temperature shock). After those experiences it can be concluded that secondary tunnel lining should be fire resistant, especially in the case of one-tube tunnels without alternative approaches for firemen. Secondary tunnel lining can be designed and performed as monolithic construction or a construction consisting of precast elements. Precast elements for tunnel lining have been in use for many years. There are many tunnels built with segmental linings, like the Channel Tunnel, Elbtunnel Hamburg, Germany, LRTS Izmir,

Turkey, Plave-Doblar, Slovenia and other tunnels. In all these cases no fastenings are required between elements, and the dimensions of a member may be chosen to provide an “aspect ratio” sturdy enough to survive accidental damage during the processes of handling and erection. Fireproofing has always been applied separately after the secondary lining has been installed [7 – 9].
The project has been developed in co-operation of two Croatian companies: "Tribo-Beton" and "Ekovent" which in turn co-operate with the Faculty of Civil Engineering and other scientific institutions and companies.
The proposed solution for secondary tunnel lining involves construction of precast fire-resistant elements consisting of four layers, i.e. a double fire-resistant layer, a layer of structural concrete and a waterproof layer. These precast elements would play a multiple role in tunnel construction and performance. Its special composite structure makes them fire resistant even at high temperatures, thus ensuring structural stability during a fire in a tunnel. They would also serve as a self-supporting formwork for the filling of fresh concrete into the space between the precast elements used for secondary tunnel lining and the primary tunnel lining. In addition, they would provide enough space for fire protected ventilation pipes intended to supply the security chambers (passenger shelters) with fresh air.

3K ventilation

The lowered ceiling is installed at the height of 4.5 m along the tunnel, and the space above is divided by two longitudinal bulkheads into three channels. At each end of the side channels there are special exhaust fans, and reversible ones are in the centre. All of them are designed for continuous operation at a temperature of 300°C, and they operate regardless of smoke, water droplets or dust. In every channel, at intervals of 50-100 m in the lowered ceiling there are big fire-resistant electrically driven louvres.

3K ventilation in normal operation

The fans in the side channels operate constantly at minimal capacity of ca. 30%, and all the louvres are open in percentage according to the program determined in trial operation after the start-up, thus providing constant flow of fresh air through the traffic opening of the tunnel towards the tunnel centre, whereas polluted air gets sucked out of the tunnel through the louvres of the side channels. The central channel serves for the supply of fresh air to the position where sensors detect excessive pollution. By supplying fresh air to the point of pollution only the necessary airing of the polluted section of the tunnel is performed, rather than of the whole tunnel. In this way, in case of local pollution the side fans need not be turned on to maximum power. In order to maintain tunnel ventilation at the required level with minimum necessary corrections of ventilation power, all the fans have their operation regulated by frequency controllers.

Operation of 3K ventilation in case of fire

All the louvres in all the three channels, except those in immediate vicinity on each side of the fire, close down hermetically. All fans switch to maximum capacity operation for exhaust of gases and smoke from the tunnel. The louvres in the vicinity of the fire are completely open and they provide momentarily complete exhaust of the smoke mixed with fresh air flowing from the head of the tunnel towards the point of fire, thus preventing smoke from spreading against the airflow coming in from the head of the tunnel towards the point of fire. In this way the louvres on each side of the fire represent the "air gates" so that there is no longitudinal

flow of air between the open lovres, nor is there any supply of fresh air to the point of fire. This allows efficient extinguishing of fire by means of water fog from the stationary plant. Moreover, due to the sub-pressure created and the consumption of oxygen from the air caused by burning, the fire itself gets reduced, and the firemen can access the very spot of the fire, and start the fire-fighting operations immediately using any method planned for the given tunnel.
What is important is for the operator to have continuous video-surveillance of the traffic in the tunnel so as to be able to locate the exact place of accident without any delay.
It has to be noted that the exhaust of polluted air is completely controlled behind the fan, and the polluted gases can be cleaned by means of efficient filters fitted in the 3K ventilation system, thus preventing further environmental pollution. This also provides conditions which allow even the heavy-duty freight vehicles to pass through the tunnel without restrictions, excluding of course those that have to be specially controlled.

To summarise, 3K ventilation can achieve the following:

- prevent smoke and fire from spreading outside the controlled area between two louvres,
- provide efficient operation of a stable fire-fighting system by means of water fog, since there is no longitudinal airflow and no supply of new air to the place of fire,
- provide fast and safe evacuation of people and vehicles from the tunnel, as well as undisturbed arrival of firemen and rescuers to the very location of the fire with flow of fresh air from behind,
- provide flexible operation of the fan and louvres regulation system,
- that the fans are located outside the tunnel accessible above the head of the tunnel in a closed engine-room next to the power transformer stations,
- the equipment can be maintained without having to stop the traffic flow through the tunnel,
- there is no danger of either the lowered ceiling or the concrete lining from caving in.

2 PREFABRICATION OF ARCHED TUNNEL ELEMENTS

Arched tunnel elements made of reinforced concrete are precast in moulds bent to match the horizontal curve of a tunnel centre line. The moulds are closed and opened by horizontal translation of vertical mould walls.
The precast arched tunnel elements made of reinforced concrete consist of four layers, i.e. four different materials which are bonded, during fabrication, into a single body. The first layer of the arched precast member is a fireproof cement-silica plate of 15 mm in thickness; on it another layer of fireproof material, i.e. a special micro - concrete of 40 mm is placed; and then the third layer of structural concrete is cast. After concrete is hardened and set in the warehouse of a concrete plant, a forth layer, i.e. a waterproof layer, is spread (Figure 1).

The sides of elements are provided with rubber sheets - profiled to suit the concrete shape - which serve as matching and waterproof elements (Figure 1). The rubber sheets are protected against fire by using permanently elastic filling and fireproof seal resistant to temperatures up to 1350°C.
Structural concrete for precast elements used for the secondary tunnel lining meets very strict requirements with regard to water-cement ratio, concrete strength and protection of reinforcement from corrosion, i.e. requirements for durability of a reinforced concrete member. In order to meet these requirements, a new generation of superplasticizers was used. In this way an increased plasticizing effect of a fresh concrete mixture was provided, which

resulted in required strength and impermeability of concrete, and inhibition of reinforcement corrosion in the hardened concrete [11].

The multi-layer precast elements consisting of various combinations of materials were tested for fire resistance in order to obtain the optimum combination. This combination consisted of a double fireproof layer involving a fireproof plate with 1.5 cm thickness and a special micro-concrete of 4 cm thickness. The elements were tested according to the Rijkswaterstaat tunnel curve, [8, 12]. The above-mentioned combination of materials in the precast multi-layer member has satisfied the requirements of the Rijkswaterstaat test, [13].

3 CONSTRUCTION OF PRECAST TUNNEL ELEMENTS

Elements are placed under the crown of a tunnel by using a self-propelled scaffold to pull them over in a transversal direction. The scaffold has a symmetrical shape, which enables the handling, launching and installation of the elements on the left and the right side of the tunnel, depending on site conditions.
The scaffold consists of a central part - with an opening allowing site vehicles traffic - and lateral parts. The lateral parts are used for handling and constructing bottom elements of the lining, and for handling the crown elements of the lining and their launching to the top part of the scaffold. The top, rounded portion, is provided with rollers which receive and transport the crown member in the longitudinal and transversal directions.
Building procedure is presented in Figure 2 (A-D), where the whole cycle including handling, construction and jointing of the precast elements and construction formating of the arch of the secondary tunnel lining can be seen.

Figure 2. Mounting procedure of secondary tunnel lining in the tunnel.

On the side of the rear part of the self-propelled circular scaffold, a stationary pump is provided to pump concrete into the space between the tunnel calotte and the precast elements of the secondary tunnel lining. The pump is installed in such a way as to be directly fed with concrete from a mixer truck, and to pump concrete through a platform “l’affut”, into the space between the precast arch and the tunnel calotte. Concrete is placed on the left side and then on the right side, in succession, from the arch foot and the tunnel calotte (Figure 3). The concrete used for filling may be concrete with or without reinforcement, as may be provided by the design of the tunnel construction.

Before concrete is placed, ventilation pipes are laid. After the space between prefabricated lining and the tunnel calotte is filled with concrete, and before the construction of the next arch is started, further ventilation pipes are connected to those already covered with concrete and fastened, if necessary, to the tunnel calotte. After the installation of the ventilation pipes is completed, the construction of the following arch is carried out (Figure 3). In case of fire in the tunnel, pipes installed in this way are protected by the lining, which allows them to provide uninterrupted delivery of both fresh air and compressed air required by firemen.
After the erected arch is stressed with longitudinal force of about 150 kN, and the arch is supported by adjustable bolt foundation as well as stressed with the already built arch, the scaffold is lowered to a transport beam and pulled over into a new position for the construction of the next arch. In this position, first a platform “l’affut” is installed, and then concrete carrying pipe is connected to the stationary concrete pump. After all preparations are completed, the concreting of the arch supports and the space between the previous arch and the tunnel calotte is commenced. In this way huge saving of time will be done, because the

scaffold and tools used for the arch construction can also be used to provide effective and controllable placement of concrete between the tunnel calotte and the constructed arch. Working processes are automated and run by remote control of all the stages of handling a precast member, its bringing into the centre line of the circular self-propelling scaffold and putting it in the final position. Unfitting of the scaffold and its relocation to a new working position is also ensured by remote control, i.e. laser guidance allowing high degree of accuracy measured in millimetres.

4 ADVANTAGES PROVIDED BY PREFABRICATED LINING ELEMENTS APPLIED IN CONSTRUCTION OF ROAD TUNNELS

The construction of secondary lining of the road tunnel presented in this paper provides the following technical and technological advantages:

- The constructed precast multi-layer concrete elements are connected so as to form an arch and no other finish for a tunnel surface is required; in addition, it also fills the role of a fire protection element.
- The waterproof layer on the outside surface in conjunction with the rubber seals at the side surfaces of the elements make them waterproof.
- The stage of tunnel construction that involves the waterproofing of shotcrete is eliminated.
- Formwork used for construction of the monolithic lining of a tunnel is no longer required.
- The already installed precast reinforced concrete elements serve as forms for concrete filling.
- Built-in ventilation pipes supply safety chambers with sufficient quantities of fresh air during a tunnel fire.
- Fastenings used during construction to handle and erect plates are also used to fix ventilation, tunnel lightning and other signals and signs in the tunnel.
- If slight modifications to the self-propelled scaffold are made, it can also be used as a working scaffold in regular maintenance of road tunnels and in possible tunnel rehabilitation allowing the tunnel to remain for traffic.
- Fire resistant plates on the inner surface of prefabricated linings are bonded during fabrication in a factory, thus providing the best adhesion of these plates with the layer of micro-concrete.
- In the space between primary lining and the precast lining a number of ventilation pipes can be built-in around the tunnel periphery to supply safety chambers (passenger shelters) with air in the event of a tunnel fire. The location of these pipes described in this paper is found to be the best solution compared to the existing solutions involving pipe laying under the pavement structure or their installation under the tunnel crown with subsequently placed fire resistant coating.

5 CONCLUSION

The prefabricated self-supporting arched elements, consisting of reinforced concrete, fire resistant and waterproof layers, in order to be used in tunnel construction as a secondary tunnel lining, are found to be a technically and economically viable solution.

The combination with 3K ventilation, whose elements are manufactured in the quality of secondary fire-fighting prefabricated lining, and fire extinguishing by means of water fog with high-quality video-surveillance have made the vision of the project "TUNNEL FOR SAFE TRAFFIC" come true.

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