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CONTENTS

"TUNNEL SAFETY AND VENTILATION"
Graz, May 3 – 4, 2010

POSTERPRESENTATIONS

AUSTRIAN TUNNEL SAFETY INITIATIVE – STATUS AND OUTLOOK

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ABSTRACT

ASFINAG plans, builds, maintains and collects toll charges on the entire Austrian motorways and expressway network, which extends over 2.172 km. 1997 ASFINAG was granted usufruct rights on land and facilities. Since then ASFINAG has not received any money from the federal budget. Building and planning of new roads partly has to be financed by loans from the capital market. All other activities are completely funded by toll income.

1. INTRODUCTION

Since the tragic events in 1999, people in Austria have attached great importance to the issue of tunnel safety. With the help of both, technical developments and organisational measures, tunnel safety has been significantly improved, which comprises minimizing the risk of an accident happening as well as ensuring maximum safety for tunnel users in case of an incident.

Status Tunnel Safety

ASFINAG currently operates a network comprising approximately 2,200 km of high level roads. This network includes approximately 140 km of special toll roads, such as the Bosruck tunnel, the Gleinalm tunnel, the Arlberg tunnel, the Karawanken tunnel, the Katschberg tunnel and the Tauern tunnel. 350 km of motorways and expressways are currently either at the planning stage or under construction.

A total of 140 tunnel facilities with a total length of approximately 324 km are currently in operation on the ASFINAG network. This adds up to the distance from Vienna to Salzburg on the A1 West motorway. Approximately 135 km of tunnel facilities are either at the planning stage or under construction. This adds up to a journey from Salzburg to Villach on the A10 Tauern motorway.

Bearing in mind this large number and aggregated length of tunnels on the network, ensuring the highest possible level of safety and economic efficiency in motorway and expressway tunnels has to be one of ASFINAG's main objectives.

Tunnel databases

In order to meet the provisions of the Road Tunnel Safety Act, several tools were developed, including a tunnel safety database. This database has been in operation since 01.01.2006. All accidents, fires and cases of property damage relating to tunnel operation have been recorded in the database in order to allow improvements to be made as quickly as possible.

In the database were collected in total 1541 events up to 25.02.2010.

Figure 1: Tunnel database

A simple analysis of these 1541 database records shows

- 377 cases of personal injury (26 of which casualties)
- 1080 cases of damage to property
- 46 cases of fires
- 38 other events

In addition ASFINAG has been operating a tunnel closure database since 01.01.2009. Closures are separated into three categories: planned (=scheduled) closures, events (e.g. accidents, fires) and incidents (e.g. tunnel lighting failure, vehicle height control)

- Number of all closures: 8473 (01.01.2009 to 25.02.2010)
- Number of planned closures: 1281
- Number of closures due to events: 6576
- Number of closures due to incidents:616
- Total time of closure: 175 days, 1 hour, 56 min
- Average duration of closure: 30 min

Tunnel database and tunnel closure database provide us a tool to quickly identify black spots and derive measures of mitigation. For more details on tunnel databases and safety provision please refer to Mr. Rattei's presentation on the conference.

Training our Personnel

Apart from technical improvements tunnel well trained employees are a prerequisite for maximizing tunnel safety. That is why RVS 14.02.15 „Qualifikation und Schulung für das Betriebspersonal von Tunneln und Einhausungen“ describes requirements for skills and training for personnel involved with tunnel operation. Based on this ASFINAG has developed and started a detailed training program for all concerned employees.

The main objective of this program is to provide all needed knowledge to cope with the demanded duties, including periodic refreshing, updating and consolidation. This proves to be more and more important due to the increasing duties and responsibilities.

This program consists of a Basic training and periodic follow-up trainings. Training success is monitored in a standardized way by written exams. These results as well serve for documentation purposes. Every employee, who passes the examination receives a written document approving his skills to cope with the respective function. So far 145 employees in the area of tunnel operation have been trained and examined. The exam was designed in a very demanding way. The nevertheless very good results point out the high level of skills and knowledge of the employees assigned to tunnel operation. This notion is confirmed by in depth analysis of events and incidents, which were all handled in a very professional way.

Outlook Tunnel Safety

In order to comply with effective EU legislation (Road Tunnel Safety Directives) several measures need to be implemented by 2019 depending on expected traffic levels. This includes additional second tunnel tubes, optimized escape and emergency routes as well as intensified fire protection and prevention.

ASFINAG plans an awareness campaign for tunnel safety for 2010. Information will be provided at resting areas and on roadside posters. A dedicated brochure aims at teaching how to react in specific situations in a tunnel. Furthermore information will be available on the ASFINAG web site, including a movie clip.

ASFINAG fosters and initiates innovative Research- and Development Projects (not only) in the field of tunnel safety. Recent ones are: *Tunnel Help* and *AKUT*.

Tunnel Help aims at identifying emergeny calls from cell phones in a tunnel. Currently emergency calls are connected to provincial emergeny call centers without the instrinsic information that is included with an emergency call from a dedicated phone booth; but normally there is no information on location transmitted when using a cell phone. Drivers in the situation and stress of an emergency often are not capable of delievering precise information. All involved emergency forces would benefit from reliable information concerning location and direction. Measures could be started earlier.

Another innovative project being realised is **AKUT** (acoustic tunnel monitoring). This system aims at identifying critical events and incidents by using automatic sound detection. After filtering out ambient noise potentially dangerous situations are recognized automatically. Alerts can be triggered consequently. For detailded information on this topic please refer to the dedicated presentation on the conference by Mr. Gruber and Mr. Ruhdorfer.

In close cooperation between ASFINAG, the Austrian Federal Ministry for Transport, Innovation and Technology, the Austrian Provinces, Austrian Federal Economic Chamber, the fire brigade and other involved institutions a bulletin was worked out on how to assess the risk of transport of hazardous goods in road tunnels. Concrete assessments will be carried out within the next months.

2. SUMMARY

Currently the risk to get involved in an accident in a motorway or expressway tunnel is lower than in a non-tunnel section. Due to more severe accidents in tunnels the risk to perish in a tunnel is twice as high than on non-tunnel motorway sections (and thus is on the same level as Austrian expressways). Looking at the decreasing numbers of fatalities in the entire ASFINAG network (2008: 81 compared to 2001: 179 fatalities) we notice that motorways and expressways have become even safer roads. Results and experience of the last years clearly show, that significant improvements in tunnel safety and road safety in general still are possible when using a wide mixture of ambitious measures and this is what we are going for. The ASFINAG Road Safety Program 2010-2020 clearly shows 13 fields of activities, 32 focus activities and 130 concrete measures to further improve road safety. Our aim is to cut the number of fatalities per billion km driven in our network by another 50%. One of the most important fields of activities clearly is tunnel safety. This is not going to change in the next ten years.

TUNNEL SAFETY BY VENTILATION – AN ILLUSION?

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ABSTRACT

The ventilation is considered to be a vital component of road tunnel safety plans. Accordingly, substantial amounts have been invested for this purpose. However, though the installation and operation concepts have been discussed, decided and implemented by specialists, weaknesses continue to appear in routine operation, tests and emergencies. While work to eliminate these weaknesses is an ongoing process, it must not lead us into the error of increasing the complexity of the systems and thus creating new weaknesses. The problem is to find the golden mean.

Key words: tunnel ventilation, safety, smoke detection, safety gallery, escape door

1. INTRODUCTION

The safety of tunnel users is ensured by a whole range of interconnected individual components and subsystems. The systems are mainly designed for the first phase of a vehicle fire in which the persons trapped inside the tunnel have to reach safety on their own. To this end, there are various systems of optical and acoustic signals which provide tunnel users with the information and indications needed to make the appropriate decisions for themselves. In addition, there are also systems intended to ensure that the escape routes can be found and reached even in the case of a fire.

The primary purpose of tunnel ventilation in the event of an incident is simple, namely to give the persons concerned in the tunnel sufficient opportunity to identify and reach a way out of the danger zone. In modern tunnels, this purpose is usually achieved by means of a longitudinal ventilation system, with or without smoke extraction, depending on the type of traffic. After the rapid detection of an incident, the next priority is the measurement and control of the longitudinal air flow in the traffic space.

Other objectives include support for the specialised emergency services during the rescue phase and, during later phases, the protection of the structure.

Experience has shown that various causes may contribute to a situation getting out of control. For example, the scale or course of an incident may exceed the design limits of the system, individual components may not function properly or the concepts may not be appropriate.

From the reports by emergency services on major incidents, we know that, within 10 to 20 minutes – i.e. just as the rescue specialists are arriving – the situation may have escalated to such an extent that the fire brigade can no longer rely on the tunnel-related concepts. The commander on the spot must be prepared for surprises since there are limits as to what the systems can do.

The following critical comments relate mainly to tunnel ventilation systems and, in this regard, we set out a number of experiences concerning ideal concepts, real-life behaviours, erroneous assumptions, lack of knowledge and promising approaches.

2. WISH AND REALITY

The following ten topics serve to illustrate the difficulties and the approaches to solutions.

2.1. Ventilation concepts

In the past, tunnels were equipped with distributed exhaust extraction systems. At the time, the extraction process was homogeneous over the length of a whole section. People were so confident in the concept that the smoke layer should be extracted under the ceiling that, in general, little provision was made for escape doors in such tunnels. Distances of 3 km and more between exits were considered sufficient. Although some critical spirits expressed doubts during the 1990s as to whether this method of ventilation with fixed openings at intervals of around 10 m in the false ceiling would prove effective in the event of fire. However, despite the positive experiences already available at the time (e.g. from Austria), it took a great deal of persuading to bring about the change to extraction by means of controllable dampers. In December 1998, the Federal Roads Office (FEDRO) began drawing up the Road Tunnel Ventilation Directive (the directives and the technical manual for the equipment for operation and safety EOS can be downloaded from www.astra.admin.ch). Since the year 2000, the directive has served as the binding basis for ventilation conception and design. The changeover was hastened by the fatal tunnel incidents at the turn of the century, which revealed that the earlier concept of efficient smoke extraction was an illusion.

All of the foregoing is now familiar and has come to be seen as self-evident in the meantime. However, there is at least one argument against the ‘mechanisation of the false ceiling’ which cannot simply be brushed aside. It has to be recognised (i) that the clearly improved extraction at the scene of the incident depends on a means of detection that is both rapid and precise, plus extremely reliable maintenance of the damper system and (ii) that if wrong dampers open in the event of an incident, there can be fatal consequences, with the smoke being actively carried over sections with tunnel users. The problem is not a trivial one and it must not be underestimated, particularly in the case of concepts with dampers that remain open in normal operation which again demands perfect maintenance. .

2.2. Detection

Nowadays, heat detection with linear sensors under the tunnel ceiling is a widely accepted standard. In the past, the adequate response time of this system was called in question and different proposals were made as to how improvements might be achieved with complementary systems.

There is no denying that, in the past—for example in the Gotthard road tunnel—fires were almost invariably first detected by the opacity sensors despite the fact that there is an interval of more than 1 km between these measuring points. Together with the reaction of the mechanical system—the mass of air in the Gotthard tunnel amounting to around 1,000 tonnes—a stationary condition was not established until after around 15 minutes.

In order to permit the expensive ventilation systems to fulfil their appropriate function in good time, FEDRO decided to equip all of the mechanically ventilated tunnels with additional systems capable of detecting cold smoke within one minute. The measurement principle is not defined in the Fire Detection Directive. In the Gotthard road tunnel, such devices have recently been installed at intervals of around 100 m at every exhaust damper. The sensors have exceeded expectations in respect of function security, false alarm rate, maintenance intervals and, not least, cost.

However, a decision to dispense with the thermal line sensors seems unjustifiable because, in an initial phase, it still has to be expected that there will be a long smoke zone. In such an eventuality, a thermal signal can provide a reliable detection of the seat of the fire and the basis for manual intervention and control.

In any event, the evaluation of the smoke sensor signals raises considerable new control requirements. Before a concentrated extraction can be initialised, it is first necessary to ensure that the smoke source is no longer in motion (Figure 1). Moving smoke sources are particularly frequent in the Gotthard as it is a summit tunnel. A method for processing the smoke sensor signals is proposed in the EOS technical manual published by FEDRO.

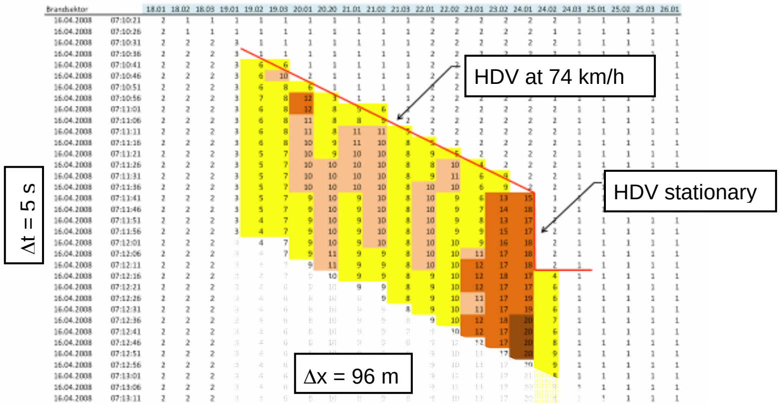

Figure 1: Time-location diagram of opacity from a driving smoke source in the Gotthard tunnel. Δx between rows: 96 m, Δt between lines: 5 s

The cost of installing smoke sensors—usually at intervals of 100 m (up to a maximum of 300 m)—is considerable and, without adequate maintenance, the functionality of the system is limited. In any event, if ventilation is initiated too late, the hazard for the tunnel users could be even worse than with no ventilation at all.

2.3. Air flow measurement

The measurement of an airstream with a velocity of ± 0.2 m/s represents no great challenge under laboratory conditions. However, it is an illusion to assume that the results can simply be transposed directly to a tunnel, where the issue in question is the mean velocity in the traffic space. The difficulties of achieving a reliable air flow measurement are numerous, ranging from the problems of the positioning of the sensors in the traffic space, through electronic difficulties, to problems of the concept.

In most incidents, the ventilation has to be adjusted in accordance with the values measured in the traffic space at the time. As a consequence, in Switzerland the plausibility of the air flow data has to be tested on the basis of three independent measurements. As a fallback, it is possible to make use of the less precise measurement of the pressure measurement at the exhaust fans.

2.4. Fire size

As indicated in the introduction, it is in the self-rescue phase that the effectiveness of the safety systems is the focus of attention. However, the discussion and determination of fire size is also important as the basis for the principles for the design of the structure and the equipment for operation and safety. At the present time, there are wide differences between countries in terms of limits, ranging from 30 MW (as in Switzerland) up to 200 MW. However, we need to differentiate and must be careful not to be misled into thinking that a higher requirement in terms of fire size signifies greater safety. If operated inappropriately, powerful jet fans can create additional hazards for tunnel users. In any event, it must not be forgotten that even a smoke source that does not generate heat has to be brought under control.

It is our opinion that the interpretation of fire size—the real art in this domain—must be contained in the design specifications. Even a slight longitudinal gradient in a tunnel sets the temperature distribution and the resulting buoyancy effect as a function of time to a focus of interest. The undifferentiated use of a fire size in any ventilation software can lead to illusory results.

2.5. Interference effects in the aerodynamic system

The design and operation of ventilation systems for tunnels with a small longitudinal gradient and fluid traffic might be considered a simple matter. However, attempts to transpose the design to very long tunnels, to short tunnels or to tunnels with a gradient of over 1.5 % must be treated with special caution.

In the case of long tunnels, the continuous and rapidly changing interference effect resulting mainly from exiting traffic leads to conditions that cannot be controlled in the short-term. A reduction of the indicated speed limit from 80 to 60 km/h would theoretically reduce the interference pressure but it would then last longer. In the case of short tunnels, the length may be insufficient to accommodate the necessary thrust and in addition to maintain interference-free zones. It is an established fact that the consequences to be feared of a fire are not proportional to the tunnel length. In both cases, it is necessary to acknowledge the limits to the effectiveness and, under certain circumstances, even the applicability of mechanical ventilation. In addition to the imperative need for rapid detection to raise the alarm for tunnel users and the reliable control of a ventilation system, there are other possible approaches to solutions, including escape doors at short intervals, or even alternative track routing in the case of a planned tunnel.

2.6. Safety galleries and escape doors

About ten years ago, it became evident that the effect of ventilation systems cannot substitute emergency exits. Hence, the necessity arose to build single-tube tunnels with safety galleries and existing tunnels to be retrofitted. The resulting investment cost is considerable. The FEDRO Directive Ventilation of Safety Galleries requires a low-level permanent operation for the ventilation of safety galleries and, in the event of an incident, an adequate air flow through up to three open escape doors. This gives rise to an over-pressure of around 350 Pa in the safety gallery. The specific fan power to be installed for operation during an incident is about 15 kW/km. The energy consumption for permanent normal operation is very low.

As a result of the decision to put the safety galleries to an over-pressure in order to preclude smoke intrusion and of the requirement that the opening of the escape doors should not be mechanically assisted, it was necessary to make provision for sliding doors.

Figure 2: Sliding escape door - view from the side of the safety gallery

Sliding doors with an opening force of only 60 N at operating pressure have already been produced. In Switzerland, the maximum force is stipulated to be 120 N. Since the Gotthard tunnel was opened 30 years ago, it has been equipped with sliding doors in the traffic space. Today there are certainly escape doors in some tunnels that could not be opened in the event of an incident, due to pressure differences generated by fans and the residual traffic. The tests for the necessary opening force can be carried out properly only under real operating conditions.

2.7. Recirculation of smoke

From exhaust opening to the portal

Ventilation systems using single-point extraction without a mechanical air supply draw in air from the outside through the portals.

It has been shown that the positioning of portals and exhaust openings can be a tricky matter. If smoke in the tunnel suddenly comes from the direction in which the user has been expecting fresh air, the effect can be, to say the least, unsettling.

Figure 3: Left: South portal of Gotthard tunnel during the 2001 fire. The distance between portal and stack is 70 m. Right: Test with cold smoke at Islisberg tunnel, jet speed of 20 m/s

Between portals

In longitudinally ventilated tunnel systems, the smoke is expelled through the exit portal. To ensure that a second tube and thus the escape routes remain smoke-free, the air flow is reversed into this second tube. However, the process can take a few minutes. For this phase, structural measures are indispensable to prevent any recirculation between the portals, an arrangement that is also favourable for normal operation.

From portal or exhaust opening to safety gallery

The air intakes for the ventilation of the safety galleries are located at the two exits. The exits are equipped with locks for a permanent over-pressure. The safety gallery exits and, in general, the traffic space ventilation station are situated close to the portals of the single-tube tunnel. It is necessary to ensure that smoke is not drawn into the safety gallery, which can be achieved by a favourable positioning of the air intakes of the safety gallery or by means of smoke detection in the area of the suction intake and subsequent adequate ventilation reaction.

2.8. Exhaust duct leakage

In the past, there was hardly ever any question about the leakage, e.g. between supply and exhaust air duct or between traffic space and exhaust duct. With the deployment of controllable exhaust dampers the sufficient seal between the exhaust duct and the traffic space became important. Recent measurements have demonstrated the relevance for new tunnels of the indications concerning duct leakages contained in the Road Tunnel Ventilation Directive.

Considerable importance attaches to the often underestimated supplementary requirement that the maximum under-pressure in the exhaust duct as compared with the traffic space must remain restricted to 2.5 kPa. Technically, it would be feasible to achieve under-pressures of up to 5 kPa but this would considerably increase the leakage flow and thus lead to an undesired difference in longitudinal air flow in the traffic space.

2.9. Complexity of ventilation control

A major difficulty in the design of ventilation control systems lies in harmonising the automatic responses of the system to the multitude of possible incident scenarios. Designers of control processes often try to cover a vast number of eventualities. However, the increased complexity of the system is paralleled by an increased risk that an incident will be accompanied by unanticipated conditions and system failure. What we need to avoid is system reactions that could place tunnel users at risk.

We must follow the principle that the only acceptable system is one that the technical specialists consider transparent and testable and that offers an appropriate service life.

2.10. Cost savings

As financial resources are restricted, we are under an obligation to keep expenses down. The main method used in this regard is currently risk analysis but the theoretical and pragmatic approaches have yet to be standardised. At the same time, attempts are being made to define requirements and to rationalise processes. The essential aspect here is that field personnel responsible for operation are involved so that the terms of reference do not simply appear from someone's desk. In Switzerland, the national road network is on the point of completion. Thus, for the future, the crucial task will be to ensure that the infrastructures provided continue to be properly maintained and to function perfectly. In the event of any incident, danger could arise if active components like exhaust dampers or ventilation controls have not been appropriately serviced and integrally tested.

For the future, maintenance costs are expected to rise considerably. In today's world, it is a badge of distinction for the manager if he is able to obtain a certain performance for the lowest possible price. With a price weighting of 50% and more, contracts are hardly going to be awarded on the basis of quality criteria. Moreover, once the work has begun, it is extremely difficult if not impossible to exert pressure for changes or to make corrections.

3. CONCLUSION

There have been great changes in the tunnel ventilation field over the last ten years. For those who have to deal with these tasks daily, the new requirements quickly become self-evident. Today, facilities are planned and constructed on the basis that the structure concerned will have a service life of 50 years or more. Nevertheless, it is only to be expected that, with changing parameters and new knowledge, we may well look back and, with hindsight, call in question some of the things that presently appear to be self-evident.

Since predicting the future is an uncertain science, our best approach is to be critical of the requirements and objectives that are set; to be self-critical with the specific solutions that we propose as engineers; to be consistent with the concepts for solutions; and to be communicative in order to allow and, where applicable, to accept outside criticism. If we can do all of this, we will be able to get rid of illusions and to increase the safety of tunnel users.

HIGHWAY AND TUNNEL CONTROL CENTRE S35 AT BRUCK/MUR AND SAFETY STANDARDS FOR TUNNELS ALONG THE S35 EXPRESSWAY

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ASFiNAG Bau Management GmbH

ABSTRACT

ASFINAG is responsible for all planning, financing, construction, maintenance, operation and toll collection for the entire Austrian highway and expressway network - approximately 2,135km of roadway including 160km of tunnels and 2010km of bridges.

The construction programme for the current period, which runs through 2013 and has been confirmed by the overseer of ASFINAG, provides for about 7.8 billion Euro in investments into the expansion of the Austrian high-speed roadway network.

Simultaneously there is a need for expanding the existing roadway network as well as construction of new highway and expressway sections due to ever increasing traffic volume. ASFINAG Bau Management GmbH is planning and constructing both new high-speed roadway sections and second tunnel tubes for existing tunnels such as the section between Mixnitz and Bruck/Mur on the expressway S35 which is currently being completed.

The Austrian high-speed road network is operated by means of control centres, such as the control centre at Bruck, which are staffed round the clock. The construction of such control centres is overseen by the ASFINAG Bau Management GmbH.

1. INTRODUCTION: KIRCHDORF TUNNEL AND KALTENBACH TUNNEL

In May 2010 ASFINAG will open the second construction section of the expressway S35 Brucker Schnellstraße between Stausee Zlatten and Mautstatt (see Figure 1). The aims of this project are increased safety for roadway users and improved traffic flow. In addition, disturbances related to transit traffic for people living in the surrounding area will be significantly reduced. This expressway section (Stausee Zlatten – Mautstatt) is about 7km long and includes centrally two twin-tube tunnels, namely Kaltenbach Tunnel and Kirchdorf Tunnel, the construction of which is being carried out according to national and international standards and regulations.

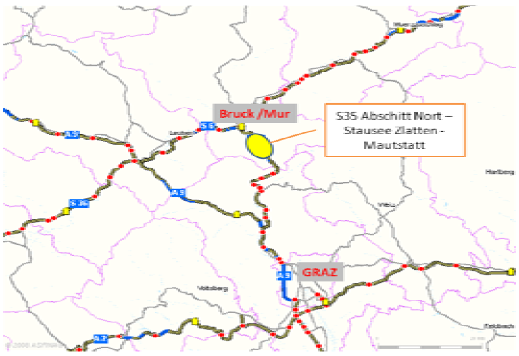

Figure 1: S35 construction section Nord Stausee Zlatten - Mautstatt

2. OPERATION AND TUNNEL SAFETY EQUIPMENT OF THE KIRCHDORF TUNNEL AND THE KALTENBACH TUNNEL

The operation and safety equipment for both the Kirchdorf Tunnel and the Kaltenbach Tunnel are to be planned observing parts of the following national guidelines for road construction (RVS[1]:) in addition to international regulations (EU Directive)

Austrian Road Tunnel Safety Law	
Operation and Safety Tunnel Equipment	RVS 09.02.22
Ventilation Tunnel Equipment - Fundamentals:	RVS 09.02.21
Ventilation Tunnel Equipment - Calculation of Air Requirement	RVS 09.02.32
Tunnel Equipment- Lighting:	RVS 09.02.41
Tunnel Equipment – Radio Communication:	RVS 09.02.61

The current AADT for the local federal road is approximately 18,000 vehicles per 24 hour period, 20% of which are heavy transport vehicles. The traffic volume for 2017 is expected to be about 22,700 vehicles per 24 hour period. Due to these traffic estimates the Kaltenbach Tunnel and the Kirchdorf Tunnel are assigned as danger class II and danger class III respectively according to the Austrian RVS guidelines.

As the two tunnels are located very close to each other – only about 300m separates them – all facilities of both tunnels are designed in compliance with RVS 09.02.22 for danger class III.

The Kirchdorf Tunnel is a unidirectional tunnel; the first tunnel tube in the direction of Bruck is 2,647m long and the second tube in the direction of Graz is 2,787m long. Each tube has been equipped with two breakdown bays. The tunnel tubes are connected with a total of ten cross connections, eight of which provide the possibility for people to use and two may be used by emergency vehicles. The distance between the cross connections is on average about 250m. Both tubes are provided with 45 emergency phone areas (niches) which are spaced 120m apart. The IP emergency call system can be operated from both the local operation centre and the control centre at Bruck. In addition to the possibility for an emergency call from an enterable call box, people in need of assistance can trigger a SOS or fire alarm by pressing a button.

In both tubes, 49 fire extinguisher niches are arranged at regular distances of about 125m; they are equipped with hydrants and hoses of approximately 100m length with spray nozzles and there is also a power supply. In the breakdown bays, so-called wall hydrants containing foam admixes are installed. This facility essentially consists of a 60m long hose on a spool, a fire extinguishing foam dispenser and a spray unit.

When the door of the emergency call cabin or the fire extinguisher cabin is opened, a camera in the control centre at Bruck is automatically switched on. Making an emergency call, taking down a fire extinguisher or pressing an emergency button (fire and/or SOS) initiates the respective control programmes which start measures of various levels ranging from the imposition of speed limits to the complete closure of both tunnel tubes. In addition, various events such as traffic congestion, a driver driving in the wrong direction, smoke in the tunnel, vehicles in breakdown bays, etc. can be automatically detected by means of cameras which are installed at maximum distances of 125m.

The road pavement within the tunnel is made of concrete and the driving lane is bordered by two elevated hard shoulders which are demarcated using LED reflectors. If specific events occur these reflectors start blinking, either only in a certain section of the tunnel or over the entire tunnel length. Up to a height of four metres the tunnel side walls are coated with a clear

[1] Prepared and issued by the Austrian Association for Research on Road, Railway and Transport, Karlsgasse 5, 1040 Wien

light-reflecting coating which can be easily cleaned. In addition emergency exit lights and highly reflecting emergency exit signs indicating the distance from the two nearest cross connections are installed in the walls at distances of respectively 50m and 25m in both the tunnel entrance and the exit area. In the tunnel interior zone the emergency exit signs are also spaced 25m apart.

Both tunnel tubes are equipped with tunnel radio facilities which can be used by the emergency services, the ASFINAG operating staff and traffic broadcast services.

The Kirchdorf Tunnel is equipped with a longitudinal ventilation system providing ten jet fans per tube, each of them having a power rating of 22kW and producing a shear force of 875N. The functioning of these ventilators at temperatures exceeding 400°C must be guaranteed for a time period of at least two hours. The appropriate functioning of the ventilation system is regulated by carbon monoxide and visibility measurements as well as by measurements of the longitudinal airflow. On the one hand, the ventilation system provides for overpressure in the tunnel tube which is not affected by the fire in order to prevent smoke from entering the tunnel tube and the cross connections. On the other hand it guarantees optimal stratification of hot smoke gases in the tube affected by the fire allowing people to escape exiting via the nearest cross connection.

The Kirchdorf Tunnel is the first tunnel in the world to be equipped with an acoustic monitoring system. In recent years the Austrian Research Association “Joanneum Research” in Graz in collaboration with ASFINAG has been testing a pilot acoustic monitoring system in the Plabutschtunnel. This pilot system is intended to collect specific sounds and then save them in a database. In addition, in different tunnels various tests have been carried out and recordings made (e. g. a vehicle crashing against the tunnel wall) and the resulting sound data was entered into the database. This allows for real-time classification and evaluation of different events on the basis of characteristic sounds. After a specific sound has been detected several cameras automatically activate within the detection area. The sounds are detected by means of 54 microphones installed at an average distance of 100m. The evaluation is performed in the operation centre by comparing the relevant data with the archived data in the database; the results are then sent to the tunnel control system. On the basis of a decision matrix, the associated cameras are switched on automatically by the tunnel control system. Taking the relevant video information into consideration the tunnel operator chooses the appropriate control mode, in the worst case initiating a total closure of the tunnel.
The tube of the unidirectional Kaltenbach Tunnel in the direction of Bruck and that heading towards Graz have a length of respectively 1,014m and 1,109m and are equipped with breakdown bays; they are connected with each other by a total of four (4) cross connections at distances of about 230m. One (1) cross connection is intended for emergency vehicle use.

The equipment is principally the same as that of the Kirchdorf Tunnel but with differing numbers of emergency call niches (19), fire extinguishing niches (21), cameras (48), cross connections (1 EQ) and jet fans (14) used for tunnel ventilation.

ASFINAG has prepared special planning manuals which are intended to complete the national guidelines specifying in detail the facility designs defined in the applicable guidelines. In issuing these planning manuals, ASFINAG pursues the aim of setting an Austria-wide standard with regard to the design and the application of safety equipment for roadways and tunnels, streamlining operation, maintenance and operator training as well as inventory control for replacement materials. For example, the planning manual “Ventilation PLaPB 800.542.10” defines the requirement for only six standardised ventilators for longitudinal ventilation systems. All ventilation systems have to be designed and set up observing the regulations contained in the national guidelines RVS 09.02.31 and RVS 09.02.32, in addition the utilisation of the types of ventilators prescribed in the planning manual.

3. INTRODUCTION: CONTROL CENTRE AT BRUCK/MUR

The control centre at Bruck has been in operation since 1984. Until today all tunnel structures on the expressway S6 Semmering Schnellstraße between St. Marein and Leoben East and the open sections (i.e. the emergency call system) of the expressways S35 Brucker Schnellstraße and S36 Murtal Schnellstraße has been controlled from this centre. There are six (6) twin-tube tunnels (i.e. Tanzenberg, Bruck, St. Ruprecht, Oberaich, Niklasdorf and Massenberg) on the section of the S6 specified above. The section between St. Marein and Gloggnitz of the S6, including the tunnel structures Semmering, Spital, Steinhaus and Ganzstein, are currently controlled by the control centre at Mürzzuschlag.
The section of the A9 highway between Kalwang and the junction Deutschfeistritz/Peggau, including the tunnels Wald, Pretall, Gleinalm and Schartnerkogel, are currently monitored and controlled by the control centre at Gleinalm (Figure 2).

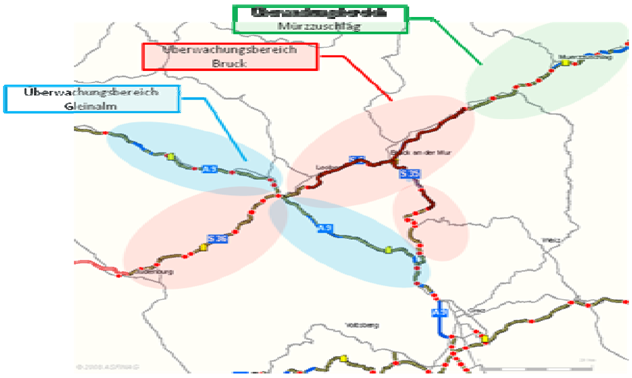

Figure 2: Monitoring and oversight areas

In 2005/2006 a study defining the pros and cons of consolidating the above mentioned control centres was carried out. On the basis of this research, ASFINAG prepared a new operation model envisioning the creation of a central control centre in Bruck for all monitored areas. Hence the new control centre at Bruck is to oversee both the existing and the planned new roadway sections as shown below (Figure 3).

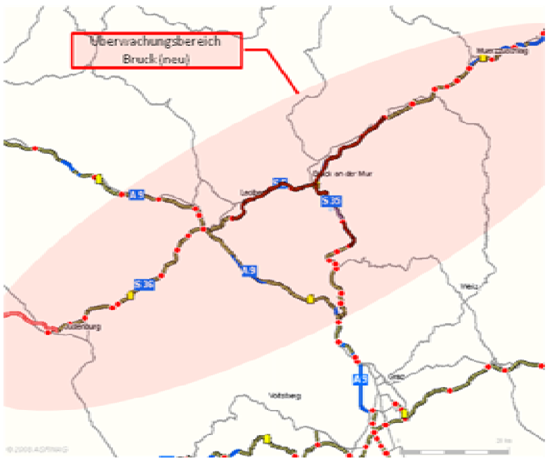

Figure 3: Area monitored by the control centre at Bruck after completion of the roadway network

Thus the new control centre at Bruck will monitor open roadway sections[2] with a total length of approximately 218km and tunnel sections having a total length of about 71.01km including 30 tunnel tubes[2].

This means that, after the completion of the planned roadway, the control centre at Bruck will be the second only to the control centre St. Jakob in Tyrol as to the length of the Austrian roadway network monitored.

In planning the control centre at Bruck, extensive research has been carried out focusing on ergonomic design, lines of sight and operating cycles (Figure 4 and Figure 5). The operating staff defined the most frequent operating cycles and weighed them by percentages. Then the lines of sight were analyzed along with the types of monitors needed to carry out operations with optimal arrangement of the monitors.

The findings of the research together with the expansion of the areas to be monitored suggest the need for eight process control monitors per operator (instead of four, as was used previously) as part of their immediate workspaces.

Due to the expansion of the area to be monitored (tunnels and open roadways) the control centre is now staffed by two operators and also has an additional workplace.

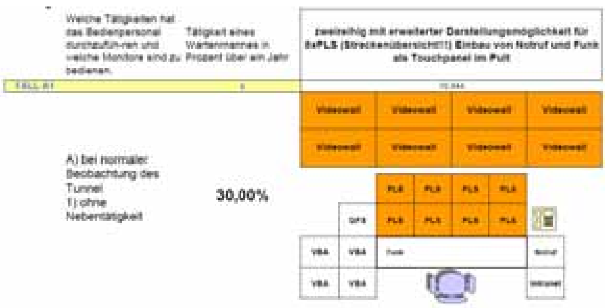

Figure 4: Monitoring without incidents

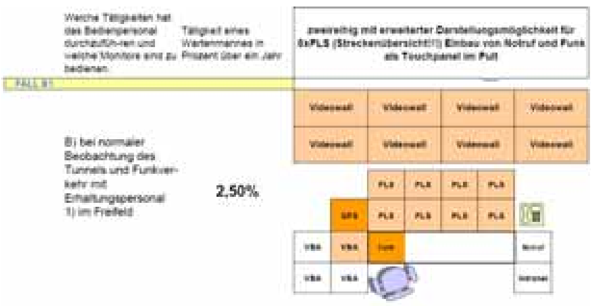

Figure 5: Winter service without incidents

The new facility arrangement of the control centre has three workplaces, two of which are staffed round the clock and one for the supervisor.
In front there is a video wall including 16 (2 rows of 8) 70” monitors for the display of both video images and data visualisation (Figure 7).
All three of the operating desks are ergonomically designed and adjustable for height in order to guarantee optimal desk fit and monitor height for the operating staff and supervisor.
Operators are free to choose whether to do their work standing or seated and can adjust the angles and height of the monitors.

[2] After completion, taking into account the section of the S36 between Judenburg and Scheifling and the second tube for the Gleinalm Tunnel

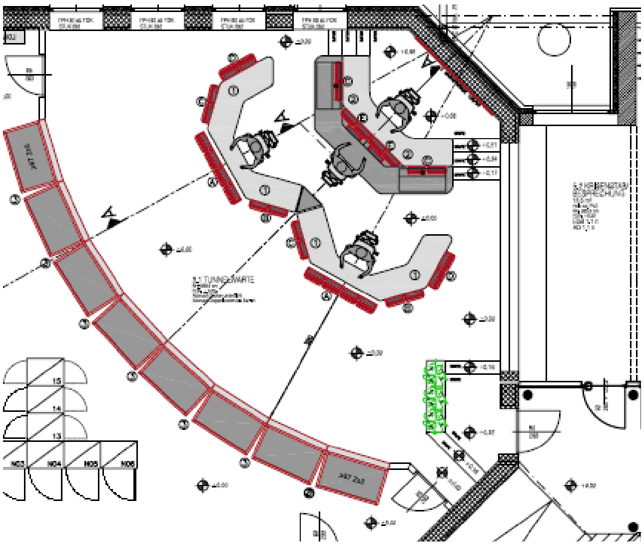

Figure 6: Overhead view of operating stations for operators and supervisors with video wall

In order to comply with all requirements and regulations contained in the applicable standards, a model desk was assembled for assessing both correct lines of sight and sitting positions. An expert in ergonomic design was involved as a consultant throughout the planning of the control centre. This was particularly important for the overall design and the graphic set-up of the entire screen layout focusing on colour design for images and distance-based type sizes in compliance with the regulations.

The construction of the entire addition to the existing control centre has been carried out without causing any traffic restrictions in the monitored areas.

The existing control centre equipment was temporarily put into storage while the modifications to the control centre were carried out as described below:

Figure 7: Model desk

As the Tanzenberg, Bruck, St. Ruprecht, Oberaich, Niklasdorf and Massenberg tunnels had previously been provided with redundant connections to the control centre at Bruck, a parallel operating facility could be set up before establishing the temporary control centre. This was done by installing a gateway in one of the redundant connections through which the existing data were transformed into the IEC standard protocol 60580-4-104 in order to transmit them to the control centre at Bruck via the fibre optic cables of the ASFINAG telecontrol system.

At the same time the processor designed for the new control centre which already contained the future visual data representations was installed in the temporary control centre.

After putting the processor into operation in the temporary control centre, the data connection to the existing control centre was cut and the facilities were completely disassembled in order to install the new facilities in the room.

As the new connections to the control centre are likewise redundant and there are three fully equipped operating desks, the new control centre could at the same time be put into operation after installing additional processors.

The new control centre at Bruck was completed and put into operation in August 2008 (Figure 8); it then started monitoring the section between St. Marein and the junction at St. Michael of the S6 expressway.

The new control centre includes a crisis intervention room which is located directly adjacent to the monitoring and control room; it is acoustically separated by a glass wall in order to provide a good view of the video wall for the emergency services personnel who may ask the operator for specific TV images of the tunnel concerned. (Figure 9).
All radio services can be operated from the crisis intervention room.

Figure 8: Control centre at Bruck

Figure 9: Crisis intervention room

In 2008/2009 the monitoring system of the renovated Tanzenberg Tunnel was completely integrated into the control centre; this required no more effort than carrying out adaptations in terms of data and visualisation systems. Likewise the remaining tunnels (i.e. Bruck, St. Ruprecht, Oberaich, Massenberg and Niklasdorf), which will be completely refurbished within the current period which runs through 2014, will also be integrated.

As provided for in the ASFINAG protocol, all tunnel structures are connected to the control centre via an interface (the so called “tunnel head”) installed in the respective operation centre which transmits the relevant data in the form of an IEC protocol to the control centre.

The integration of the Kirchdorf Tunnel and the Kaltenbach Tunnel on the expressway S35 Brucker Schnellstraße has been carried out in the same way, i.e. the connection to the control centre functions via an interface installed in the operation centre.

In summer 2010 the Semmering Tunnel Chain (currently monitored by the control centre at Mürzzuschlag) as well as the both the Gleinalm Tunnel and the Schartnerkogel Tunnel (currently monitored by the control centre at Gleinalm) will be integrated into the control centre at Bruck.

Lastly the section between Judenburg and Scheifling and the second tube of the Gleinalm Tunnel will be completed and integrated into the control centre at Bruck which will then be in full operation; a summary of the information is listed below:

	Tunnel tubes with unidirectional traffic.	Tunnel tubes with bidirectional traffic.	Total tube length [km]	Emergency call devices	Cameras	Open roadway [km]
S6 Semmering Schnellstraße:	28		35.38	188	403	88.5
S35 Brucker Schnellstraße:	5		8.23	84	139	36.0
S36 Murtal Schnellstraße:	10		8.30	103	108	58.0
A9 Pyhrn Autobahn:	4		19.10	97	140	36.0
Total	**47**		**71.01**	**472**	**790**	**218.5**

With this I would like to close my presentation. Thank you for your attention.

ON THE SAFETY OF SHORT ROAD TUNNELS

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ABSTRACT

Many road tunnels are comparatively short and a large number of them are in the range of 500 to 1’000 m of length or shorter. Such tunnels are typically longitudinally or naturally ventilated and have emergency exits at a distance in the range of 300 to 500 m. The detailed specifications vary from country to country. Risk analysis and experience show, that the safety level of such tunnels is frequently unsatisfactory, particularly in case of bi-directional traffic and tunnel slopes in the range of 2-3% or higher. This is basically related to the short time scales characterizing such tunnels, which can result in extremely rapid smoke propagation. This was tragically demonstrated e.g. in the fire in the Viamala tunnel (16 September 2006), on the Swiss A13 motorway.

The present papers reviews some of the characteristics and safety-relevant weaknesses of the current design approaches for short tunnels, based on our design and design-support experience. We strongly feel that the current, guideline-oriented approaches need to be enhanced by genuinely risk-based methodologies, which allow for a clear identification of weaknesses and possible solutions. A further potential for improvement can be identified at the level of SCADA systems: faster and more integrated, “intelligent” automatic responses of all tunnel’s equipment will be provided by next generation’s SCADA technologies which are currently developed within the EU research project EMILI.

Keywords: short road tunnels, safety, ventilation, SCADA

1. INTRODUCTION AND OBJECTIVES

Most tunnels are short or very short, as illustrated in **Figure 1**. Roughly 75% of the Swiss tunnels are shorter than 1 km (representing roughly 30% of the total tunnel length) and 60% shorter than 500 m (representing roughly 15% of the total tunnel length). Data for other countries are provided e.g. by Lotsberg (2009). Such tunnels frequently represent a problem from the point of view of safety. Several quite obvious reasons are well know also laypersons: the higher accident rate in the immediate vicinity of the portals, where the environment conditions for the driver change very rapidly, the reduced equipment (e.g. radio, ventilation, water supply, CCTV etc.), the sometimes reduced availability of escape routes etc.

More subtle reasons for this situation are related to the particularly small time scales characterizing short tunnels. The air velocity and smoke propagation patterns in the tunnel change very rapidly depending on traffic, ventilation modes, thermal effects, portal wind etc. Many short tunnels, particularly in the Alpine range, have a significant slope. They are therefore particularly sensitive towards the local heating by the fire, which can generate a violent “stack-effect”. As it will be shown below, these problems are accentuated by the limited usefulness of ventilation in very short tunnels. Tunnels with bidirectional traffic are obviously particularly challenging.

The risks related to short tunnels are frequently underestimated. Because of this misperception, joined with the objective difficulties raised by the large number of such tunnels, necessary upgrades are frequently delayed or reduced.

Some of the specific risks related to short tunnels are discussed in the present papers and possible paths for improvement are outlined.

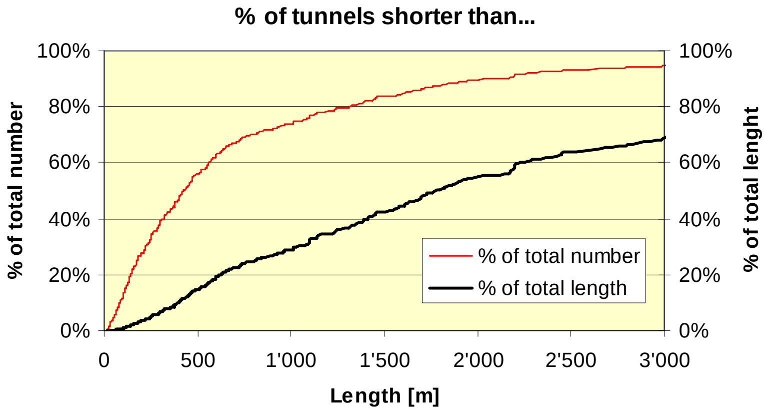

Figure 1: Length distribution of Swiss tunnels, presented as the percentage (based on number and on length) of tunnels shorter than a certain value (data from Lotsberg 2009).

2. THE FIRE IN THE VIAMALA TUNNEL

The safety problems related to short, steep tunnels were tragically demonstrated during the Viamala tunnel fire, on the Swiss A13 motorway (16 September 2006). The key data of the tunnel - opened in 1967 and thoroughly retrofitted in the past few years – are not particularly unusual: length 760 m, slope 5% (North to South), bi-directional traffic on two lanes, about 8’000 vehicles/day, longitudinal ventilation, no emergency exits.

Figure 2: The fire in the Viamala tunnel (16 September 2006).

The fire developed at about 100 to 150 m from the lower North portal. It was originated by a collision between a coach and a car and rapidly involved both vehicles and a second car. According to the whiteness’s reports fire was instantaneous and smoke propagation was extremely rapid (values up to 10 m/s were reported). 9 persons tragically died in the smoke (among them a young family and the persons who died while heroically trying to save them, Claudia Coduri and Francesco Franciamore). Nevertheless 21 persons from the coach and about 20 cars succeeded to escape from the tunnel. Numerous car drivers behind the accident site left the tunnel through the South-portal turning their vehicles. As the tunnel alignment is a long S-shape curve many people could not see the other portal and the accident site. Further details on the fire are reported e.g. by the Tiefbauamt Graubünden (2006) and Mundwiler (2007).

The most striking aspect of the Viamala fire is that the tunnel's equipments were essentially in line with the current Swiss requirements (FEDRO 2000) and performed as expected. The fire was signaled at 13:13 by the fire-detection system and immediately confirmed by a phone call and the use of a fire extinguisher, the alarm was correctly transmitted and the automatic measures immediately initiated (maximum lighting, emergency lighting, tunnel closure, jet fans activation and CCTV images transmission). The radio broadcast of the alarm did not work properly. The rescue teams were on site about 10 minutes after the receiving the fire alarm and reported heavy smoke exiting from the southern (higher) portal and smoke-free conditions at the northern extremity (Mundwiler 2007).

Why this tragic outcome, if almost everything worked properly? The main reasons could be identified as follows:

- Rapid fire evolution caused by ignited fuel during the collision ("Fire broke out in five seconds").
- Extremely rapid smoke propagation (velocity up to 10 m/s) and complete loss of stratification.
- Wrong user's behavior with fatal consequences was observed.

The main lessons to be learned from this tragic tunnel fire are:

- Self rescue by the concerned tunnel users is crucial and must begin very quickly.
- The involvement of a coach with many people on board had a huge potential towards higher consequences. Fortunately only two persons from the coach died. 6 victims traveled in a car, one was a truck driver.
- 150 m to walk in heavy smoke towards the north portal was a too long distance for some of the victims.
- Even the short reaction time of the fire services, of the order of 10', was too long for most of the tunnel users.
- A public dispute about permissibility of U-turning cars and escaping from the tunnel rose. In the Viamala case this fact might have limited the number of victims.

3. SMOKE PROPAGATION

The key elements affecting smoke behavior in road tunnels are:

- Traffic.
- Thermal effects (natural temperature differences, fire heating).
- Meteorological effects (portal wind).
- Mechanical ventilation.

The influence of thermal effects increases with increasing tunnel slope. Tests and real fires showed that in case of fire the temperature increases significantly only over a distance of 500-1'000 m. Thermal effects act therefore faster and have a larger effect on the air and smoke motion in short tunnels, as illustrated in **Figure 3**. In shorter tunnels significant longitudinal velocities are achieved even with moderate slopes of the order of 2% (**Figure 3** left). Similarly, the time scales for the velocity development are of the order of only 2'-3' for short tunnels, as compared to 4' and more for tunnels of 2 km and longer (**Figure 3** right). Even faster developments can be expected in case of a faster fire dynamics, such ad the one observed in the Viamala case. Similarly, short tunnels can be extremely sensitive towards external wind portal loads.

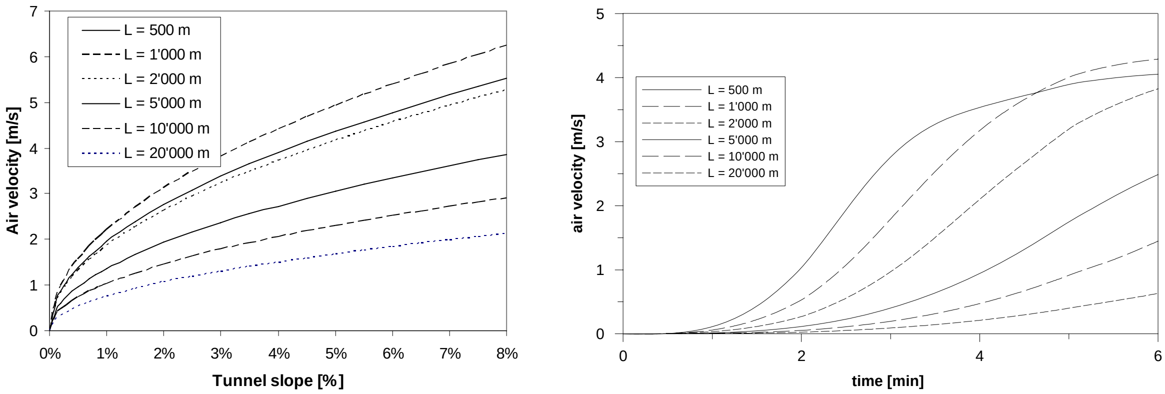

Figure 3: Longitudinal air velocity generated through a 30 MW fire (devel. time 5'), without mechanical ventilation. Left: Peak vs. tunnel slope; Right: Time development (slope 5%).

A simple example can illustrate the combined effect of traffic and thermal effects, **Figure 4**. Let us consider a 760 m long tunnel with a uniform slope of 5% and a moderate traffic volume, in both directions 600 vehicles/h, 80 km/h, 10% HGV. A "standard" HGV fire located at ¼ of the tunnel length is modeled as follows: 30 MW fire, with a linear increase of heat-release rate between 0 and 5', followed by a 60'-long phase with constant heat-release rate. The traffic is stopped 2' after ignition. Note that this setup does not correspond to the Viamala case.

The results, assuming no mechanical ventilation, are presented in **Figure 4** (simulations were carried out using the 1D code TunSim, Bettelini, 2008). During the initial 1'-2' the scenario is dominated by the traffic, but the "stack-effect" becomes rapidly dominant. Conditions for self rescue are clearly very unfavorable. On both sides of the fire smoke propagation is faster than the expected escape velocity.

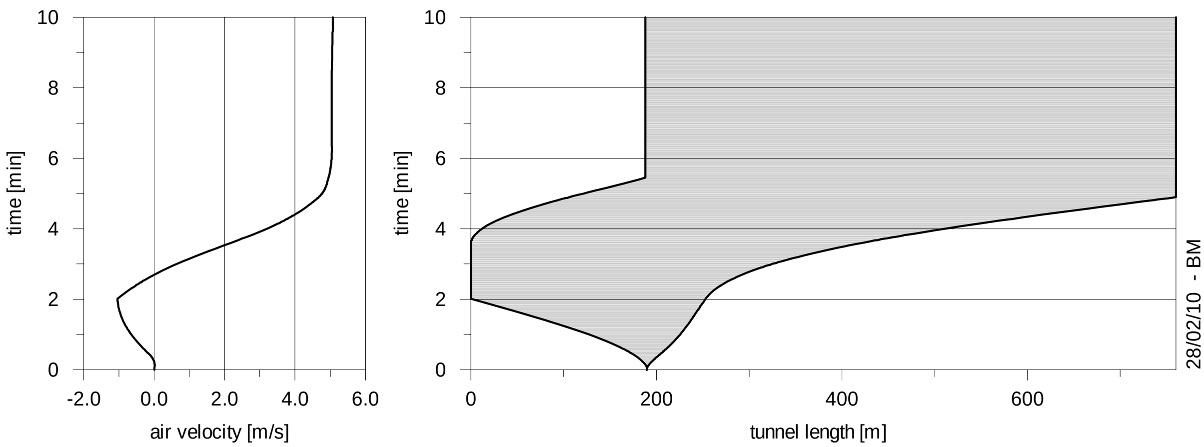

Figure 4: Longitudinal air velocity in the tunnel (left) and smoke propagation (right). The tunnel is rising from left to right, 30 MW fire, no mechanical ventilation.

The very short time constants relevant for tunnel aerodynamics and smoke propagation in short tunnels, of the order 2', impose extremely strict constraints to all tunnel safety facilities: detection, system's response, escape etc.

4. TUNNEL EQUIPMENT

The safety requirements for Swiss tunnels are stated in the norm SIA 197/2 (SIA, 2004) and in a number of directives developed by the FEDRO (Swiss Federal Road Authority). Full requirements are applicable for tunnels longer than 600 m, reduced requirements starting with 300 m. For tunnels between 300 and 600 m, CCTV equipments and radio (communication and broadcast) are not mandatory.

The minimum requirements from the European Directive 2004/54/EC apply only for tunnels longer than 500 m and full requirements are applicable only starting with 1’000 m. The situation in other countries was reviewed e.g. by Day (2004) and Kim et al. (2008). Details are not relevant for the present purposes.

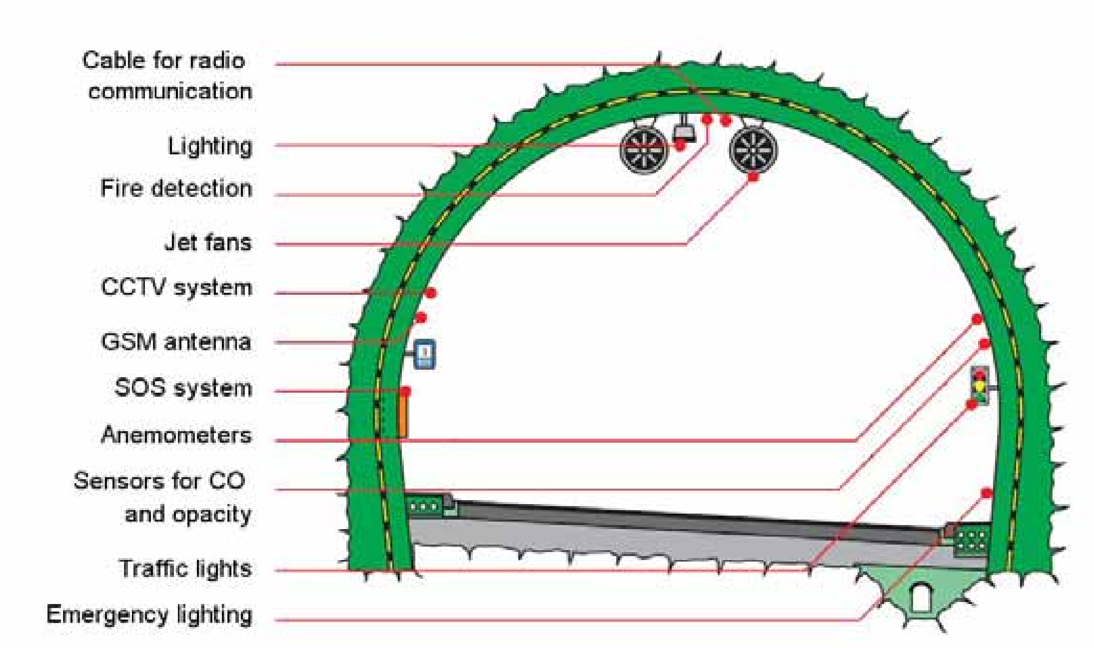

Figure 5: Typical equipments according to the Swiss guidelines for short tunnels (adapted from Tiefbauamt Graubünden, 2006).

Based on the considerations exposed in the previous chapters, the key elements for a successful emergency management in sort tunnel are:

- Very early detection of fire principles certainly represents the most fundamental requirement. The currently used systems are: linear thermal detectors, discrete smoke detectors and CCTV with automatic detection. These systems reacts to different types of events (Liu et al., 2009) and the combination of such signals is certainly the key for rapid, error-free detection. At least two of the three systems should be present in every short tunnel.
- Rapid and precise user information represents the second key step. This is mostly based on radio broadcast of emergency information. While very effective, integration of this equipment with loudspeakers and VMP should be considered in short, steep tunnels.
- Ventilation and emergency exits are treated in separate chapters. The exigencies on other equipments are similar as for longer tunnels.

5. THE VENTILATION DILEMMA

Fire ventilation is straightforward in case of unidirectional traffic without congestion. All available jet fans are activated in the direction of traffic with the goal of exceeding the critical velocity and preventing smoke spread in the upstream direction.

A number of test cases were discussed by Zumsteg and Steinemann (2006) from the point of view of ventilation. As expected, the analysis showed that ventilation alone cannot meet the challenges imposed by short, high slope tunnels with bidirectional traffic. Effective fire ventilation in short bidirectional tunnels (or, similarly, in case of congestion in unidirectional tunnels) is almost impossible during the evacuation phase, for the following reasons:

- Rapidly changing forces acting of the tunnel's air require a delicate control.
- Anemometer's readings could be faulty because of the presence of smoke.
- The activation of jet fans will in many case destratificate the smoke and dramatically reduce the visibility level.

Numerical investigation of fire scenarios represents an instructive exercise. **Figure 6** shows a possible ventilation strategy for the tunnel presented in Chapter 3, with minimization of the longitudinal air velocity. These and many other results are clearly not satisfactory.

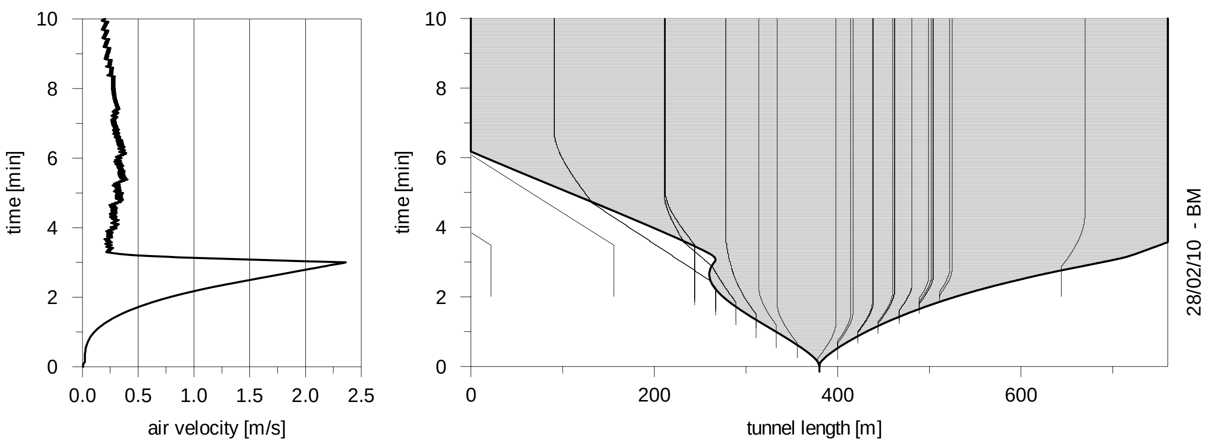

Figure 6: Longitudinal air velocity in the tunnel (left), smoke propagation and representative trajectories of escaping users (right). Conditions are as in Figure 4.

Thus ventilation control during evacuation represents for many short, steep tunnels an irresolvable dilemma. In most cases it will be preferable not to ventilate during evacuation and use the jet fans only for supporting the selected firefighting strategy, after evacuation has been completed.

We therefore must fully agree with the conclusions by an estimated colleague (Day, 2004): "Mechanical ventilation is not a suitable mitigation measure for short road tunnels, particularly those with significant longitudinal gradients; the risks have to be mitigated using other measures such as reducing the spacing between emergency exits."

6. EMERGENCY EXITS AND HUMAN BEHAVIOR

Emergency exits certainly represent the best and most expensive path for increasing the safety of many short tunnels. The directive 2004/54/EC prescribes emergency exits at least every 500 m. The requirements on the maximum distance between emergency exits in Switzerland are more differentiated and stricter (SIA 197/2):

- Maximum distance 500 m for slopes smaller than 1%.
- Linear decrease of allowable distance from 500 m to 300 m between 1% and 5%.
- Maximum distance 300 m in case of separate safety tunnel or cut and cover construction.

In the case of short, steep tunnels the applicable maximum distance between emergency exits will be typically in the range of 300-400 m, depending on slope. A number of older tunnels still suffer from much less stringent previous regulations (ASB, 1983), which prescribed, in case of longitudinal ventilations with jet fans in tunnels with bidirectional traffic:

- L < 1 km: no emergency exits required.
- 1 < L < 1.5 km: one emergency exit or one point smoke extraction in the middle.
- 1.5 < L < 3 km: two emergency exits or a smoke extraction over the whole tunnel length.

The distance between emergency exits has to be assessed based on the comparison between escape time and the time scales of smoke propagation discussed above. Assuming escape velocities in tunnel in the range of 1 m/s (good visibility) to 0.3 m/s (smoke), the escape times are in the range of 2.5’ to 8’ for a distance of 150 m (300 m between emergency exits) and 4’ to 14’ for a distance of 250 m (500 m between emergency exits). This simple estimate shows that the issue is not trivial for short tunnels and a specific analysis is required.

National and international directives dictate only minimum requirements, which must sometimes be exceeded e.g. in the case of large tunnel slopes. The “correct” distance for every particular tunnel must be established based on the overall tunnel setup. This point was made very well in the UNECE (2001) report: “Should the fire scenario analyses (smoke extension and spreading velocity under prevailing local conditions) show that the above-mentioned provisions are insufficient to ensure the safety of the road user, additional measures must be taken. These may involve emergency exits every 200 to 500 metres (or even less), using e.g. short perpendicular escape galleries to the open, when the topography so allows, or a parallel safety gallery.” Additionally, in countries, such as Switzerland, where the choice between different technical solutions for realizing emergency exits leads to different maximum distances (e.g. 300 m with safety tunnel and 500 m with seprate exits), the choice must be risk-oriented.

The technical support for escape (lighting, signalization etc.) is a now well solved issue which does not call for additional comments. Nevertheless, because of recent disappointing experiences, a fundamental aspect must be stressed: emergency doors must be easy to open under all relevant conditions, independently on door type or technical details.

The issues related to human behavior, already treated in great detail by more qualified specialists, shall not be treated here. But it is important to state that in the Viamala fire, as in virtually every other fire, incorrect behavior by part of the user led to unnecessary loss of lives. It is therefore important to stress the importance of rapid and clear information of the users in case of emergency (see also Chapter 4). The awareness of being in a short tunnel could lead to a dangerous underestimation of dangers.

7. THE NEED FOR NEW TECHNICAL SOLUTIONS

Because of the specific needs and issues, short tunnels could greatly benefit from new approaches and innovative ideas. A systematic exploration would exceed the scope of the present work. We will therefore just sketch a few promising ideas:

- New concepts for alarming of the tunnel users, probably based on a combination of audio, voice and visual information would be important for shortening the delay between fire detection and escape.
- For fire cases it is important to reduce the fire intensity and the peak heat-release rate. This could be achieved by automatic fixed fire suppression systems (Bettelini and Seifert, 2009). In short tunnels water mist extinguishing systems have probably a good cost/benefit balance.
- Rapid smoke propagation in short tunnels could be counteracted also by setting up fire compartments. This could be realized by means of flexible solid curtains or by water curtain systems, which either block smoke propagation or reduce the longitudinal air velocity.
- New concepts for providing a fair chance for self-rescue in tunnels with inadequate escape facilities are under investigation. An example is GEPE ("Galerie d'Evacuation Parafumée Escamotable"), which forms a protected escape corridor within the tunnel by means of folding down metallic curtain lamellae.

In our opinion these elements could be very helpful punctually, for solving specific problems, particularly in case of difficult renovations.

8. THE NEED FOR NEW APPROACHES

More advanced approaches are needed at two distinct levels: risk-oriented design and new-generation SCADA systems for the optimum exploitation of the complex tunnel equipments in case of emergency.

The current approach towards tunnel safety is in several countries strictly regulation-oriented. This means that the minimum normative requirements are strictly implemented, but the readiness to implement additional measures, on a case-to-case basis, is lacking. As a consequence, in deep investigations on the safety level are either not carried out or are carried out only in a qualitative manner. We strongly feel, that in-deep, quantitative investigations of scenarios are necessary for any tunnel with significant safety-relevant peculiarities. The software QRAM (OECD 2001), jointly developed by OECD and PIARC for the analysis of the transportation of dangerous goods through tunnels or alternative roads, is an adequate tool in all cases where dangerous goods are not the main concern. If fire is the main concern, this tool proved in the author's opinion too less sensitive towards design optimization.

Existing SCADA systems allow mostly only for a comparatively basic exploitation of the existing tunnel infrastructure (Bettelini, 2008). The large amount of detailed sensor data and the operational flexibility allowed by modern tunnel equipment need an enhanced level of "intelligence" while dealing with emergencies. Because of the pressing time constraints, this can only partially be provided by tunnel operators. The main requirements on next generation's SCADA systems will be (Bettelini, 2008):

- Use all available information, intelligently aggregated, for providing a precise, reliable view of the situation (event characterization, smoke extension and evolution, user's location etc.).

- Make extensive use of rapid “what if” analysis for the (semi-)automatic assessment of different possible courses of action. The physical models shall be sufficiently accurate for allowing reliable investigations, but run within a few seconds. If necessary, the different options will be presented to the operator, with clear recommendations.
- Provide as much automation as possible and provide enhanced man-machine interfaces, for preventing excessive operator’s load through routine operations and allowing him to focus on the really safety-relevant aspects of the emergency.
- Improve the simulation capabilities required for training on real-life emergency situations.

This vision is being developed in the research project EMILI (“Emergency Management in Large Infrastructures”) as part of EU’s Seventh Framework Programme, Theme Security, FP7-SEC-2009-1.

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INVESTIGATIONS ABOUT METHODS TO CONTROL AIRFLOW IN ROAD TUNNELS

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ABSTRACT

For road tunnels with and without smoke extraction, the control of longitudinal airflow is essential in order to limit smoke propagation in case of fire.

Various concepts for the handling of longitudinal airflow have been investigated. These include jet fans, the use of (semi-)transverse ventilation, directed point air injection (Saccardo-nozzles), local air extraction, air curtains and mechanical curtains.

At present, the application of jet fans is the standard solution, but not necessarily the optimum for all applications.

Jet fan installation in the traffic envelope often leads to problems with corrosion and accessibility for maintenance and repair. Jet fans require extra space under the ceiling or in niches. This may lead to high additional costs if jet fans have to be retrofitted during ventilation system upgrades in existing tunnels.

Particular attention is paid to the rededication of existing supply air ducts in tunnels with transverse ventilation systems. Many tunnels of medium lengths were equipped with this kind of system when vehicle emissions were very high and the need to control the longitudinal airflow was secondary. In many of these tunnels, the distributed air extraction is going to be abolished during a safety upgrade and replaced by concentrated smoke extraction through remote controlled dampers. Distributed supply air is no longer needed because for mechanical ventilation in normal operation, concentrated extraction or longitudinal ventilation can be applied.

As these supply air ducts are connected to functioning ventilation stations a new use for them suggests itself which could be an economic application of control of the longitudinal air flow in case of tunnel fires. This leads to the concept of directed point air injection, which is one of the main focuses in this investigation.

Many descriptions of simulations, small-scale tests and real tunnel applications are found in the available literature. The one-dimensional calculation method by application of the energy equation and the balance of momentum is well established and very similar to that used for the design of jet fan applications.

Nevertheless, some decisive parameters are uncertain and depend on the actual layout. To reduce the uncertainties, a series of tests has been performed with a full scale model of a Saccardo nozzle in an existing road tunnel.

The results of the measurements and simulations are in close agreement to the assumptions applied. They enhance the knowledge about the decisive parameters. Limits for the application of point air injection have been identified.

Keywords: Aerodynamics, retrofit, tunnel fire, smoke extraction, ventilation, measurements.

1. CONTROL OF AIRFLOW IN CASE OF FIRE

Immediately after the start of a tunnel fire, the smoke spreads along with the existing airflow in the tunnel.

When using a smoke extraction system, the paramount goal of the fire ventilation is to support the escape of tunnel users by confining the spread of smoke to a limited space. Without effective control of the airflow, this may fail.

Effects acting on the airflow in the tunnel are:

- Traffic, dying away after the start of the fire
- Mechanical ventilation in normal operation, shut down automatically
- Wind on portals, of unknown magnitude
- Barometric pressure differences between portals, of unknown magnitude
- Buoyancy due to temperature differences between tunnel and vicinity, varying
- Buoyancy due to fire heat, possibly increasing
- Inertia of the air column in the tunnel

2. CLASSIFICATION OF AIRFLOW CONTROL METHODS

Airflow control can be classified in two main groups.

Device adds no momentum in tunnel axis:	**Device adds momentum in tunnel axis:**
Air extraction	Jet fans
Undirected fresh air injection	Directed fresh air injection (e.g. by Saccardo nozzles)
Air curtain	Distributed directed injection of supply air
Mechanical curtain	

3. EXPERIMENT

3.1. Objective

At present, a number of road tunnels in Switzerland as well as in other countries are subject to critical review in respect of fulfilling the requirements given by the valid guidelines and state of the art of tunnel ventilation design.

In some cases, the existent ventilation system is oversized by far considering the normal operation due to the massively decreased vehicle emissions. On the other hand, the same systems often lack the capabilities to effectively cater for tunnel fires and the related smoke extraction requirements.

It is intended to refurbish certain tunnels that are equipped with transversal ventilation systems to adapt them to the present requirements.

In some cases, there is no space available for the installation of jet-fans in the existing structures. So the choice is either to carry out massive construction works in order to provide a number of jet-fan niches throughout the tunnel or to search for alternative solutions.

Being a very suitable object to investigate this kind of alternative solutions, the Crapteig Tunnel in Switzerland has been chosen for experiments.

3.2. Description of the Tunnel

The Crapteig Tunnel has been inaugurated 1997. It is 2.2 km long and located on the A13 San Bernardino transit highway between the villages Thusis and Andeer.

The cross section area is relatively large due to 2 lanes going upward from North to South and one lane going downward at a slope of approximately 6.5%. Due to the steep slope, the Crapteig Tunnel is subjected to a discernable stack effect while at the same time the portals are also subjected to wind forces.

At present, the ventilation system comprises distributed fresh air supply for normal operation and distributed smoke extraction in the case of a tunnel fire.

Two ventilation stations close to the portals each accommodate a supply air fan and a dual mode fan. The latter can be used for supply as well as for extraction purposes and comprises variable pitch. All fans are equipped with variable speed drives which makes this system very versatile and a good basis for experiments.

Isolated by a false ceiling against the driving space, two ducts extend throughout the tunnel in the ceiling.

One of the ducts is used for air supply only. It is connected to a supply air fan at each end and connected to the driving space by secondary ducts, injecting the fresh air above the road level perpendicular to the tunnel axis.

The second duct is divided in two sections by means of an isolation damper in the middle of the tunnel, resulting in two ventilation sections, each connected to its own dual mode supply/extraction fan. Via slots in the ceiling (see

Figure 1), air can be either injected with a momentum to the tunnel axis, or extracted. Linear, distributed extraction was originally intended for fire ventilation.

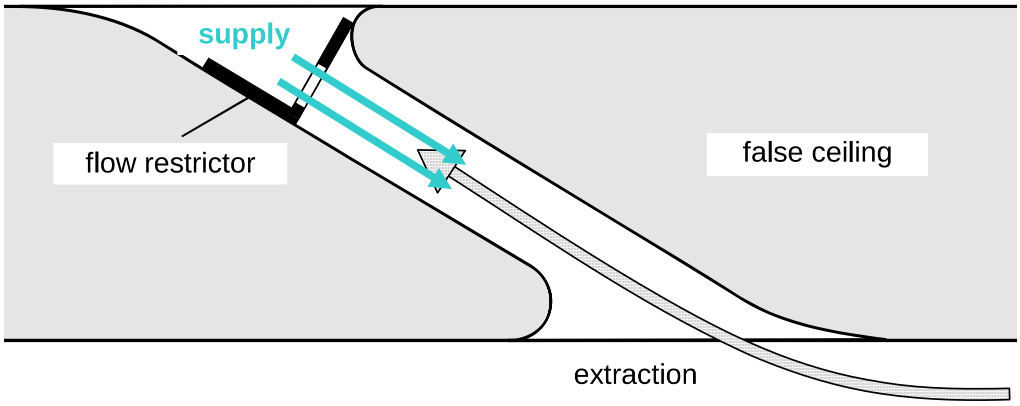


Figure 1: Sketch of openings for distributed injection/extraction in false ceiling

As a unique feature, the tunnel comprises large, hydraulically operated flap gates at each end of the extraction duct. This facility was intended for the concentrated removal of waste tunnel air before reaching the portals. Measured against the axis of the tunnel, the flaps are inclined at an angle of 18.5° in the open position, see Figure 1.

Figure 2: Flap gate, used for portal air extraction, open position

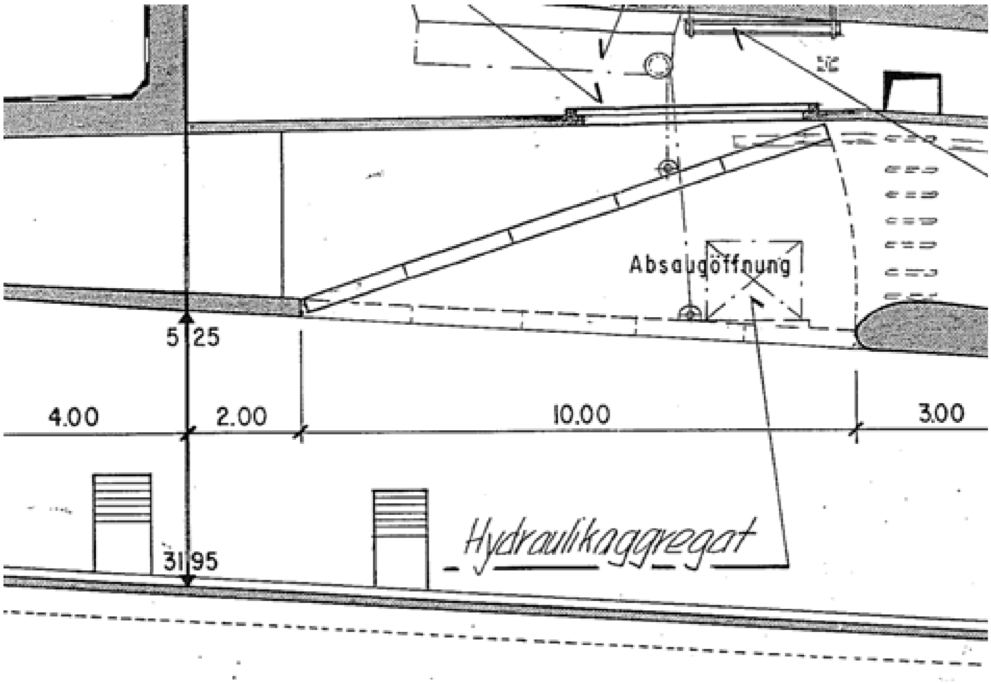


Figure 3: Longitudinal section of flap gate

3.3. Experimental Setup

Using the equipment of the Crapteig tunnel, various operation modes of air injection could be tested. By operating the dual mode fan in supply mode, both, point injection through the flap gate or distributed, directed injection through the slots in the ceiling could be applied. The large opening of the existing flap gate also provided space to install a provisional Saccardo nozzle mock-up.

The flap gates are situated approximately 150 m from the portals. At 2 locations, the air velocity in the tunnel is measured by a group of 3 ultrasonic anemometers. The readings of those instruments have been calibrated against results of a grid measurement according to ISO 5802.

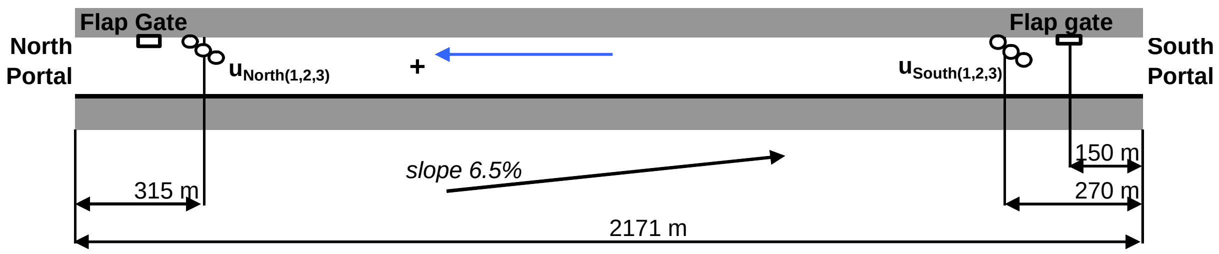


Figure 4: Location of anemometers and flap gates

As the fans are not equipped with volume flow meters, this value has been determined by evaluation of the fan curves at the operating points for the different modes.

To introduce disadvantageous propulsion forces, a mobile jet fan was used, see Figure 5.

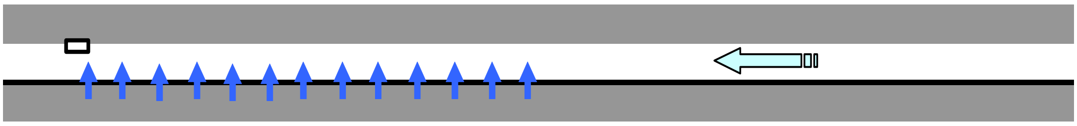
Figure 5: Mobile jet fan

Figure 6: Setup of Saccardo nozzle mock-up

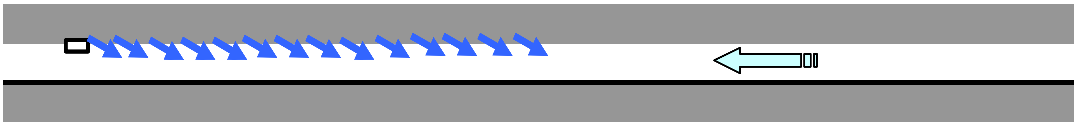
3.4. Configurations

The following scenarios have been investigated:

- Deceleration of flow by distributed and undirected fresh air supply in one of two supply air sections



- Deceleration of flow by distributed and directed fresh air supply in one of two supply air sections



- Deceleration and reversal of flow by point injection of fresh air (open flap gate)

- Acceleration of flow by point injection of fresh air (Saccardo Nozzle)

- Deceleration and reversal of flow by point injection of fresh air (Saccardo Nozzle)

3.5. Calculations

The following dimensions and specifications of the tunnel and of the propulsion devices have been used in the 1-D calculations:

Dimensions of tunnel:

L (length of tunnel):	2171 m	D_H (hydr. diameter):	7 m
A (cross section area):	60 m^2	(friction coefficient):	0.03

Distributed injection – undirected:		Distributed injection – directed:	
Angle of injection:	90°	Angle of injection:	ca. 30°
Volume flow rate:	100 m^3/s	Volume flow rate:	95 m^3/s
Length of supply air section:	1050 m	Length of supply air section:	1050 m
Exit velocity:	estimated 20 m/s	Exit velocity:	est. 20 m/s

		Not calculated:	
Saccardo-Nozzle:		Single point injection through flap gate	
Angle of injection:	15°	Angle of injection:	ca. 20°
Exit velocity:	25 m/s	(estimation)	
Nozzle exit area:	4.65 x 0.65 m	Volume flow rate:	100 m^3/s
Volume flow rate:	80 m^3/s	Cross section area of jet:	unknown
		Exit velocity:	unknown

3.6. Results

The following full scale measurement has been used to validate the 1-D model.

Deceleration and reversal of air flow in the tunnel by means of the Saccardo nozzle.

At the start of this experiment, a steady air flow from North to South in the order of 1.5 m/s was present due to a temperature difference between the warmer tunnel and the ambient air. Using a reasonably estimated momentum exchange coefficient of k_{MX} = 0.8, a good agreement between measurements and calculation results can be observed (see Figure 7).

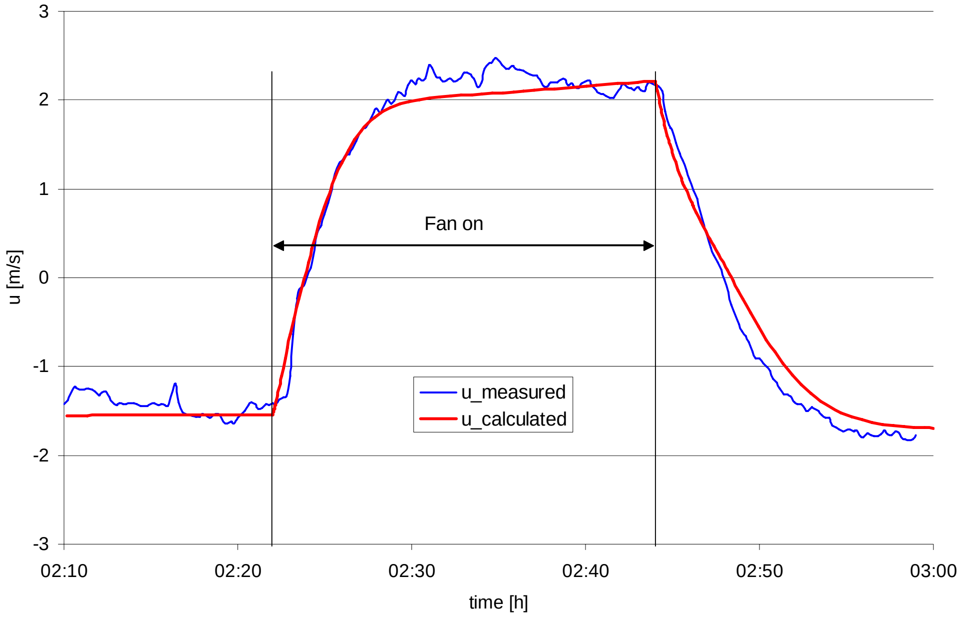


Figure 7: Air velocity in tunnel during operation of Saccardo nozzle

Comparison of propulsion methods

For comparison purposes, the effect of the injection of air by four different propulsion methods has been calculated. In each case, the nozzle air volume flow and a nozzle exit velocity has been applied according to the specifications above.

Alternatively, a group of 3 jet-fans or one Saccardo-nozzle is located in a distance of 100 m to the entry portal. Beginning from that location, a section of distributed supply air injection extends over a length of 1000 m into the tunnel. The resulting velocity is calculated for the exiting air at the end of the tunnel.

Possible delays due to the inertia effects in the supply air ducts or caused by the start-up of the connected fans have not been considered in this stage of the model.

In Figure 8, the unsteady behaviour of the air flow in the downstream half of the tunnel is illustrated. Figure 9 shows the distribution of the static pressure along the axis of the tunnel tube for the equilibrium steady state.

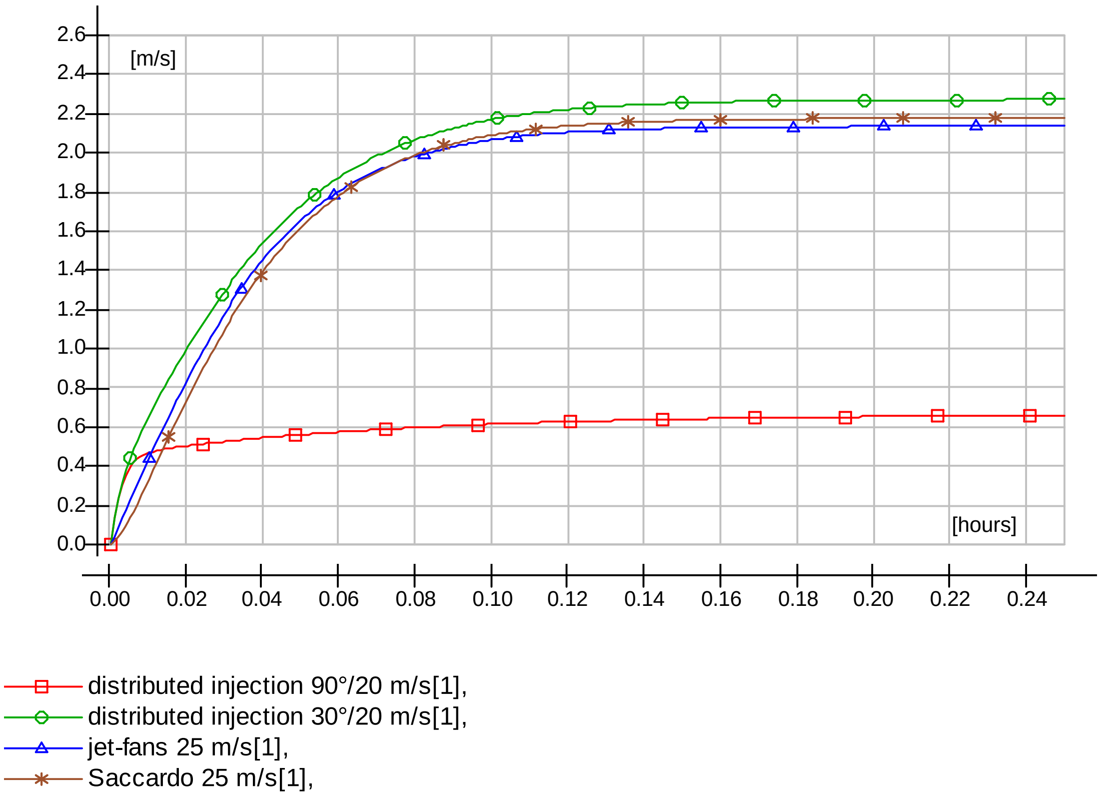


Figure 8: Calculated air velocities in tunnel for the four different propulsion methods

In Figure 10, the effect of the different propulsion methods is shown as it was recorded in the full scale experiment.

As the exit velocities of the distributed air injection are not known exactly, this result is of qualitative use only.

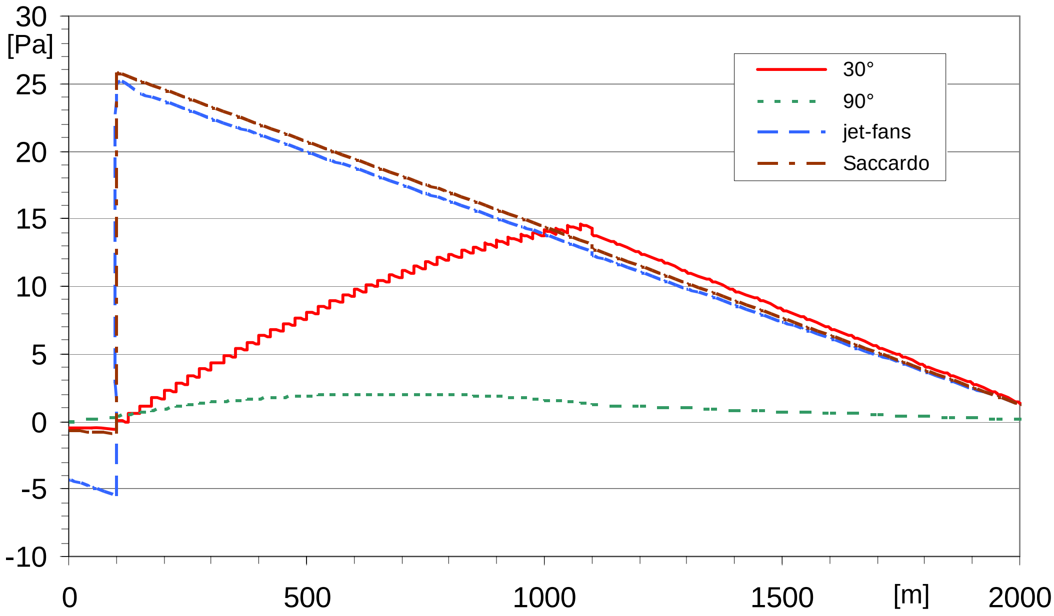


Figure 9: Distribution of static pressure along tunnel axis

As to be expected according to the calculations, the effect of the distributed and directed air injection is of the same order as the effect of the Saccardo nozzle. The effect of the undirected injection is much less effective.

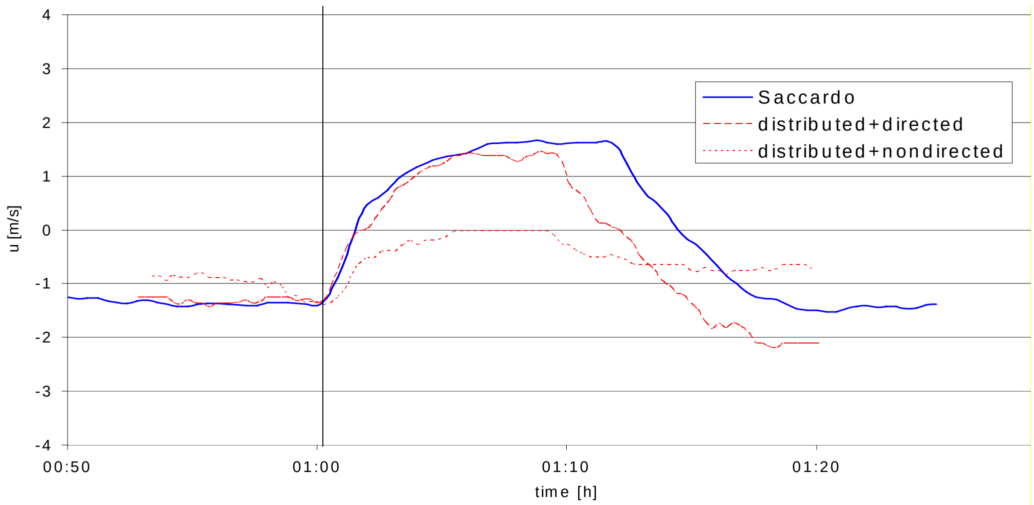


Figure 10: Qualitative comparison of propulsion methods in full scale experiment

Even though the distributed injection may be effective for the control of longitudinal airflow, it is not applicable for fire ventilation as long as the section with openings extends far into the tunnel. The injection of air into a possible smoke layer would further enhance the smoke procurement. The Swiss guideline does not allow the injection of air through the ceiling for this reason.

4. CONCLUSIONS

The following conclusions can be drawn:

i. For the control of airflow in a tunnel, only methods that directly inject momentum into the flow are useful without restrictions. Primarily these methods are either jet fans or Saccardo nozzles.

ii. Only in long tunnels with powerful transversal ventilations systems and various dedicated ventilation sections can the distributed air injection be used to control the longitudinal airflow efficiently.

iii. For most applications, jet fans are useful due to their efficiency, simple installation and easily achievable redundancy.

iv. Saccardo nozzles may be considered where space requirements, serviceability without restriction and protection from corrosion are important.

v. Especially for the refurbishment of tunnels with existing ventilation stations, Saccardo nozzles may be a cost-effective solution.

vi. The application of directed air injection at fixed points is a suitable option for the control of longitudinal air flow in case of tunnel fires. Although the energy efficiency is clearly smaller than in a jet-fan setup, this does not matter much because it is operated only during the hopefully rare case of a tunnel fire.

vii. Apparently, the propulsion effect of an injection of fresh air through an adapted Saccardo nozzle, through the geometrically much less defined damper opening and through distributed openings for directed injection is of nearly equal order, considering the velocity if the air flow at the opposite end of the tunnel.

viii. The one dimensional simulation technique is an adequate instrument to predict the dynamic performance of control of longitudinal ventilation in road tunnels. However the efficiency coefficients for the propulsion devices may have to take into account the flow regime, i.e. whether the jet is directed against the main airflow or not.

5. ACKNOWLEDGEMENTS

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EXPERIENCES ON THE SPECIFICATION OF ALGORITHMS FOR FIRE AND SMOKE CONTROL IN ROAD TUNNELS

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ABSTRACT

The main objective of ventilation systems in case of fire is the reduction of the possible consequences by achieving the best possible conditions for the evacuation of the users and the intervention of the emergency services. The required immediate transition, from normal to emergency functioning of the ventilation equipments, is being strengthened by the use of automatic and semi-automatic control systems, what reduces the response times through the help to the operators, and the use of pre-defined strategies. A further step consists on the use of closed-loop algorithms, which takes into account not only the initial conditions but their development (air velocity, traffic situation, etc), optimizing smoke control capacity.

Key Words: Ventilation, fire safety, smoke control.

1. INTRODUCTION

The transposition of the European Directive 2004/54/CE (1) to the Spanish regulation was finalized with the publication, in 2006, of the RD 635/2006 (2) on minimum safety requirements for road tunnels. One of the key aspects included in these two regulations is the necessity, in most of the tunnels, of automatic ventilation control systems, both in normal operation and fire case.

The main requirements to be achieved by the use of control systems are the reduction in the response time for ventilation activation and the implementation of predefined strategies both for manual and automatic response of fire safety facilities.

However, when trying to establish the criteria for the specification of predefined ventilation strategies, various aspects must be taken into account which depends on the type of ventilation system and traffic operation conditions previous to the incident development. Even, in some cases, an appropriate management of fire incidents requires complex multi-step strategies that must be predefined and implemented in the control systems.

2. BACKGROUND

During the last decades, a great amount of resources have employed for the study and development of ventilation control systems during normal operation, which included the use of closed loop algorithms and fuzzy logic for the optimization and improvement of the efficiency (CETU, ref. 3). However, during the last years, the reduction of the emission levels of the vehicles is reducing the efforts involved in the development of new technologies and methods for the control of the ventilation during normal operation.

On the opposite, ventilation control in case of fire is becoming of the utmost importance. Going to the past, the PIARC report on “Fire and Smoke control in Road tunnels” (ref. 4) in 1999 already reflected the importance, and lack of unique rules, on the use of active control systems for the operation of ventilation.

From then, several national guidelines have included recommendations on the operation of ventilation systems in incident cases: Austria (RVS 09.03.31) (ref. 5), Germany (RABT) (ref. 6), France (Circulaire Interministérielle 20-63 dated 20th August 2000) (ref. 7) or Switzerland (FEDRO) (ref. 8). One common aspect to all of these references is the distinction between the self evacuation phase and the fire fighting phase, and the importance of the longitudinal control of the air velocity in the tunnel, with no dependence on the type of mechanical ventilation system installed, to achieve the desired goals for smoke control.

Taking into account these criteria, different contributions can be found in the literature in what concern to practical application of automatic control system use in road tunnels: Pospisil et all (ref. 9), Wehner et all (ref. 10), Stroppa (ref. 11) or Bettelini et al. (ref. 12).

With the intention of describing some practical experiences in Spain, in the following, the authors describe in detail the criteria and algorithms developed and implemented for the automatic control of ventilation in road tunnels. It is important to note that the criteria and tools are mainly focused on the evacuation phase, even if some considerations are made on the general approach.

In addition, some results from the evaluation tests are presented as far as the authors consider that the whole process: design, implementation, test and adjustment is crucial to evaluate the reasonable performance of ventilation control system.

3. VENTILATION STRATEGIES IN CASE OF FIRE

Ventilation strategies to be used in case of fire are usually dependant to the operational configuration (unidirectional or bidirectional traffic) and the traffic conditions (free flow or standstill).

In case of tunnels with unidirectional traffic without congestion, a “high” velocity longitudinal ventilation strategy is the one most widely adopted, which consists in the generation of a longitudinal air flow in the vicinity of the fire, in the sense of the traffic flow, enough to avoid the back layering of the smoke.

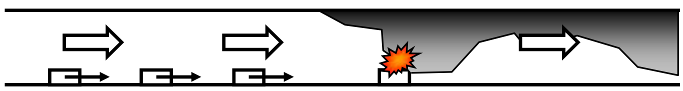

Figure 1: Ventilation strategy for unidirectional free flow traffic

In case of unidirectional tubes with traffic congestion, a two-stages longitudinal ventilation strategy is commonly recommended which would consist in the generation of a “low” velocity longitudinal air flow until the vehicles stopped downstream the fire has left the tunnel. In a second stage, a “high” velocity longitudinal strategy would be desirable as far as no vehicles, or users, should be situated in the route invaded by the smoke (portal, intermediate exhaust point, etc).

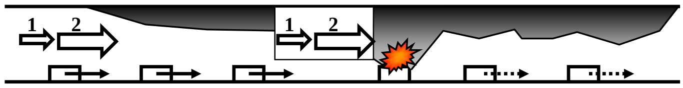

Figure 2: Two stages longitudinal strategy for unidirectional congested traffic

For bidirectional tunnels the two strategies explained before are not longer valid, as far as there will probably be vehicles at both sides of the fire location, what would recommend to adopt ventilation strategies focused on maintaining so long as possible the stratification conditions of the smoke, what is favored by the smoke extraction (if possible), the switch off of the fans that can cause turbulence, and the reduction of the air velocity inside the tunnel.

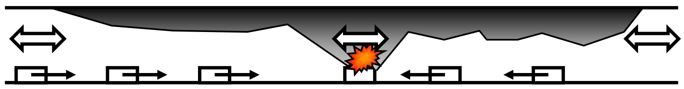

Figure 3: Stratification strategy for bidirectional traffic

4. CHALLENGES FOR DESIGN OF VENTILATION CONTROL SYSTEMS

Consequently, it is of the outmost importance to handle the quick transition from normal operation to the emergency mode, which includes from the point of view of the ventilation system, the following steps:

1. Normal operation
2. Automatic incident detection
3. Ventilation safety response
4. Location and validation of the fire
5. Predefined ventilation response plan
6. Follow-up and correction (if necessary)
7. Emergency service strategy
8. Return to normal operation

All these stages must be implemented in accordance to the general emergency response plans so, coherence between the different equipments activation can be guaranteed.

However, when accomplishing the design phase, even if all the steps are clearly defined into specifications documents, some practical details must be taking into account to reduce the incidence of mistakes. It has been considered interesting to describe some of them:

- Reception of multiple automatic alarms: once an incident occurs, the great amount of alarms that are received from the different equipments installed in the tunnel can interfere in the activities of the operator. For example, in the case of the AID (Automatic Incident Detection) system, the queue formation upwind the traffic stop point generates multiple alarms in areas far from the fire situation.
- Excessive demand of information from the operator: when designing the interface human-computer application, the excessive request of information must be avoided and, if totally necessary, priority criteria must be established.
- User failure protection: even if sometimes it is not possible to guarantee that the actions taken by the operator are correct, a great amount of mistakes can be avoided without complex means (for example, the use of 'double confirmation' messages for fire alarm cancellation as are used in standard applications)
- Exhaustive and permanent training: as far as, fortunately, fire situations are not common during the operation of the tunnel, it is necessary that the operators can receive permanent training in the management of the application, general concepts, expected behavior, practical cases, etc. In some tunnels, very good experiences are being obtained with the use of training 'simulators', where the use of the graphic interface screens for fire situation can be used reducing the 'surprise' of the operator to new situations.

It is important to note that the development of these applications require clear criteria, detailed specifications, considerable implementation efforts and rigorous test procedures, what in practice means time and economic provisions to be considered.

5. PRACTICAL EXAMPLES

The tunnel of study has two independent unidirectional traffic tubes of about 2000 meters length. The proximity of an urban area produces a highly unbalanced traffic distribution what causes standstills in the morning and evening commuting times.

The ventilation system is longitudinal with jet fans uniformly distributed through the tunnel, although according to the new Spanish regulation in the close future the tunnel will be refurbished and the ventilation system modified.

For the detection phase, an automatic algorithm has been implemented which consider (through a weighting procedure) the signal coming from different types of sensors (fire detectors, quick changes in the measures of CO and turbidity sensors or alarms generated by the DAI) to propose the operator a “most probable fire location”. The result of the algorithm is to provide him, for each section a detection index, ranging from 0 (no alarms) to 100 (all alarms).

Depending on the detection index value for any of the sections, different predefined procedures can be activated (pre-alarm mode), i.e. stop of the ventilation in both tubes to avoid the de-stratification of the smoke during the early stages, starting of a pre-defined number of jets, etc.

In addition, a closed loop air velocity control algorithm has been implemented with the objective of maintaining the control on the longitudinal air flow what should facilitate the users evacuation.

The two main parameters taken into account by the algorithm are the air velocity inside the tunnel and the target air velocity. For the case study presented, the air velocity in the fire location is calculated as the average of the values given at every instant by some representative anemometers (not all the installed anemometers should be used because some of their measures can be influenced by the jet fans flow or the smoke layer around the fire).

The implemented algorithm follows a predictive - corrective logic, based on the average air velocity in the tunnel and the trend shown during the control intervals. Both magnitudes are evaluated at the end of each control periods by a linear adjustment to try to avoid the random temporal fluctuations (see red line in the decision figure). The algorithm estimates the value of the velocity expected (V_{est}) to occur at the end of the time interval and the slope of the linear regression curve (m).

Finally, from the values obtained for the control variables, the decision on the number of jet fans to be connected is taken based on pre-programmed charts with predetermine actuations (see next table) which depends on the velocity estimated comparison to the reference interval and the sign of the slope of the linear regression (m).

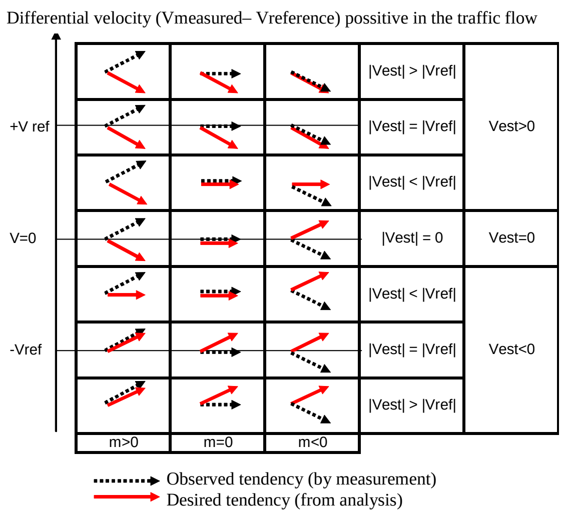

Figure 4: Scheme of the close-loop logic applied

An additional tool has been implemented in the control system to evaluate the traffic conditions in the downstream area based on the information gained from the AID system. Due to the reduced reliability of the information provided by the cameras in case of fire, it was decided that this system only provides a proposal to the operator about the traffic situation during the emergency which is responsible to modify the reference velocity for the activation of the automatic control system.

6. CONCLUSIONS

The research on ventilation control methodologies and algorithms, for application into road tunnels, is focusing more and more on fire situation instead of normal operation. This fact is being reflected in the national and international regulations and guidelines.

However additional research and development efforts seem to be necessary to improve the design, specification, implementation and testing of ventilation control systems.

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NEW AUSTRIAN GUIDELINE FOR THE TRANSPORT OF DANGEROUS GOODS THROUGH ROAD TUNNELS

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ABSTRACT

In the Austrian guideline RVS 09.03.11 the Austrian Tunnel Risk Analysis Model TuRisMo defines how to assess the risk for tunnel users. The same guideline stipulates that the specific risk involved in the transport of Dangerous Goods (DG) through road tunnels should be assessed in a separate procedure. Consequently, based upon European Directive 2004/54/EC and the Austrian Road Tunnel Safety Law, a uniform risk assessment procedure for the transport of DG through road tunnels has been developed. For a methodical risk analysis approach, the OECD/PIARC-Model DG-QRAM was chosen. The results shall be published in new Austrian guideline RVS 09.03.12 in 2010.

The main objectives of the research project are the verification of existing DG transport data, the development of a complete risk assessment procedure in line with the new ADR tunnel regulations and the definition of decision criteria for each level of risk evaluation.

Keywords: dangerous goods, road tunnel safety, quantitative risk assessment, expected value, FN-curve

1. LEGAL ASPECTS OF TUNNEL SAFETY

1.1. Directive 2004/54/EC

This Directive defines minimum safety requirements on an international level to be met by road tunnels forming part of the Trans European Road Network (TERN). The remarkable aspect about this Directive is the fact that it combines both a “regulation-based” and a “risk-based” approach. According to Article 13, a risk analysis shall be performed for all tunnels featuring a special characteristic, taking into account all design factors and traffic conditions.

1.2. Austrian Road Tunnel Safety Law

The Road Tunnel Safety Law translates the requirements contained in the EC-Directive into Austrian law. It defines the following measures for the transport of dangerous goods (DG):

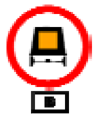
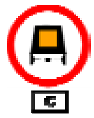
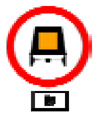
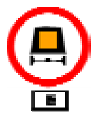
- Prior to the definition or modification of regulations and requirements regarding the transport of DG through a tunnel, a risk analysis is to be performed.
- To enforce the regulations, appropriate signs indicating alternative routes, are to be posted ahead of the last possible exit before the tunnel and at tunnel entrances.
- In individual cases, specific operating measures designed to reduce the risks related to some or all of the vehicles transporting DG in tunnels are to be checked (e.g. escorted passage in convoys).

1.3. ADR 2007 / 2009

When the European Agreement concerning the International Carriage of Dangerous Goods by Road, commonly known as ADR was revised in 2007, so called tunnel restriction codes were assigned to all dangerous substances according to their potential of damage, amount (mass) and carriage type. These codes serve as a basis for a uniform European regulation governing the transport of dangerous goods though road tunnels.

To enforce restrictions of DG transporting vehicles through a tunnel the relevant authorities shall assign the tunnel to a category defined in the ADR (**Table 1**). The new tunnel regulations of the ADR have been valid since the 1st of January 2010.

Table 1: ADR tunnel categories and signature

Tunnel categories	Restrictions	Sign	Traffic Sign
A	No restrictions for the transport of dangerous goods	No sign	-
B	Restriction for dangerous goods which may lead to a **very large explosion**	Sign with additional panel bearing the letter B	
C	Restriction for dangerous goods which may lead to a **very large explosion, a large explosion or a large toxic release**	Sign with additional panel bearing the letter C	
D	Restriction for dangerous goods which may lead to a **very large explosion, to a large explosion, to a large toxic release or to a large fire**	Sign with additional panel bearing the letter D	
E	Restriction for all dangerous goods other than UN Nos. 2919, 3291, 3331, 3359 and 3373	Sign with additional panel bearing the letter E	

2. DATA BASE

At the beginning of the research project great emphasis was put on the data base. From 2006 to 2007 investigations of DG transports were carried out at 12 different cross sections on Austria's main traffic routes. In March 2009, the results of these earlier investigations were evaluated and expanded by a detailed review of DG transports in cooperation with the police. For one month (March 2009) the police stopped DG vehicles and controlled their transport documents. The investigation was accomplished in all Austrian federal states and assigned detailed information about the UN number, amount, carriage type and destination of the dangerous substances.

The applied risk model includes for the most part very "severe" scenarios with huge amounts of dangerous substances involved. For example scenario 4 stands for a pool fire of a 28 ton tank of diesel/petrol. Using the model scenarios without an adjustment would lead to an overestimation of risks. For that matter the data collected in the detailed investigation were used to define more realistic allocation rules (see example in **Figure 1**).

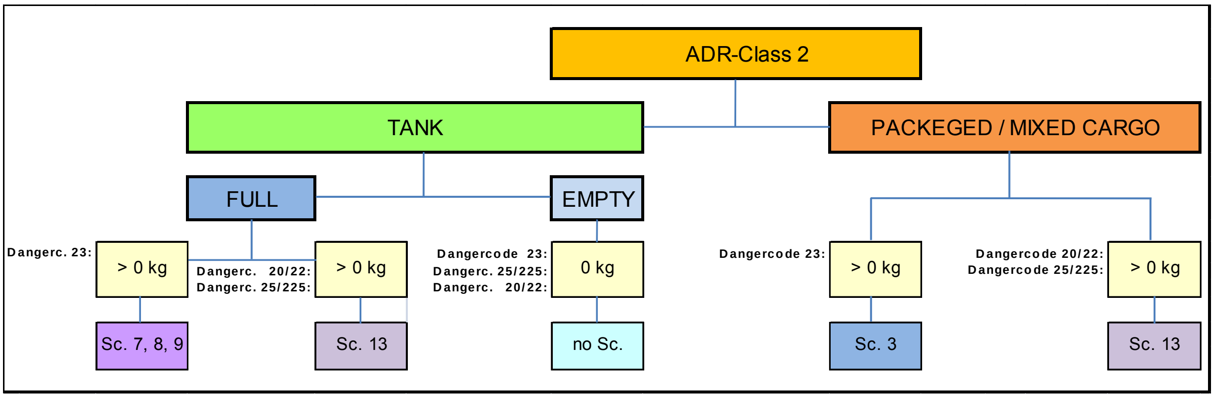


Figure 1: Allocation key for flammable gases (ADR class 2)

In addition, the results of the investigations revealed that in Austria the composition of the DG carriage varies only slightly on different traffic routes and that these variations have only little influence on the risk faced by tunnel users. Eventually, a standardized, averaged scenario allocation for Austria based upon a detailed DG investigation was found (**Table 2**).

Table 2: Standardized scenario allocation for Austria (DG-QRAM)

Accident scenarios - DG-QRAM		**Proportion**
Scenario 3:	BLEVE of flammable gases in 50kg-cylinder (e.g. Propane)	0,0226
Scenario 4:	pool fire of flammable liquids in bulk (e.g. Petrol, Diesel)	0,4270
Szenario 5:	VCE of flammable liquids in bulk which may lead to explosive air fuel mixture (e.g. Petrol), assigned as fraction of s*cenario 4*	*0,3610*
Scenario 6:	release of very toxic gases in bulk (e.g. Chloride)	0,0010
Scenario 7 / 8 / 9:	BLEVE / VCE of flammable gases in bulk (e.g. Propane)	0,0113
Scenario 10:	release of toxic gases in bulk (e.g. Ammonia)	0,0010
Scenario 11:	release of toxic fluids in bulk (e.g. Acrolein)	0,0133
Scenario 12:	release of toxic fluids in 100kg-cylinder (e.g. Acrolein)	0,0113
Scenario 13:	burst of a tank of non flammable gases (e.g. liquefied refrigerated CO2)	0,0452

3. OECD/PIARC MODEL (DG-QRAM)

To calculate the risks involved in transporting DG an international accepted risk analysis model called DG-QRAM is applied. The risk model was developed on behalf of OECD/PIARC and is widely used on an international basis, but is obviously not the only method available for assessing the risk resulting from the transport of DG.

The results of the risk analysis model are depicted as Expected Values (EV) or F-N curves, illustrating the relation between accident frequency (F) and accident consequences (N number of fatalities). Whereas the EV represents the average expected number of fatalities as a result of all DG accidents, the F-N curve gives more comprehensive information on the extent of damage in relation to the probability of individual accidents (**Figure 3**).

4. DEVELOPMENT OF A COMPLETE RISK ASSESSMENT PROCEDURE

In the year 2009, the Austrian Federal Ministry for Transport, Innovation and Technology (BMVIT) launched a research project with the objective of establishing a complete investigation and assessment procedure concerning risk analyses for DG (using DG-QRAM). The research project was exclusively focused on assessing the risk of DG accidents, whereas mechanical accidents and conventional fires are addressed by the risk model TuRisMo. The final results have been presented in a new Austrian guideline (draft). The finalized version should be published in 2010.

The research project served the purpose of defining a clearly structured risk assessment procedure in line with the new ADR tunnel regulations, based upon reliable DG data. In the course of this project, risk reference criteria for every step of the assessment procedure had to be laid down. The project was supported by a work group comprising technical and legal experts of the BMVIT and the Austrian Ministry of Internal Affairs, the Austrian federal provinces, the Austrian Chamber of Commerce, the ASFINAG, the fire brigade, the transport industry as well as ILF Consulting Engineers.

In principle, the risk involved in the transport of DG is determined in a multi-stage assessment procedure.

4.1. Stage 1 – Classification Matrix

Stage 1 involves using a simple classification matrix (**Figure 2**) to define DG risks of road tunnels. The application of the matrix shall permit a simple identification of tunnels with a low DG transport risk.

The classification matrix takes into account the following main risk factors:

- the tunnel length
- the type of tunnel (bi-directional or uni-directional traffic)
- the ventilation system (natural, longitudinal or transverse)
- the traffic volume
- the percentage of heavy goods vehicles (HGV)

The respective parameters of the matrix were defined in a former study performed in 2008. Then, a systematically risk calculation were performed for a set of selected reference tunnels using DG-QRAM. As decision criteria an expected risk value of EV = 1×10^{-3} fatalities/year was applied for the elaboration of the matrix.

If a tunnel is assigned to a dark field of the matrix, a risk analysis has to be performed.

A first examination of the Austrian road tunnels revealed, that approximately half of the tunnels require no further risk investigation. These tunnels could, in line with the ADR, directly be allocated to tunnel category A.

The application of the matrix is only admissible, if a set of requirements is fulfilled (e.g. proportion of heavy goods vehicles ≤ 25%, longitudinal gradient ≤ 3%, no extraordinary proportion of DG, etc.).

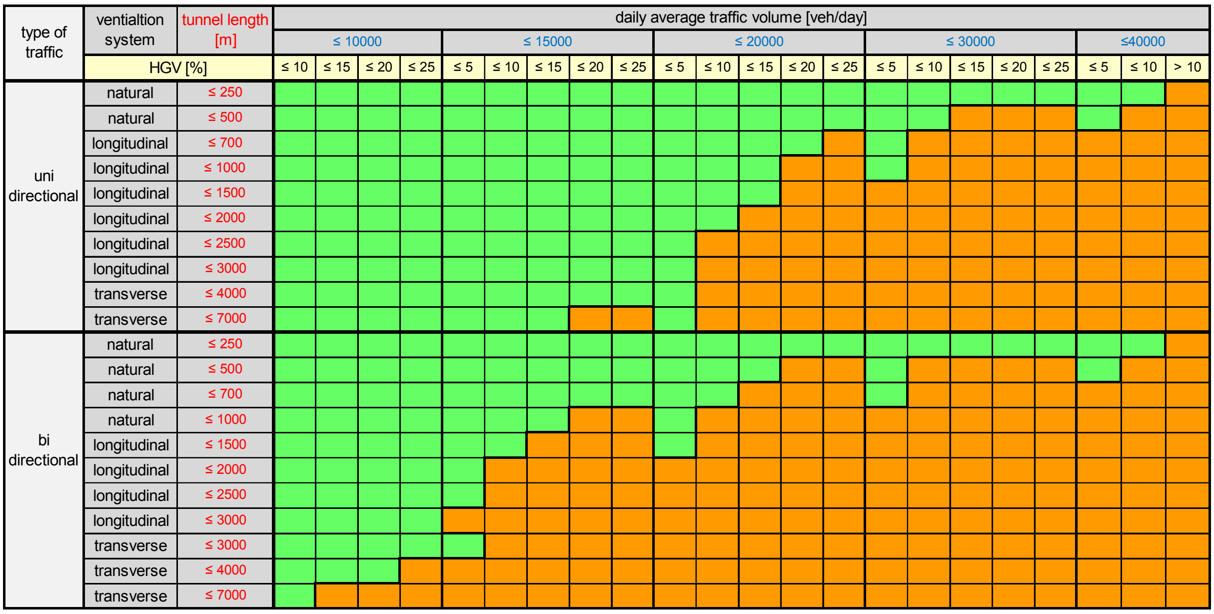


Figure 2: Classification matrix (stage 1)

4.2. Stage 2 – Detailed Approach

All those tunnels which indicate a relevant DG risk in stage 1 are subsequently reviewed in a detailed, tunnel-specific risk analysis using DG-QRAM (Stage 2a).

Whereas the decision criterion in stage 1 is based upon the expected value, in stage 2 the assessment is assigned to the log scaled F-N diagram. The results (scenario-based FN-curves) are evaluated by comparing them to a defined reference line in the F-N diagram (see example in **Figure 3**). If the reference line is exceeded, additional risk reducing measures are to be investigated (Stage 2b).

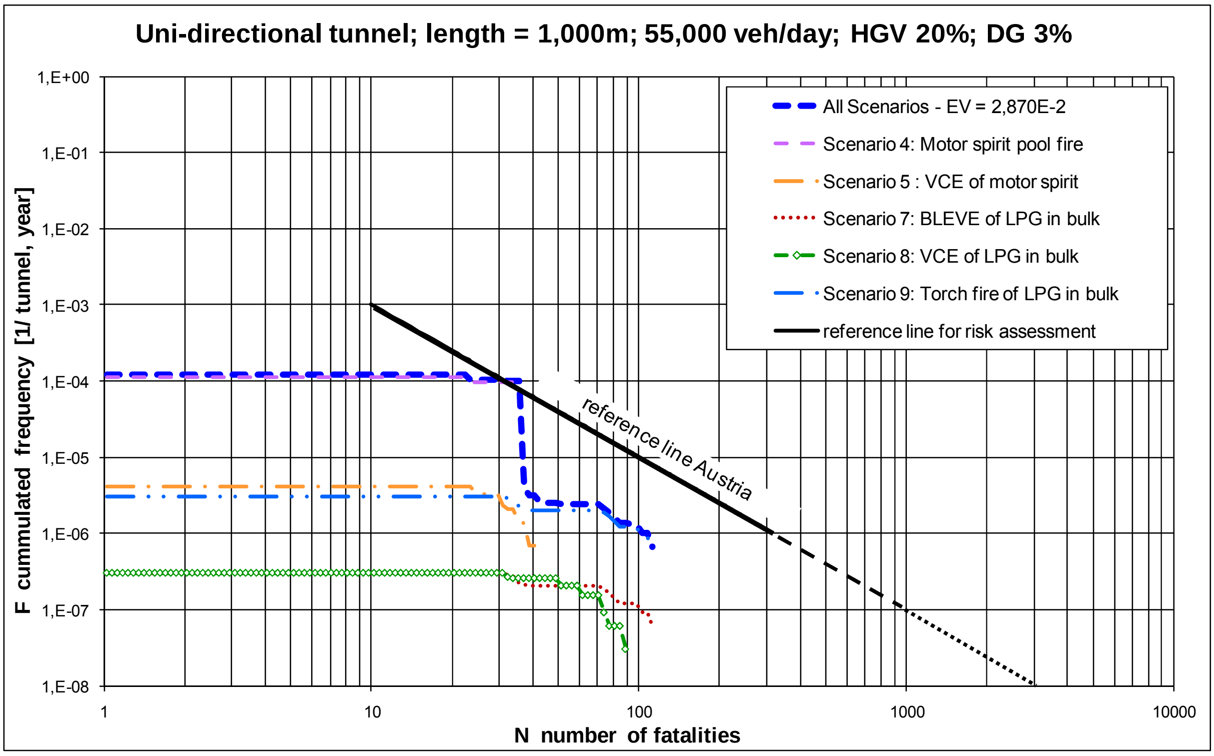


Figure 3: Reference line as assessment criterion in the F-N diagram (stage 2a)

4.3. Stage 3 – Alternative Route

Generally, the transport of DG on the road is not restricted as long as the requirements of the ADR are met. If the assessment procedure determines that the investigated tunnel possesses an intolerably high risk, restrictions to the DG transport for a tunnel are to be examined. In this case the existence of an adequate alternative route is investigated. A road only qualifies as an alternative route if the entire road segment is suitable and approved for heavy goods traffic. This requires such aspects as: the number of lanes, the longitudinal gradient, the road width, curve radii, etc. (be reviewed on a case-to-case basis).

The examination of the alternative route follows the principle that a generally allowed, existing transport volume of DG should be carried on that route which shows the slightest transport risk. Therefore, it must be shown that the risk of transporting DG on the alternative route is significantly lower for the resident population than the risk of unrestricted transport through the tunnel for the tunnel users.

The risk calculations for the alternative routes (open road sections) are also performed by application of the risk analysis model DG QRAM.

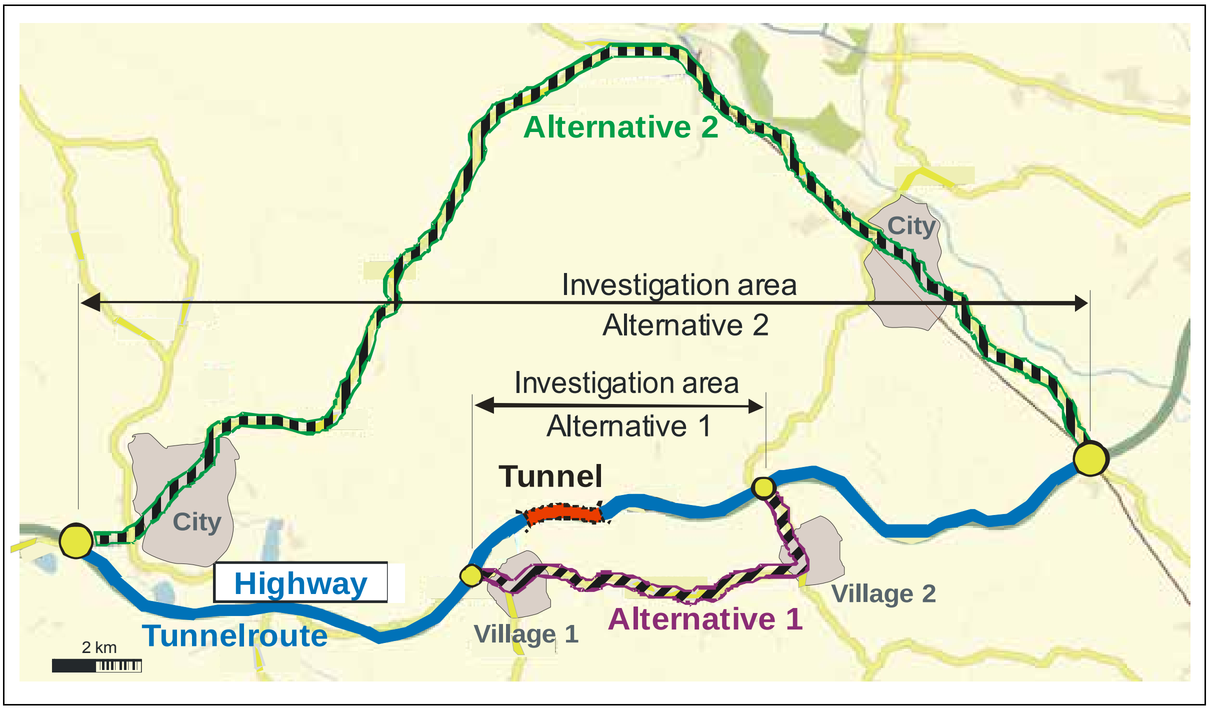


Figure 4: Alternative route (stage 3)

5. MEASURES

If in stage 2a the reference criterion in the F-N diagram is exceeded, the DG risk is rated as unacceptable and special additional risk reduction measures needs to be investigated (Stage 2b).

Consideration made to improve traffic safety predominantly focuses on organisational and operational measures. In this context, it should be noted that not every measure is equally suited or efficient. The envisioned measures will thus have to be checked individually for the respective tunnel system in an in-depth risk analysis.

The current regulation for highways BGBl. 395/2001 issued by the Federal Ministry for Transport, Innovation and Technology (BMVIT) already stipulates operational measures depending on tunnel length:

- Tunnels with a length between 1,000 m and < 5,000 m require a flashing warning light on the vehicle.
- Tunnels with a length of > 5,000 m require a flashing warning light, an escort vehicle following the transport unit and the distribution of transport documents to the personnel of the escort vehicle.

Additional operational measures aimed at reducing the transport risk of DG may include:

- Introduction of an overtaking ban
- Introduction of a speed limit
- Installation of an information system
- Installation of a speed control system

6. DEFINITION OF RISK CRITERIA

As mentioned earlier, the societal risk is usually expressed in a graph (F-N diagram). To determine whether the safety level is acceptable or not, an assessment of the societal risk can be made. This is based upon a risk reference criterion which is often determined specifically for the project in question.

For example, an officially established risk limit line concerning DG is used in Switzerland (in the Swiss Accidents Ordinance).

6.1. Reference line for risk assessment

In the detailed analysis (stage 2), the assessment is based upon a defined assessment criterion in the F-N diagram. This reference line was calculated by the following formula:

For $N \geq 10$ fatalities: $$F = \frac{10^{-1}}{N^2}$$ ... for 1 km of tunnel (1)

The slope of the equation reflects the risk aversion level. If the number of fatalities increases by a factor of 10, the acceptable occurrence frequency decreases by a factor of 100.

The reference line was defined taking into account several aspects:

- risk level in comparable reference systems (e.g. aviation)
- reference criteria used in other countries (e.g. Switzerland, Netherlands)
- special model characteristics of DG-QRAM (e.g. adjustment for length)

6.2. Adjustment of the reference line for tunnel length

A risk assessment based upon the defined reference line requires a standardized tunnel length, as the reference criterion (1) is usually based on 1 km. For the assessment criterion to be used in the F-N diagram, an adjustment for the length of the tunnel had to be made.

Concerning the tunnel safety topic, the length of the tunnel is an especially critical factor. Therefore, the adjustment should not be linear to the length of the tunnel. Hence, the relationship between tunnel length and risk was modelled as an exponential function:

For N ≥ 10 fatalities: $$F = \frac{10^{-1}}{N^2} \times L^{0.5}$$ ... L = tunnel length [km] (2)

To evaluate the reference criterion (2) transport risks of several common road tunnels in Austria were calculated and assessed in the F-N diagram.

7. INTERNATIONAL OUTLOOK

The ADR's tunnel regulations have been valid since the 1st of January 2010. Although the European countries have already assigned many tunnels with restrictions to ADR's tunnel categories, this implementation process isn't completely accomplished. The network-wide risk assessment and the assignment to risk categories will take some time to be finalized; especially for states with a great number of road tunnels.

Thus current development trends in the transport industry ought to be observed and taken into account. The transport industry is likely to face certain additional costs for the transport of DG as alternative routes tend to result in longer transport times and longer carriage distances.

8. REFERENCE LIST

Directive 2004/54/EC of the European Parliament and of the Council of 29 April on minimum safety requirements for tunnels in the Trans-European Road Network

Bundesgesetz über die Sicherheit von Straßentunneln (Straßentunnelsicherheitsgesetz STSG), BGBL 54/2006, Österreichischer Nationalrat, 2006

ADR 2007 European Agreement concerning the International Carriage of Dangerous Goods by Road, United Nations 2006

Beschränkungen für Beförderungseinheiten mit gefährlichen Gütern beim Befahren von Autobahntunneln, BGBl. II Nummer 395/2001, Verordnung des BMVIT für Autobahnen

Schweizer Störfallverordnung StFV (Swiss Accidents Ordinance), EDMZ, 1991

Transport of Dangerous Goods through road tunnels – Quantitative Risk Assessment Model, OECD/PIARC/EU, 2003

RVS 09.03.11 Tunnel Safety - Tunnel Risk Model, FSV (Österreichische Forschungsgesell-schaft Straße – Schiene - Verkehr), 2008

RVS 09.03.12 Tunnel Safety – Risk Assessment of Dangerous Goods Tansports in Road Tunnels (draft), FSV (Österreichische Forschungsgesellschaft Straße – Schiene - Verkehr), 2008

DEVELOPMENT OF CONCEPTUAL RISK AND SAFETY STRATEGIES FOR THE FEHMARNBELT FIXED LINK TUNNEL

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ABSTRACT

The design of tunnels presents interesting and exciting safety and ventilation challenges. For the proposed world's longest combined road and rail sub-sea tunnel the challenges are even greater. This paper presents a case study of the proposed Fehmarnbelt Fixed Link tunnel and focuses on the risk and safety strategies and the derived impact on design and installation required to keep the tunnel operational and protect users and emergency responders in the event of an incident. The proposed tunnel stretches to 18km long, with a vast proportion of these 18km under water, and at its deepest point the Fehmarnbelt Fixed Link tunnel is 40m below sea level. The overall risk and safety philosophy is presented together with the risk acceptance criteria. The implications of applying the safety philosophy and meeting the acceptance criteria on the design are discussed and these include presentation of possible ventilation strategies including whether provision should be made for construction of a ventilation "island" at the mid-point of the tunnel, At critical locations, and for occurrence of critical events, it may be necessary to introduce risk reducing measures in order to maintain the risk at an acceptable level. In the Fehmarnbelt Fixed Link tunnel these measures are both in the form of physical installations and also operational rules and procedures. Examples are given on such measures including the installation of a suppression system. The paper debates the advantages and disadvantages of different suppression systems and considers how these can have a substantial impact on fire life safety and property protection.

1. INTRODUCTION

The Fehmarnbelt Fixed Link is a proposed permanent and direct connection between Scandinavia and continental Europe. The Fehmarnbelt Fixed Link will specifically connect Rødbyhavn in Denmark to Puttgarten in Germany and is expected to bring economic benefits to the entire region around the Fehmarnbelt.

The opening of the Fehmarnbelt Fixed Link will significantly reduce the travel time between continental Europe and Scandinavia. Instead of a 45-minute transit with the ferry, the trip by car over the Fehmarnbelt will only require about a quarter of an hour in future. Moreover, the time spent waiting for ferries and embarking and disembarking will also be eliminated.

With the opening of the Fehmarnbelt Fixed Link a good hour's travel time will be saved on the rail trip from Hamburg to Copenhagen. Rail freight traffic, which must currently be routed through Jutland and the Great Belt, will be routed directly through the Fehmarnbelt thanks to the Fehmarnbelt Fixed Link, thus saving about 160 kilometres on the Hamburg to Copenhagen stretch. This will create a strong transport corridor between the Øresund region and Hamburg.

At the time of writing a number of technical solutions are currently being investigated for the Fehmarnbelt Fixed Link in accordance with the treaty between Germany and Denmark governing the project. The two leading technical solutions are a cable-stayed bridge and an immersed tunnel. Both options present engineering challenges due to the scale of the project. This paper focuses on the tunnel option and specifically the risk and safety strategies and their derived impact on the design and installation.

2. FEHMARNBELT FIXED LINK TUNNEL DESCRIPTION

The proposed Fehmarnbelt Fixed Link tunnel if constructed will be the longest, combined road and rail immersed tunnel in the world. The tunnel will stretch 18km from Denmark to Germany and at its deepest point will be approximately 40m below sea level. The conceptual design for the tunnel contains four independent tubes and a central gallery as shown in Figure 1 allowing for uni-directional traffic in both directions for road and rail. The road tubes comprise two traffic lanes in addition to an emergency lane running continously along the length of the tunnel. Each rail tube contains a single rail line subdivided into a number of block sections and there are no cross-overs within the tunnel.

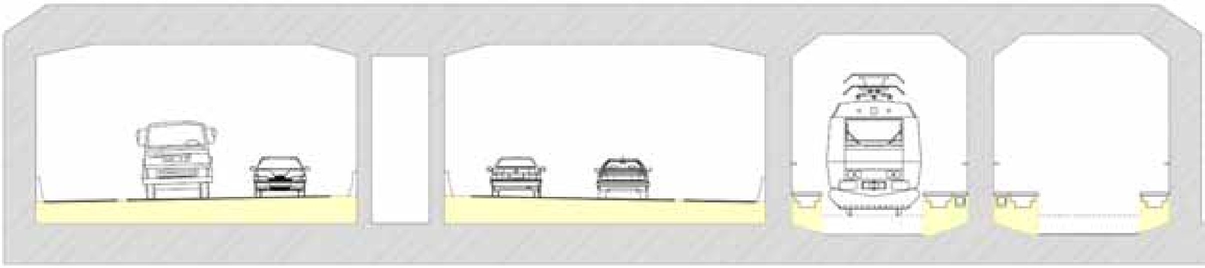

Figure 1: Fehmarnbelt Fixed Link tunnel cross section

3. SAFETY AND RISK STRATEGY APPROACH

The overall safety goals for Fehmarnbelt Fixed Link are to provide a design that has sufficient and appropriate facilities that allow all incidents to be managed in a manner that provides adequate safety in terms of;

- Life safety to road users.
- Life safety to rail users, including train crew
- Life safety to third parties not directly involved in using the Fehmarnbelt Fixed Link
- Operational interruption, that might cause the use of other less safe alternative routes or forms of transport
- Life safety to maintenance and inspection personnel
- Life safety of emergency services personnel

In order to meet these goals the safety strategy adopts an integrated, holistic, risk based approach which links design, maintenance and operations. The designs for the construction of the tunnels and all the road and rail installations in addition to the portals and ramps, and all associated facilities, have been based on the following priorities for safety:

- The primary objective is to provide a design that will prevent accidents and other emergency situations occurring ***(prevention)***
- The secondary objective of the design is to minimize the frequency and consequences of accidents and emergency situations if they cannot be prevented, i.e. to control incidents and provide facilities for self-rescue ***(control, self-rescue)***
- The tertiary objective is to provide sufficient safety systems and management procedures to ensure that accidents and emergency situations can be handled with adequate safety by the rescue services ***(response).***

In addition to the safety goals, there are societal and economic objectives which include:

- Asset protection
- Continuity of operations
- Minimimization of monetary losses
- Protection of the environment

4. HAZARD ANALYSIS

The overall safety level for a tunnel is in part a function of the traffic volumes which statistically govern the likelihood of an accident occurring in addition to impacting on the consequences as a result of the number of people affected.

For the road tunnels, the design speed is 110 km/h, the operational speed is 90 km/h and the predictive design values for the traffic volumes at the opening year of 2018, the year 2030 and also for the year 2038 are shown in Table 1.

Table 1: Road tunnel design volume per day (both directions combined)

	2018	2030	2038
Cars	8156	9822	11117
Trucks	1354	1934	2454
Buses	134	156	173
Total	9644	11912	13744

The calculated full lane capacity for the Fehmarnbelt Fixed Link is 1800 PCU's (Person Car Units)/lane/h, which means the traffic volumes for 2030 are much lower than for many other road tunnels and particular urban tunnels with high traffic volumes during morning and evening rush hours. Statistically this should mean less accidents and an improved level of safety for tunnels which, in essence, are rural tunnels with low traffic volumes.

For the rail tunnels, the maximum conceptual design speed is 160 km/h with provision for future operations at 200 km/h in addition to the 250 km/h being investigated. The design values for rail traffic volumes (no. of trains per day) are set out in Table 2.

Table 2: Rail tunnel design volume per day (both directions combined)

	2018	2030	2038
Passenger	40	41	42
Freight	47	70	91
Total	87	111	133

In accordance with current practice for most railway tunnels a train on fire should make all attempts to leave the tunnel and this practice will be initiated across the Fehmarnbelt Fixed Link. The block sections for the railway and the timetabling is not yet concluded. However in the opening year the low rail traffic volumes indicate that it is unlikely that more than one train will be present in the tunnel at any one time. Of course for future growth and flexibility it is expected that the tunnel will incorporate a number of block sections in order to not reduce capacity and therefore the possibility of multiple trains within the tunnel must be considered.

For both road and rail tunnels based on past experiences of tunnel fires and the predictive traffic volumes and composition it is possible to identify relevant fire hazards. For the road tunnel the most probable fire hazards will arise from the vehicles using the tunnel, the materials from which they are manufactured and the materials they are transporting. Another potential source of fire hazard comes from failures of equipment in the road tunnels or any plant and equipment room which, although fire separated from the tunnel, may still impact on the operation.

For the rail tunnel the hazards are in general similar although they will be heavily dependent on whether the rolling stock is for passengers or freight and whether they are pulled by electric or diesel engines.

In both road and rail there is the potential for dangerous goods to be transported across the Fehmarnbelt Fixed Link and of course the hazards presented by the transportation of such goods should be considered. Typically for large infrastructure projects a dangerous goods policy will be developed which places restrictions on the time during which dangerous goods may be transported, in order to avoid peak hours, and the quantities of dangerous goods that may be transported in one shipment, to minimize consequences in the event of an incident.

For the Fehmarnbelt Fixed Link the policy relating to dangerous goods shall be driven during design stage by the operational risk assessment (ORA). Initially the ORA has been developed conservatively on the basis of no restriction on dangerous goods transportation either with respect to time or quantity. The relative impact of placing no restriction on dangerous goods shall be assessed in the context of the overall risk level and appropriate design decision shall be made on this basis.

In practice it is expected that the ORA will identify that the contribution to the risk level as a result of dangerous goods will be very small predominantly as a result of the low frequency of such incidents. However, for a number of reasons, this does not necessarily dictate that when the Fehmarnbelt Fixed Link is operational that there will not be restriction on dangerous goods. For example, within the ORA the probability of events involving dangerous goods is calculated based on limited statistical data and therefore must be addressed within the error bounds of the calculation.

Furthermore, the consequences of an incident involving dangerous goods can be very severe involving potentially significant loss of life. Therefore, regardless of the mathematical risk it may be determined as a result of societal and political issues, and consideration of the concept of ‘as low as reasonably practicable’, that a dangerous goods policy should be implemented. This will likely be based on international guidance and similar policies governing, for example, the Øresund Link between Denmark and Sweden.

It should also be taken into account what the alternative solution may be should dangerous goods be restricted across the Fehmarnbelt Fixed Link. As an extreme example, by restricting dangerous goods, the alternative route may pass by crowded public areas, hospitals, shopping districts or schools. The total risk in this instance, and the consequences as a result of an incident, may be significantly more.

The hazards associated with dangerous goods, as previously discussed, have a relatively low impact on the overall level of safety and more typically regular road accidents and fire events impact more heavily. In dealing with fire events there are a number of safety features and installations which are incorporated into the tunnel in order to meet the safety goals of prevention, self rescue, control and emergency response. The remainder of this paper concentrates on two installations; namely the road tunnel ventilation system and suppression system.

5. ROAD TUNNEL VENTILATION

Generally when developing a tunnel ventilation system a review of the international standards and guidances is recommended. However, it should be noted that most international standards and guidance documents are typically generic and not tailored to specific tunnel scenarios and being generic they must cater for a wide range of alternative designs. Therefore it is often appropriate to introduce some level of performance based design to ensure that a suitable system is provided. This approach then considers emergency ventilation in context and within a fully integrated safety strategy for the complete tunnel.

The majority of international standards and guidance documents would recommend that a mechanical ventilation system (ranging from a non-ducted longitudinal ventilation system, to a fully ducted transverse ventilation system) should be incorporated for a road tunnel of an equivalent length to the Fehmarnbelt Fixed Link. The type of system would mainly depend on the type of tunnel (uni-directional or bi-directional) and the expected traffic capacity (i.e. non-congested or congested traffic).

The traffic data for Fehmarnbelt Fixed Link indicates a relatively low number of vehicles, and there will be a dedicated, intelligent traffic management system. It is therefore expected that under normal operation, congestion inside the tunnel will not occur and can be prevented, even during peak hours. On this basis the use of a longitudinal ventilation system for smoke control is proposed in the conceptual design.

A longitudinal ventilation system is designed to create airflow within the tunnel and push smoke in the direction of the moving traffic flow. This airflow will need to provide a minimum “critical” velocity in case of fire to ensure that the smoke is pushed downwind, and cannot “backlayer” moving upstream over vehicles stopped behind an incident.

In the event of a fire in the road tunnel it is assumed that the traffic in front of the fire will continue to drive through the tunnel and will be travelling faster than the flowing smoke layer. The traffic behind the fire will stop and the occupants of these vehicles will commence the evacuation upstream of the fire. The occupants will be notified via the dynamic signage and the alarm system to evacuate into the adjacent road tube, via into the central gallery until the non-incident tube is clear, through appropriately spaced cross passages. Cross passages into the adjacent running tube will be spaced at intervals of 100m, significantly less than recommendations in international guidance, providing an increased level of life safety.

The proposed Fehmarnbelt Fixed Link tunnel is an immersed tube structure and therefore the use of a ducted ventilation system significantly increases the cross sectional area and perhaps necessitates the need for a ventilation island in the middle of the Fehmarnbelt. Preliminary concept calculation have indicated that the required ventilation duct would be of the order of 20m2 per road tube in order to overcome the pressure differences associated with ducting hot gases up to a distance of 9km. This duct area could be reduced by the introduction of a ventilation island in the middle of the tunnel thereby only requiring hot gases to be ducted a maximum of 4.5km. This would have the benefit of providing additional space for ventilation fan stations. However, introducing an island in the Femern Belt would have the recognisable drawback of increasing the risk for ship collisions with this island in the Strait.

A ducted system however has a number of other implications for the tunnel design over and above the longitudinal system. These include a reduced reliability and an increased risk to life safety due to more single points of failure, e.g. extract fan failure or fire damper failure, both of which have the potential to impact on the effectiveness system wide. Furthermore there are increased maintenance requirements, an increased construction time and increased costs.

Typically in tunnel fires the critical areas for life safety are within the vicinity of the fire and of the order of say a few hundred metres away, particularly downstream. At that distance away from the fire, visibility is likely to be lost however smoke temperatures will be reduced (especially with the inclusion of a suppression system) and toxicity often reduced below untenable conditions as a result of dilution. Within the Fehmarnbelt Fixed Link tunnel, exits are proposed every 100m which significantly improves the capability for self rescue. Any tunnel ventilation system with extract locations in excess of say 200m to 300m in essence result in a longitudinal system for occupants evacuating within the vicinity of the fire in respect to life safety. Thus in principle, tunnel length is not a risk factor.

Although technically a longitudinal system is feasible it represents a fairly significant departure from a standard code based approach for a tunnel of this length and is certainly not known to have a precedent with regard to length. Most tunnels over a few kilometres either have a transverse or semi-transverse ventilation system which often arises as a result of congested traffic being expected to occur on a regular basis.

Although there are no tunnels as long as the proposed Fehmarnbelt Fixed Link designed with a purely longitudinal system there is precedent for significant road tunnels using non-ducted longitudinal ventilation system. The Westerscheldetunnel in the Netherlands is 6.6km long and is provided with a longitudinal system. The tunnel traffic load in 2008 was 16,600 vehicles per day in both directions combined in comparison to the Fehmarnbelt Fixed Link design volume of approximately 12,000 vehicles per day in both directions combined. Furthermore the Westerscheldetunnel has a greater spacing between cross passages of 250m, is not provided with emergency lanes and has no suppression system. Qualitatively the level of life safety in the Fehmarnbelt Fixed Link can therefore be considered greater than in Westerscheldetunnel.

Other examples include both the Øresund Link (4.0km) and the Cross City Tunnel in Sydney, Australia (2.2km). Both tunnels have a high traffic volume, a uni-directional pair of tunnels and a longitudinal ventilation system. The Cross City Tunnel has a deluge suppression system installed while the Øresund Link does not.

As the primary concern for life safety is within the vicinity of the fire, venting the smoke 2.2 km (Cross City Tunnel, Sydney), 4.0 km (Øresund Link), 6.6 km (Westerscheldetunnel, The Netherlands) or even 18 km (Fehmarnbelt Fixed Link) all represent a similar level of risk. Therefore, although there is no precedent for a longitudinal system in a tunnel of this length the principle of longitudinal ventilation is employed in a number of tunnels around the world.

6. SUPPRESSION

Until recently the general guidance with regard to suppression systems is that they should not be installed in tunnels, with many regulatory authorities citing a number of potential hazards that might be caused by such systems including concerns with flammable liquid fires and steam generation. These reasons have previously been included in guidance in a number of tunnel documents from organisations such as NFPA and PIARC andm ost of these claims have arisen in Europe and North America.

Despite these recommendations suppression systems have for many years been installed in a number of longer road tunnels in Japan and, during the last 20 years, in all road tunnels in Australia. Recently, following the major fires in the Mont Blanc, Tauern, Gotthard and Frejus tunnels in Europe, PIARC and the NFPA have both revised their recommendations concerning suppression systems to much more positive consideration, but clearly state that such systems should only be installed as a part of an overall safety approach.

The authors of this paper have conducted a study into suppression systems installed worldwide. The number of suppression systems (both water mist and deluge) installed in selected countries worldwide are shown in Figure 2 and although the study does not profess to cover all tunnels the trend clearly shows that European countries have significantly less experience of tunnel suppression systems.

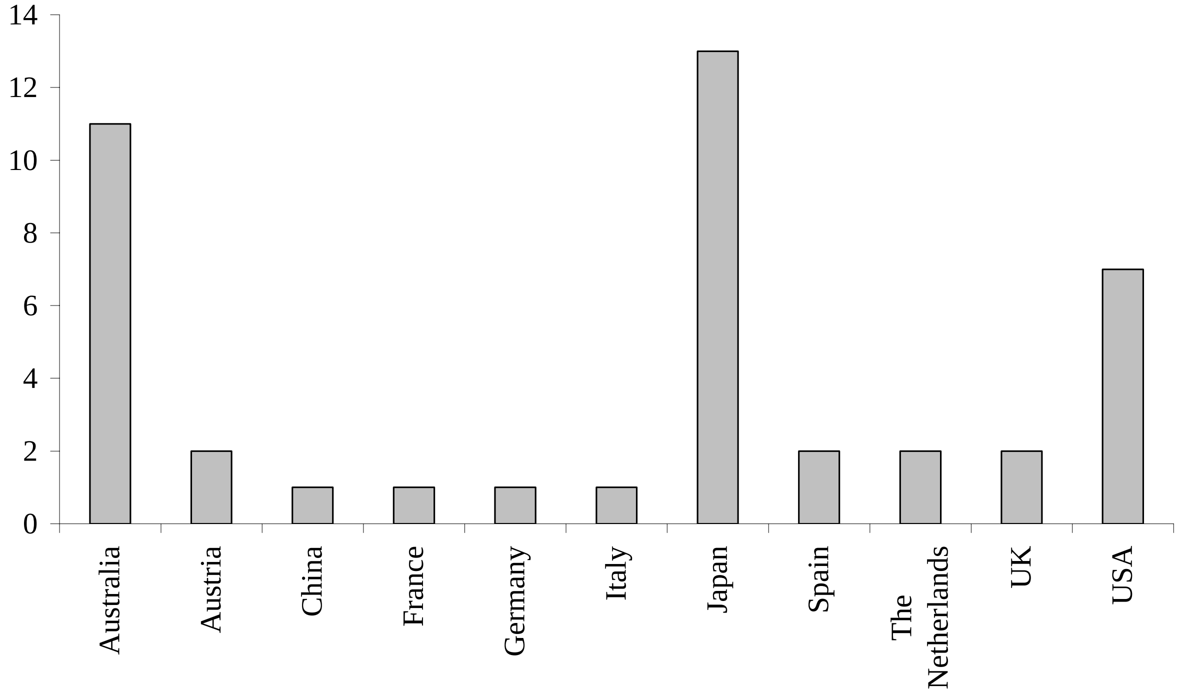

Figure 2: Number of road tunnels installed with a suppression system (water mist or deluge) per country

The trend for railway tunnels is less defined as there are limited known rail tunnels internationally incorporating a suppression system. This may be for a number of reasons including that rail fires are less frequent than road tunnel fires and, that in the event of a fire, trains are designed to drive out of the tunnel and thereby further reduce the incidents of rolling stock fires in tunnels. On this basis the cost/benefit of the suppression system may not be perceived to be significant enough to warrant the intial investment.

In both road and rail tunnels with suppression installed the immediate effect will be to limit the fire size and control the fire growth. Fires occurring in vehicles may sometimes not be directly affected by a suppression system if the fire is shielded by the vehicle. Therefore in these instances, the suppression system is controlling the fire rather than suppressing or extinguishing a fire. By controlling the fire, the development of a catastrophic fire can be avoided and the tunnel structure protected, minimizing damage and repair time. If the fire is controlled, the chances of a successful evacuation will increase whilst aiding the emergency services ability to control the situation.

By minimising the frequency of development of a catastrophic fire the risk to life safety can be drastically reduced and furthermore the downtime as a result of a fire can be minimised. In the context of the ORA for the Fehmarnbelt Fixed Link tunnel these two aspects assist in ensuring that the risk level to tunnel users, operational revenue and reputation is as low as reasonably practicable. For this reason a deluge suppression system is to be installed in both the road and rail tubes of the Fehmarnbelt Fixed Link. The decision to install a suppression system in the road tunnel can be justified financially through a cost/benefit analysis. In isolation the cost/benefit analysis for a suppression system in the rail tunnel may not be as credible. However, for the Fehmarnbelt Fixed Link, where the installation infrastructure is in place in the road tunnel, the decision is simplified. This suppression system is considered to represent the longest tunnel supression system in the world and continues the general trend towards suppression for rail networks either on board rolling stock or in tunnels.

7. SUMMARY

The Fehmarnbelt Fixed Link is a significant infrastructure project proposed to connect Scandinavia with continental Europe. At the time of writing a number of technical solutions are being explored including a cable-stayed bridge and an immersed tunnel. All of the solutions have challenges due to the scale of the link. However for the tunnel it is expected that the safety strategies and the overall risk level when using the tunnel will play a significant role in the success or failure of the solution. To this extent, the safety and risk strategies have been developed as integrated, holistic, performance based strategies to ensure that the specific features of the tunnel are captured.

This paper aims to present a brief case study of the conceptual design for the Fehmarnbelt Fixed Link tunnel solution. Some of the anticipated hazards have been discussed particularly in relation to dangerous goods and key aspects of the design specifically addressing fire hazards have been explored. The length of the tunnel is unprecedented however the principle of using a longitudinal ventilation system is tried and tested in practice as a proven technology and the functionality is independent of tunnel length. The ventilation system is part of the overall safety and risk management strategy which includes a suppression system in the road and rail tunnels, a continuous emergency lane for both road tubes and significantly shorter exit spacings than recommended in many international standards, regulations and guidance documents. The complete safety strategy is considered to present a considerable investment in safety for the Fehmarnbelt Fixed Link tunnel solution and will be subject to scrutiny by authorites in both Denmark and Germany over the coming months and years.

QUANTIFIED RISK ANALYSIS OF VENTILATION SYSTEMS IN ROAD TUNNELS: SIMPLE PORTAL-TO-PORTAL LONGITUDINAL VENTILATION VERSUS LOCAL SMOKE EXTRACTION SYSTEMS

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ABSTRACT

Road tunnel design guidelines in many European countries require a smoke extraction system be implemented for given tunnel design factors and traffic conditions. However, in some European countries, there are no design guidelines to specify the ventilation system. In those countries, a risk analysis approach based on EU Directive 2004/54/EC (minimum safety requirements for tunnels in the trans-European road network) may be applied to determine whether a simple longitudinal portal-to-portal ventilation system is acceptable. Otherwise, a local smoke extraction needs to be implemented.

A tunnel with unidirectional congested traffic is used as an example to determine, by means of a quantified risk analysis according to the above mentioned EU Directive, whether a simple portal-to-portal longitudinal ventilation with reduced spacing between the emergency exits may provide the same safety level as a local smoke extraction system compliant with the various national road tunnel design guidelines.

The results show that by reducing the distances between emergency exits, the same safety level can be achieved for both systems.

Keywords: EU Directive 2004/54/EC, quantified risk analysis, ventilation design, emergency exits

1. INTRODUCTION

In many European countries (e.g. Austria, Germany, Switzerland) national road tunnel design guidelines are in place to define the tunnel ventilation system concept for given design factors and traffic conditions. The distinction is made between natural longitudinal ventilation, mechanical longitudinal ventilation and ventilation systems with smoke extraction.

When choosing a ventilation system, European countries with no respective guidelines (e.g. Greece) may base their decision on the EU Directive 2004/54/EC [1] which leaves more leeway than offered by existing national tunnel guidelines. According to this Directive, a simple portal-to-portal longitudinal ventilation system can be used for a road tunnel, if a risk analysis proves it to be acceptable.

This paper aims to determine by means of a quantified risk analysis according to the EU Directive whether, for a two-tube tunnel with congested unidirectional traffic, a portal-to-portal longitudinal ventilation system may be used rather than a ventilation system with local smoke extraction as would be required by many national road tunnel design guidelines.

2. EU DIRECTIVE 2004/54/EC

The EU Directive sets forth the minimum safety requirements for tunnels in the trans-European network. It was adopted in 2004 by the European Union in response to the accidents occurring in the Mont Blanc (1999), Tauern (1999) and Gotthard (2001) tunnels.

The following two points of the Directive are relevant in choosing the ventilation system:

Point 2.9.3: *"In tunnels with bi-directional and/or congested unidirectional traffic, longitudinal ventilation shall be allowed only if a risk analysis according to Article 13 shows it is acceptable and/or specific measures are taken, such as appropriate traffic management, shorter emergency exit distances, smoke exhausts at intervals*."

Point 2.9.4: *"Transverse or semi-transverse ventilation systems shall be used in tunnels where a mechanical ventilation system is necessary and longitudinal ventilation is not allowed under point 2.9.3. These systems must be capable of evacuating smoke in the event of a fire."*

For a tunnel with unidirectional traffic as used in this study, the following may be said:

- If the traffic is not congested, a simple portal-to-portal longitudinal ventilation system may be used.
- If the traffic is congested, a simple portal-to-portal longitudinal ventilation system can be used provided that a risk analysis proves it to be acceptable. Otherwise, a local smoke extraction system needs to be implemented.

The EU Directive also specifies that *"a mechanical ventilation systems shall be installed in tunnels longer than 1000 m with a traffic volume higher than 2000 vehicles per lane"* (Point 2.9.2) and the *"distance between two emergency exits shall not exceed 500 m"* (Point 2.3.8).

3. VENTILATION SYSTEMS AND DISTANCES BETWEEN EMERGENCY EXITS IN SOME EUROPEAN COUNTRIES

The requirements regarding ventilation systems and emergency exits for tunnels with congested unidirectional traffic for the three German-speaking countries can be found below.

Requirements as to under what circumstances a certain ventilation system needs to be used may vary greatly. Generally, the requirements are much stricter than under the EU Directive.

3.1. Austria

Simple portal-to-portal longitudinal ventilation is only permitted in tunnels up to 1500 m. For tunnels between 1500 m and 3000 m, a longitudinal ventilation system with massive point extraction (maximum distance 750 m) has to be available, and for tunnels of more than 3000 m in length, the ventilation system must be a one with local smoke extraction. [2]

The distance between two emergency exits shall not exceed 500 m. [2]

3.2. Germany

Simple portal-to-portal longitudinal ventilation can be used in tunnels up to 600 m long and possibly up to 1200 m long if verified using a risk analysis. Above 1200 m long the emergency ventilation must be a local smoke extraction system with remotely controlled mechanical dampers. [3]

The distance between two emergency exits shall not exceed 300 m. [3]

3.3. Switzerland

Simple portal-to-portal longitudinal ventilation can be used in tunnels up to 800 m long and possibly up to 1500 m long provided a) the daily traffic flow per lane is lower than 11,000, b) the daily truck flow per lane is less than 800, and c) the gradients in the tunnel are between –1.5% and +1.5%. Above 1500 m long the emergency ventilation must be a local smoke extraction system with remotely controlled mechanical dampers. [4]

In single tube tunnel the distance between two emergency exits is between 300 m and 500 m, depending on the longitudinal gradient whereas in twin-tube tunnels the distance between two emergency exits (cross connections) shall not exceed 300 m. [5]

4. SIMPLE PORTAL-TO-PORTAL LONGITUDINAL VENTILATION VERSUS LOCAL SMOKE EXTRACTION SYSTEMS

The two ventilation systems differ mainly in the following aspects:

Unlike the longitudinal ventilation system, the smoke extraction system requires additional *civil construction works:* A smoke exhaust duct that directs the exhausted smoke towards the atmosphere. Throughout its entire economic life, the smoke exhaust duct must cope with different loading types (static air pressure, constraints, etc.) and only minor leakage (tunnel construction, closed dampers) may occur, which poses a major challenge to the manufacture of this structural element. Furthermore, ventilation station(s) to host the exhaust fan(s) and chimney(s) to safety disperse the smoke in the atmosphere are required.

The *electromechanical equipment* for local smoke extraction is substantially more comprehensive than for longitudinal ventilation. While both systems use jet fans, the system with local smoke extraction additionally uses exhaust dampers, exhaust fans, more cabling and a more complex ventilation control system.

The local smoke extraction comprises significantly more components than the longitudinal ventilation system, which is why it is more complex in *maintenance* as well. Both with regard to civil construction works (ducts/false ceilings, ventilation station, etc.) and electro-mechanical equipment (exhaust fans, exhaust dampers, etc.). Moreover, due to its high level of complexity, the system is naturally more prone to non-function and malfunction than a longitudinal ventilation system. Thus, regular maintenance is inevitable in order to ensure proper functioning of the exhaust ventilation in case of emergency. However, this requires a high degree of expertise, which could be a problem in technologically lesser developed countries.

In summary, it can be stated that the use of a smoke extraction as opposed to a longitudinal ventilation system comes with significant additional costs. Based on experience gained from previous projects, the costs for civil construction and electromechanical equipment are approximately 20% to 35% and 280% to 300% higher, respectively, than for a tunnel with simple longitudinal ventilation. Furthermore, additional costs for maintenance and power/energy throughout the economic life of the system need to be considered as well.

5. QUANTIFIED RISK ASSESSMENT

Article 13 of the EU Directive states that the risk analysis must cover all design factors (tunnel length, tunnel geometry, longitudinal gradient, etc.) and traffic conditions (characteristics, type) that affect the safety level. The Austrian tunnel risk model (TuRisMo) [6], developed by a group of experts in the field of tunnel safety and ventilation and published as an official Austrian guideline (RVS 09.03.11), fulfils this requirement.

The risk analysis used for this study is based on TuRisMo. Since this model considers dangerous goods in a simplistic manner and makes no distinction between different dangerous goods, the quantitative risk assessment model (QRAM) from OECD-PIARC [7] is used for this type of scenario.

TuRisMo follows the Austrian tunnel design guideline [2], thus the calculation of the risk for tunnel users is not possible for certain tunnel design factors. Namely for the consequences (fatalities) of scenarios involving fire, which depend on ventilation system, tunnel length and distances between emergency exits. On this account, additional one-dimensional ventilation simulations and evacuation simulations have been carried out to determine the consequences missing in TuRisMo.

5.1. Approach

Point 2.9.3 of the EU Directive states that a longitudinal ventilation system can be used, if a risk analysis shows that this is acceptable (Section 2). The term ”acceptable“ is not accurately defined (e.g. fatalities per year) and therefore leaves considerable room for personal assessment. In order to render the term more concrete, the safety level of a tunnel with local smoke extraction system and emergency exits every 500 m is defined as being “acceptable” and shall be quantified by the expected societal risk value in fatalities per year. This safety level is equivalent to the minimum safety requirements set forth by the EU Directive in cases where longitudinal ventilation is not acceptable.

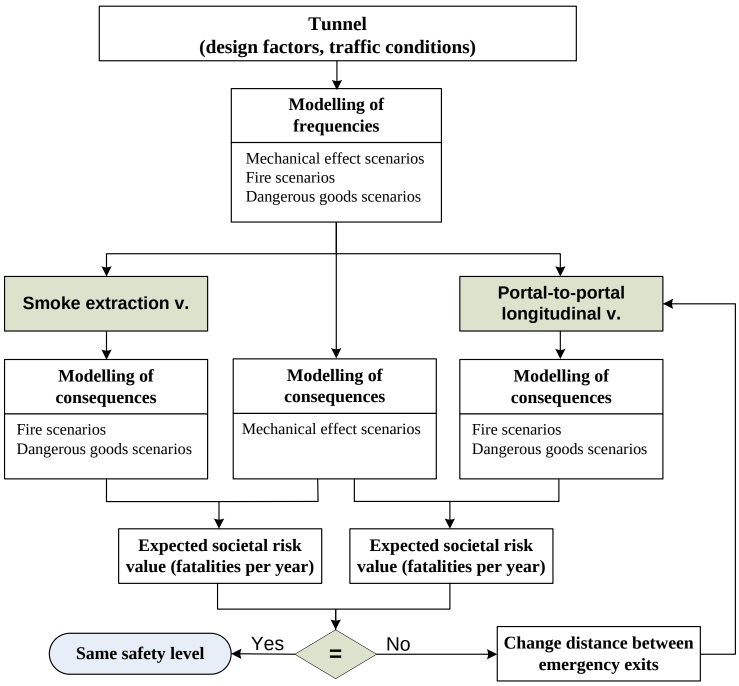


Figure 1: Approach of the safety level comparison

To examine whether a simple longitudinal ventilation system may be used, the following process within the risk analysis (Figure 1) is implemented:

The expected societal risk value for a tunnel with given design and traffic conditions using a local smoke extraction and emergency exits every 500 m has been determined. The very same value must be reached for a tunnel with identical design factors and traffic conditions using a longitudinal ventilation system with reduced distances between emergency exits. The required safely level shall be reached solely by reducing the distances between emergency exits.

The expected societal risk value is the sum of the products of frequency and consequence for all damage scenarios. The ventilation system only affects the damage extent of scenarios involving fire and dangerous goods, thus the risk analysis in this study could theoretically be limited to just those scenarios. However, since the percentage of scenarios with only mechanical effects (i.e. accidents, collisions, etc) constitutes a significantly larger part of the value, those scenarios are also being considered for illustrative purposes.

This approach is being pursued to assess whether, according to the EU Directive, a simple portal-to-portal ventilation system can be used for a tunnel (Section 5.3) when several national road tunnel design guidelines demand a system with smoke extraction (Section 3).

5.2. Damage scenarios

TuRisMo covers 28 damage scenarios with accidents or breakdowns being the initial events. The scenarios can be divided into mechanical effects, fire and dangerous goods scenarios for different vehicle types (passenger cars, heavy goods vehicles (HGV) and buses). Apart from scenarios involving dangerous goods, all scenarios are adopted from TuRisMo. For scenarios involving dangerous goods, QRAM from OECD-PIARC has been used.

Unlike TuRisMo, QRAM differentiates between various types of dangerous goods. The risk analysis covers scenarios involving flammable liquids in bulk, propane in cylinder, propane in bulk and ammonia.

5.2.1. Modelling of frequencies

The frequencies of the different scenarios in TuRisMo and QRAM are based on a statistical assessment of breakdowns and accidents. The ventilation system has no impact on the frequency of each scenario.

5.2.2. Modelling of consequences

The consequences for mechanical effects scenarios are taken from TuRisMo where they are again determined by means of a statistical assessment of accidents in tunnels. The ventilation system has no impact on the consequences of those scenarios.

The consequences for scenarios involving fire are calculated for passenger cars, HGV and buses through ventilation and evacuation simulations. The damage extent (fatalities) is calculated for one fire location (worst case) within in the tunnel and is based on the Fractional Effective Dose (FED) and the visibility.

Based on the duration of exposure, the FED concept [8] determines a person's incapacitation due to gases (CO, HCN, CO_2) produced by the fire or lack of oxygen (hypoxia). The method calculates the quotient of the dose inhaled in a certain time interval and the dose leading to incapacitation. The quotient is summed up for a series of time intervals, whereby incapacitation is reached when the sum is one. Apart from toxic effects, the FED is also used to calculate heat impacts (convection, radiation) on a person.

The visibility, which in case of fire is limited by soot particles, is of great importance in the self-rescue of people. The smoke from vehicle fires usually causes strong irritation of the eyes, which makes movement below a visibility range of 5 m virtually impossible. It has to be noted that disorientation occurs earlier. [9]

The consequences for scenarios involving dangerous goods are taken from QRAM from OECD-PIARC where they are established by means of different calculation models.

5.3. Example

A 3 km long twin tube tunnel with unidirectional traffic with the likelihood of traffic congestion is being used as an example. If the tunnel were to be built in Austria, Germany or Switzerland, the ventilation system would have to feature a local smoke extraction system. The key parameters of the example are shown in Table 1.

Table 1: Key parameters

TUNNEL, TRAFFIC, ACCIDENT AND BREAKDOWN DATA	
Tunnel length	3000 m
Tunnel cross section (LV / SV)*	53 m^2 / 53 m^2
Longitudinal gradient	3%
Number of lanes	2
Annual average daily traffic (AADT) per tube	40'000 veh/day
Traffic jam frequency	2%, 175 h/year
Vehicle proportion	Passenger cars: 76.5% HGV: 20% DG from HGV: 10% Bus: 3.5%
Vehicle speed	100 km/h (passenger cars) 80 km/h (HGV, buses)
Breakdown rate	2.372 per mill veh-km
Accident rate	9.52E-2 per mill veh-km 2.34E-2 per mill HGV-km
VENTIALTION AND EVACUATION DATA	
Response time of fire detection system (LV / SV)	1 min / 1 min
Response time of the ventilation system (LV / SV)	3 min / 3 min
Expected longitudinal velocity (LV / SV)	3 m/s; 1.5 m/s / 3 m/s, 0 m/s; 1.5 m/s
Visibility	≥10 m
Escape speed of a person	1.2 m/s
FIRE DATA	
Fire load (in 5 min with linear increase)	5 MW (passenger cars) 30 MW (HGV and buses)
Yield soot	0.13 [kg/kg]
Yield CO_2	2.07 [kg/kg]
Yield CO	0.043 [kg/kg]
Yield HCN	0.01 [kg/kg]
* LV: portal-to-portal longitudinal ventilation system SV: local smoke extraction system	

Notes on some key parameters:

For visibility ranges below 10 m, a drastic reduction of the escape speed can be expected and disorientation will begin. For the calculations it is assumed that people can save themselves, if the visibility range is greater than 10 m, and the escape speed is set to 1.2 m/s. [9]

For longitudinal ventilation systems, the air velocity is set to a minimum of 3 m/s in regular traffic and to a maximum of 1.5 m/s in a traffic jam so as not to destroy the smoke stratification. For local smoke extraction systems, it is set to 3 m/s upstream of the extraction zone and 0 m/s downstream for a fire occurring in regular free-flowing traffic. For a fire occurring in a traffic jam it is set to 1.5 m/s upstream and downstream of the extraction zone.

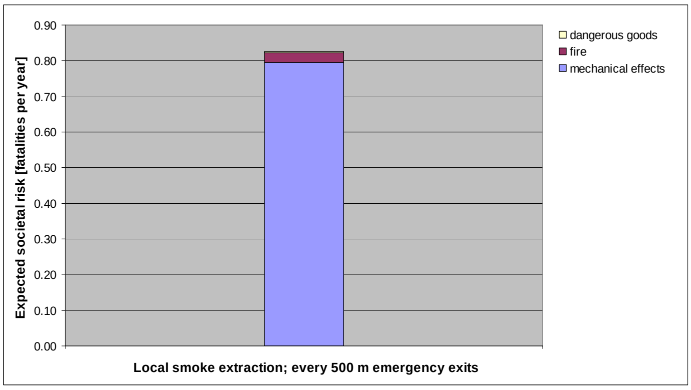
The yield values are the mean values for different material types (polyurethane foam, polystyrene, mineral oil) and are taken for all vehicle types. [10]

5.4. Results

In this section, the results of the societal risk estimation for both types of ventilation system are shown. The expected societal risk is expressed by mechanical effects, a fire and a dangerous goods component and generated for the different damage scenarios.

5.4.1. Local smoke extraction system

The figure and the table clearly demonstrate that, of the three components, the component mechanical effects has by far the largest influence on the expected value of societal risk.



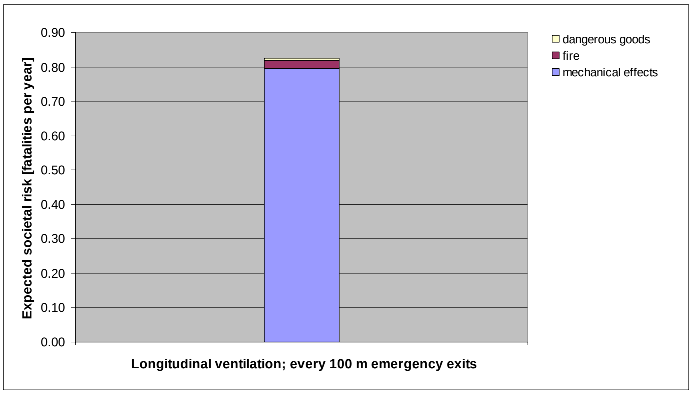
Societal risk	**8.255E-1**	**100%**
Dangerous goods	3.810E-3	0.46%
Fire	2.740E-2	3.32%
Mechanical effects	7.943E-1	96.2%

Figure 2: Expected societal risk [fatalities per year]

Considering that the twin tube tunnel can be ventilated with simple portal-to-portal longitudinal ventilation during normal traffic operation and that the smoke extraction is only necessary in emergency cases (i.e. just related to the risk components fire or dangerous goods), a large investment is needed for these rare occurrences.

5.4.2. Portal-to-portal longitudinal ventilation system

By means of an iterative approach, a distance between emergency exits of approximately 100 m was found to result in a similar societal risk as with the use of a local smoke extraction system. The results are shown in the following figure.



Societal risk	**8.247E-1**	**100%**
Dangerous goods	5.150E-3	0.62%
Fire	2.520E-2	3.06%
Mechanical effects	7.943E-1	96.3%

Figure 3: Expected societal risk [fatalities per year]

The calculation indicates that the required safety level can be achieved with a longitudinal ventilation system and a reasonable distance between emergency exits. The QRAM from OECD-PIARC features a very conservative evacuation model which does not react very sensitively to changes of the distances between emergency exits. As a result the proportion of risk due to dangerous goods cannot be sufficiently reduced by decreasing the distances between emergency exits and, thus, the risk needs to be offset by just the component fire.

6. DISCUSSION

The study shows that – based on the EU Directive – it is possible to replace the local smoke extraction system for the twin tube tunnel with simple portal-to-portal longitudinal ventilation system with reduced distances between the emergency exits while still achieving the same overall level of societal risk.

The determination of distances between emergency exits for simple portal-to-portal longitudinal ventilation systems greatly depend on fire data (fire load, yield values, fire location, reaction time of the ventilation system, etc), tunnel design factors (longitudinal gradient, etc.) and evacuation data (escape speed) concerning the escaping person. It is, thus, a very sensitive process. If for example the escape speed is reduced, plausible distances may no longer be calculated.

The study is based on recognised models. For scenarios involving fire and dangerous goods in unidirectional tunnels, TuRisMo calculates damage consequences for traffic jam situations only. The calculation shows that fire scenarios in free-flowing traffic do not cause any consequences, which is not the case for scenarios involving dangerous goods in free-flowing traffic.

Damage scenarios involving dangerous goods are based on QRAM from OECD-PIARC. This model proceeds on the assumption that the traffic in front of the accident can leave freely, whilst the traffic behind is blocked. Due to its low likelihood, the jam situation is not considered in this model. These scenarios are being accounted for very differently by the two models.

Furthermore, the risk assessment demonstrates that the societal risk components considered (mechanical effects, fire, dangerous goods) have different influences. The component mechanical effects has by far the largest impact. The proportion resulting from fire and dangerous goods is very small and depends on the duration of the daily traffic jam. If this value increases, the proportions of the two components in the societal risk are higher.

The safety level of a local smoke extraction system can be achieved more easily by measures which mainly concern the mechanical effects component. Such measures encompass reduction of speed for HGV traffic or a section speed control.

7. CONCLUSIONS

This study illustrates that the local smoke extraction system for the twin tube tunnel can be replaced by a simple portal-to-portal longitudinal ventilation system with reduced distances between emergency exits. Its validity will, however, largely depend on the input values used for the calculation. It needs to be stressed that this study does by no means question the requirements set forth by national ventilation guidelines. It merely wants to draw attention to the fact that considerable resources are being expended on localised smoke extraction systems to mitigate against the minor risks relating to fire and dangerous goods.

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TRAFFIC MANAGEMENT FOR AN URBAN MOTORWAY TUNNEL IN BERLIN

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ABSTRACT

Tunnels in Berlin were planned - due to the current standards - to be operated without periodic congestion. But often during morning peak hours traffic demand exceeded capacity in the TOB-tunnel (Tunnel Ortskern Ortsteil Britz) on the motorway A100 with the result that the tunnel had to be closed. To avoid this situation – at least to reduce the duration or the number of closings – a three level strategy was developed. By these means the number of complete tunnel-closings could be fixed to about 10 closings a year although the motorway is connected in the meanwhile to the Berlin Motorway Ring and traffic has grown.

Keywords: city tunnels, traffic control

1. INTRODUCTION

Since 2000 the TOB-tunnel is part of the Berlin urban motorway ring and has a daily flow of about 60.000 vehicles in each direction with three lanes (total cross section 120.000 veh/24h). The first years in operation daily traffic volume grew and the congestion extended more and more often into the tunnel, e.g. 200 times in the year 2009. Especially during morning peak hours the downstream interchange AD Funkturm is often congested for northbound traffic. Considering the actual German guidelines RABT 2006 the tunnel has to be prevented from periodic congestion and the standard mean is to close the tunnel upstream to avoid vehicles from entering the tunnel. Typical closure duration has been 20 minutes. The southbound direction doesn't have this problem because the afternoon peak usually isn't so high as the morning peak. But this approach had some disadvantages. On the one hand the road users considered the closure as very unpopular and on the other hand it took a too long time for the new congestion at the tunnel entrance for dissolving. A third reason for activity was the extension of the motorway A113 southwards (carried out 2008) and the planned prolongation of the A100 to the east with expected growing traffic on the highway. The new motorway projects A100 are discussed intensively in public, therefore it is very important to show that the already existing links still are able to manage daily traffic.

2. REQUIREMENTS AND SITUATION

In RABT 2006 it is required that a tunnel is free of congestion in normal use. Considering the volumes and speeds of a typical day downstream (figure 1) and upstream (figure 2) there is a significant risk for congestion between 7:00 and 8:30. This observation corresponds to the closure times and durations shown in table 1. The prognosis for the year 2025 (GVP 2025, 2009) shows a significant increase of traffic demand compared with 2006 but the main reason is the commissioning of the motorway A113 in 2008, compared with the present day there will only be small changes and we needn't expect that the situation gets worse. On the other hand, the congestion's cause is the oversaturation of the interchange A100/A115 AD Funkturm in the morning peak. There will be only minimal changes within the next 15 years, too. Thus solutions have to be cheap and first to be found in operation actions with already existing systems because the problem will not grow in the future.

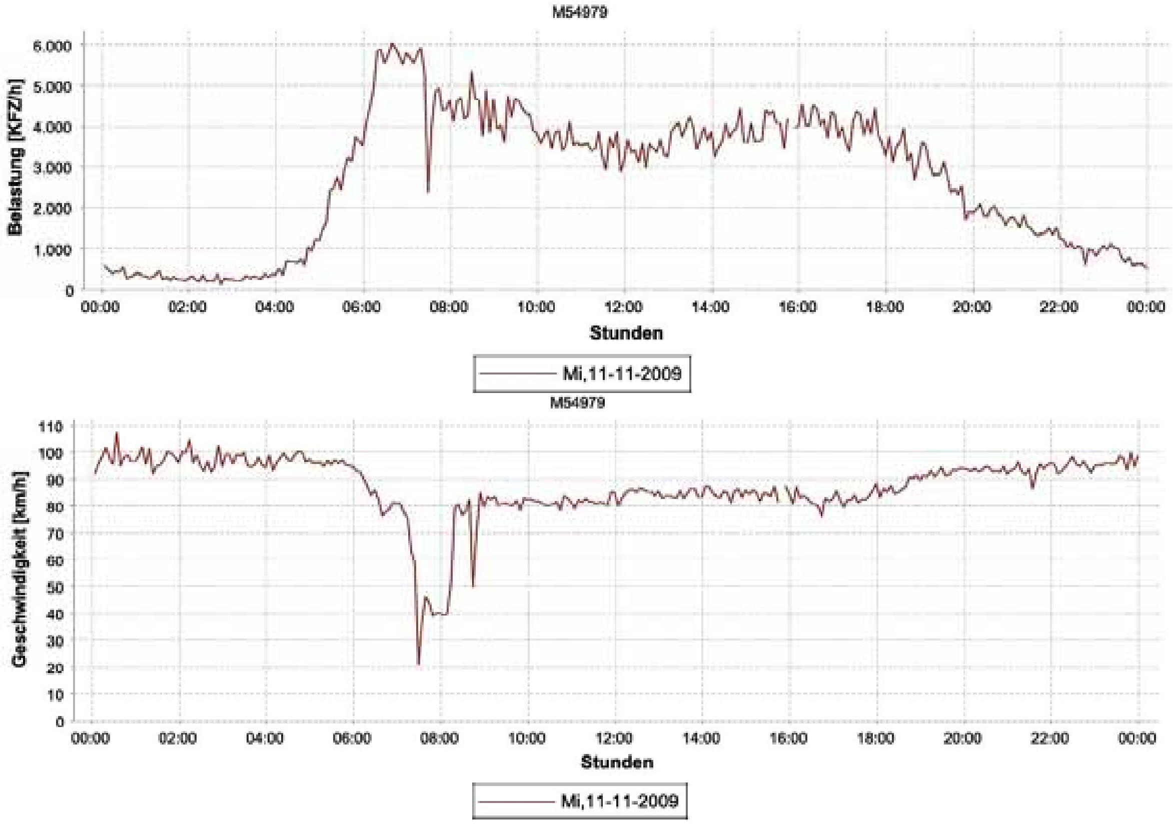

Figure 1: Typical volumes and speeds downstream (11.11.2009)

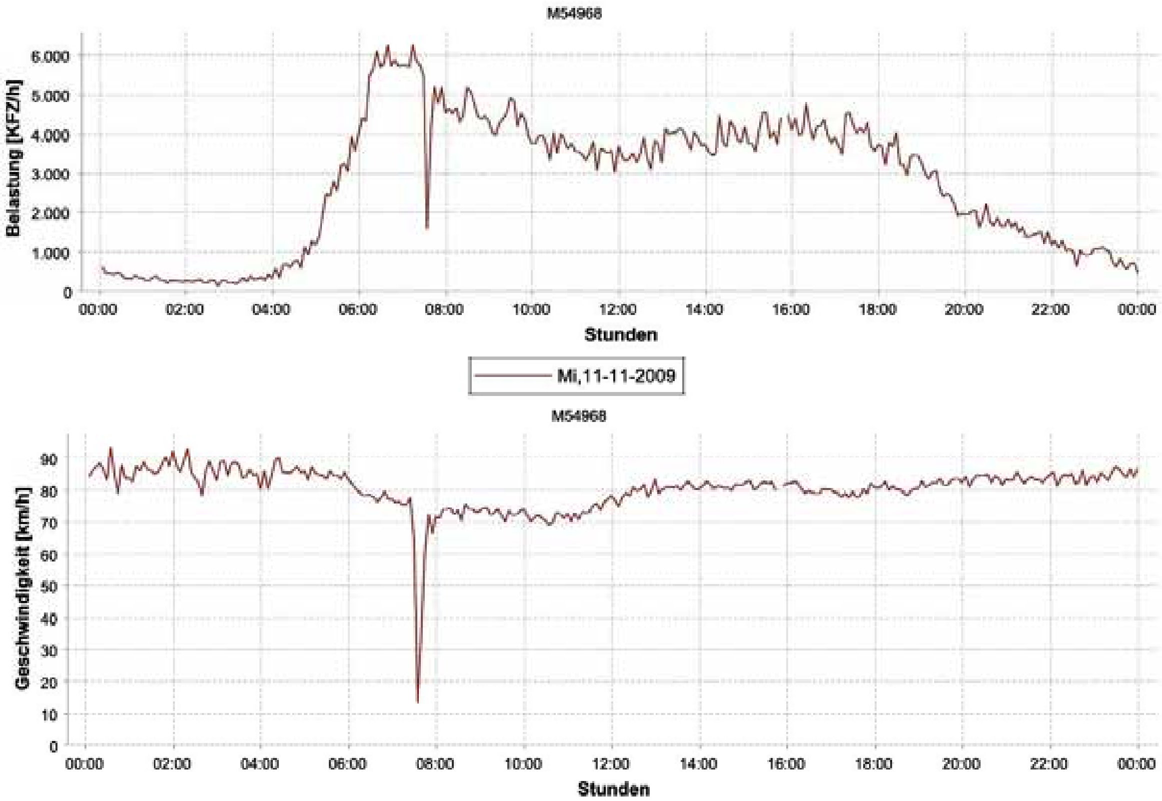

Figure 2: Typical volumes and speeds upstream (11.11.2009)

Table 1: Typical tunnel closure time and duration

Date	begin	date	end	
11.11.2009	07:29	11.11.2009	07:42	ADN ->TOB Zuflusssteuerung, erh. Verkehrsaufkommen
11.11.2009	07:34	11.11.2009	08:12	A100 -> N AS Britzer Damm gesperrt, erh. Verkehrsaufkommen
11.11.2009	07:36	11.11.2009	08:18	A100 -> N AS Buschkrugallee gesperrt, erh. Verkehrsaufkommen

The tunnel has opened in 2000 and has up-to-date equipment for ventilation, safety and traffic control. A scheme of the traffic control equipment at the eastern ramp equipment is shown in figure 3.

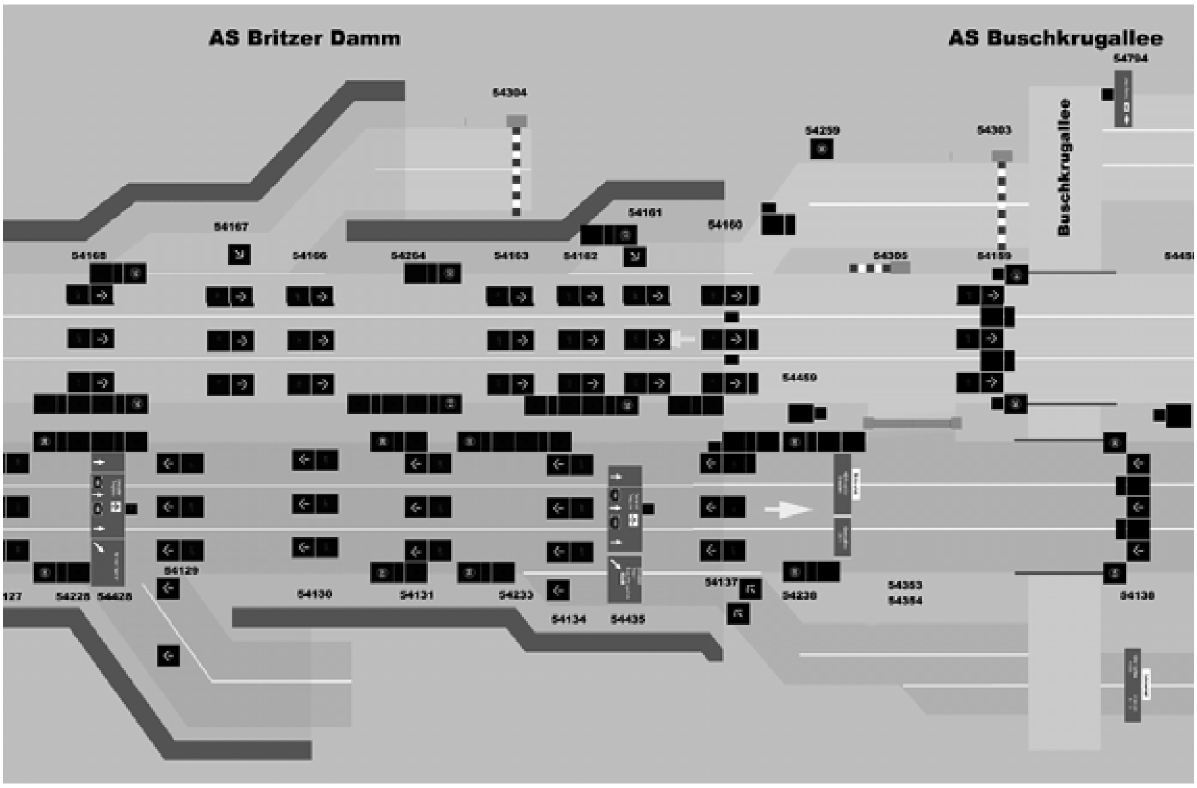

Figure 3: Traffic control in the eastern ramps

All motorways in Berlin have Variable Message Signs for speed limits, congestion warnings, black ice warnings and lane control. According to the tunnel requirements there is closing equipment consisting of signals, booms and illuminated ground marks und dynamic route direction signs.

An emergency or congestion-caused tunnel closing procedure consists of

- closing the tunnel at the portal
- closing the lanes
- closing the ramps and
- activation of information signs at surrounding roads.

A typical traffic situation in the entering directions after some minutes of closure is shown in figure 4.

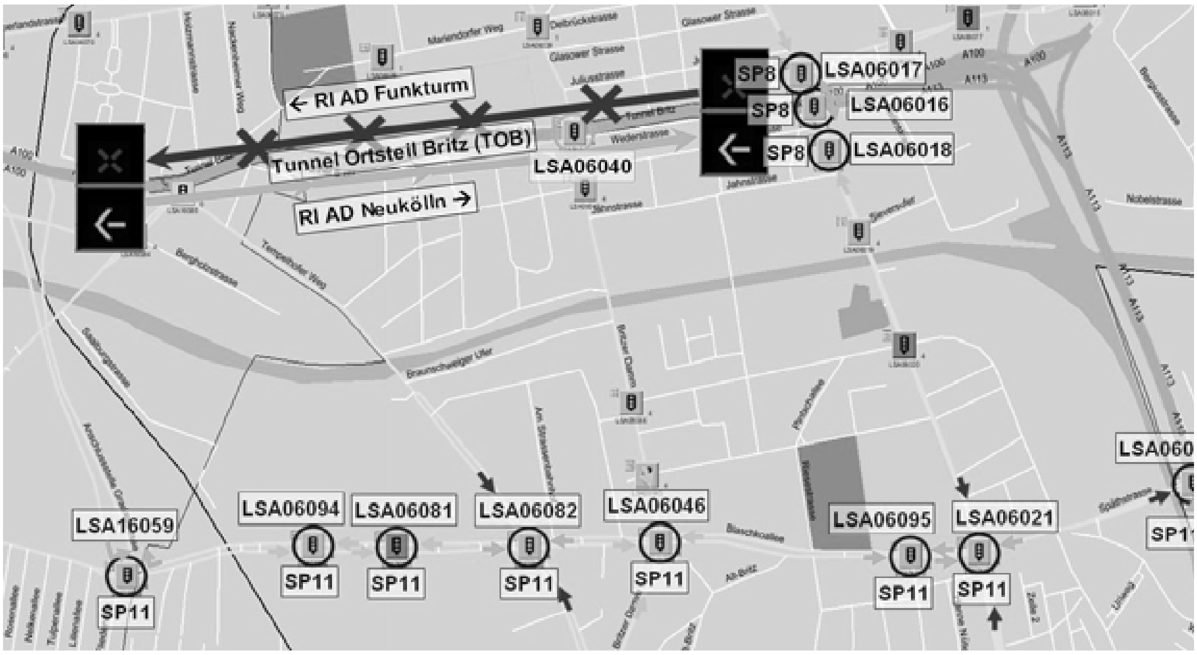

Figure 4: Traffic situation at the TOB during tunnel closure

If the traffic situation improves downstream operation staff identifies the time of re-opening an after about 10-30 minutes the upstream congestion is dissolved.

3. STRATEGY

To avoid tunnel closure by capacity overload there are two starting points: the first is to increase capacity downstream and the second to reduce entering volumes upstream. Increasing output capacity is very difficult to achieve because of the close interchange, missing alternative routes and missing technical equipment for e.g. ramp metering. Reducing entering volumes is easier because the standard motorway equipment can be used for the closure of single lanes to generate a bottleneck and reduce capacity. If three lanes are passed by up to 5700 veh/h closing one lane will reduce capacity to about 3800 veh/h. Also the emergency booms can be used not only in the case of tunnel closures but also for a kind of ramp metering. A closure of the ramps Buschkrugallee and Britzer Damm may reduce entering traffic by up to 700 veh/h in the morning peak. To reduce the impact of a more intensive use of ramp closures to secondary roads signal plans for 8 signalised intersections along the alternative route have been developed to increase capacity. In average the capacity can be temporary increased of 25 per cent (from about 1000 veh/h to 1200 veh/h) at the expense of lower level directions by the new signal plans. Because of several crossing bus lines this capacity increase may only be very moderate.

4. IMPLEMENTATION

The actions

- lane closure to drop capacity,
- ramp closure without tunnel closure and
- activation of special signal plans for the alternative route
- activation of dynamic direction signs
- generation of a TMC-message for broadcasting and dynamic route guidance systems

have been integrated into the existing central control system. A geographical overview is shown in figure 5.

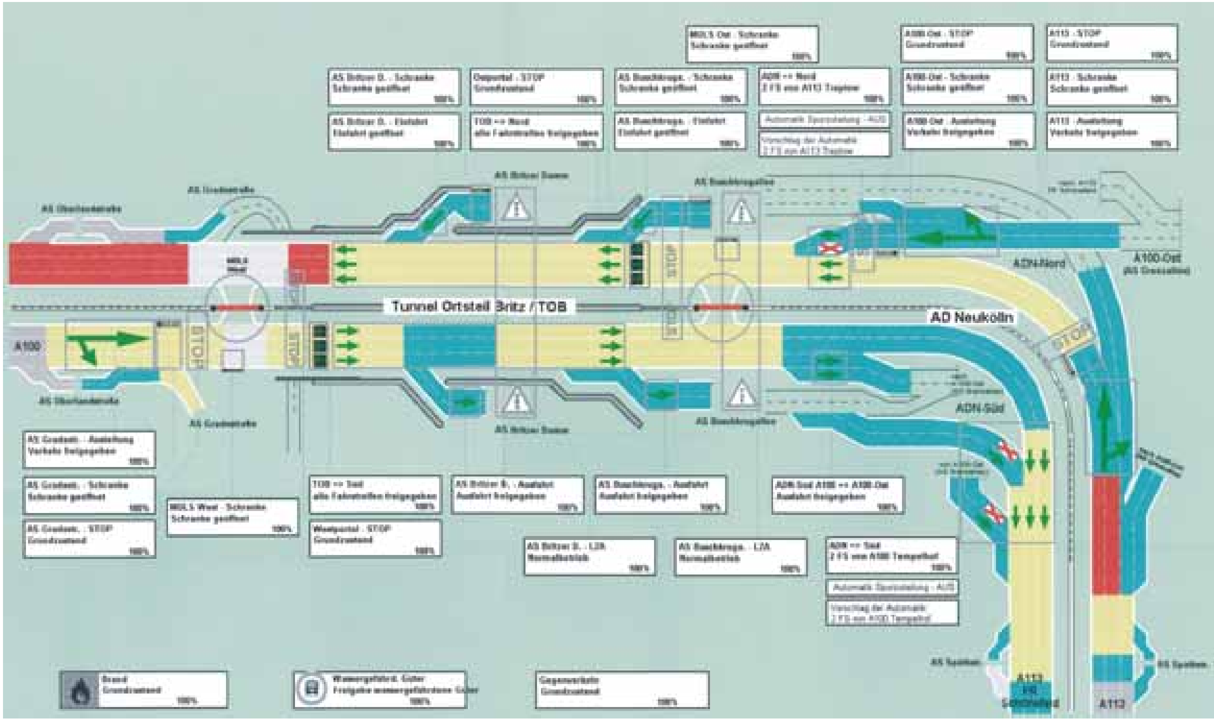

Figure 5: Traffic management infrastructure TOB northbound

All actions are undertaken by the operation staff in the Berlin traffic control centre manually. As soon as staff expects a tunnel congestion one lane in upstream direction will be closed outside the tunnel, as a consequence the congestion will increase on the motorway A113 instead of the tunnel. Usually some minutes later staff is able to decide on a ramp's closure. The last suitable action is the closure of the tunnel.

5. RESULTS

Strategies were implemented in November 2007 and had been activated 6 times in 2007. By intensive traffic observation the staff's experiences has grown and the actions are now activated up to several times a week. In May 2008 the new motorway section A113 was opened and an increase of tunnel closures was expected in public due to increased traffic. Exact volumes, numbers of tunnel closures (northbound) and numbers of staff actions are shown in table 2.

Table 2: Volumes, tunnel closures and activated strategies

	veh/24h	tunnel closures of capacity lack	strategy activations	remark
2005	90.000			
2007	110.000	9	6	11/2007: start of strategies
2008	118.000	3+8	19+52	5/2008: new motorway
2009	120.000	8	75	

Although there is an increase in traffic an increase of tunnel closures could be avoided as a result of strategy activations, the public's expectation didn't fullfill.

6. CONCLUSIONS AND OUTLOOK

German RABT 2006 guidelines have to be applied for all tunnels in Germany. Because of different conditions in the surrounding road network in addition more actions have to be undertaken to guarantee free-flow traffic.

Especially in city regions tunnel safety doesn't stop at the tunnels' portals. Congestion is also dangerous on motorway and has to be avoided by all means of traffic control infrastructure (e.g. direction signs, ramp metering and signals) and also by updated information for passengers.

Pre-emptive traffic control by several means has improved traffic in Berlin very often and avoided a lot of tunnel incidents. These positive experiences will be assigned to more tunnels in Berlin.

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AUTOMATIC CONTROL OF TWO-WAY TUNNELS WITH SIMPLE LONGITUDINAL VENTILATION

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ABSTRACT

An effective automatic control system (FCVC) is introduced for relatively long, two-way tunnels with longitudinal ventilation. Although it is increasingly rare to build long tunnels of this type, many exist already. The proposed system was developed especially for responding to fire, but it is also effective in routine operation, easily out-performing feed-back, feed-forward and AI-Fuzzy control. The effectiveness of the method is demonstrated by using it to control a virtual tunnel. Its tolerance of unavoidable measurement errors in practical operation is assessed by deliberate falsification of values determined by the virtual tunnel at sensor locations. The control method is equally suitable for fixed-speed or variable-speed fans, but the latter are recommended on practical and environmental grounds.

1. INTRODUCTION

Japan has hundreds of two-way, longitudinally ventilated tunnels with elementary control systems. In this paper, only tunnels with purely longitudinal ventilation are considered, namely those with no intermediate shafts or smoke extraction facilities. Some of these are quite short, but others are relatively long – up to at least 3000 m. It is estimated that 500 such tunnels exist in the length range from about 500 m to about 3000 m. There is much debate about the maximum desirable length of *future* tunnels of this type, but those that exist already must be used as efficiently and safely as possible.

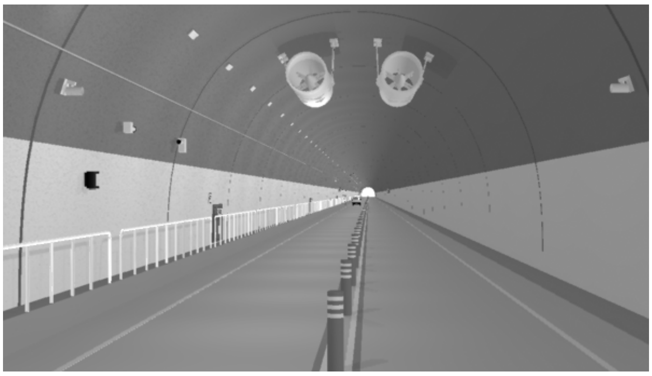

Figure 1: Longitudinally ventilated tunnel with two way traffic

The tunnels under consideration herein have no provision for fire detection. The aim now is to install detection systems and to use them in the automatic control of installed jet fans. Since the ventilation is wholly longitudinal and the tunnels have no shafts or branches, the control objective in the event of a fire is to approach zero air flow as soon as possible and to maintain this condition indefinitely.

The tunnels already have jet fans that are used in routine operation. In most cases, they are either (i) switched on and off at predetermined times based on historical records of traffic data or (ii) operated using FB or AI-Fuzzy control. The installation of a control system for responding to fire provides an opportunity for also upgrading routine control. The proposed system achieves this in a simple and reliable manner. Moreover, its design is such that the response to fire is a simple sub-set of routine control. As a consequence, an unusually high level of confidence can be placed in the robustness of the response to fire (see later).

The proposed control system includes provision for manual over-ride, but supervised control centres will typically be tens of kilometres from any particular tunnel. The controllers will be well trained in the use of the systems, but they will have only limited access to information about what is happening at any particular instant. This is especially relevant for control in response to an incident, but it also influences the choice of control during routine operation.

2. AUTOMATIC CONTROL SYSTEMS

Figure 2 shows the general layout of a tunnel with jet fans and sensors. For the new control system, it is essential to have a fire detection system and air velocity sensors. In the case of routine operation, it is also essential to have VI and/or CO sensors and desirable to have traffic sensors.

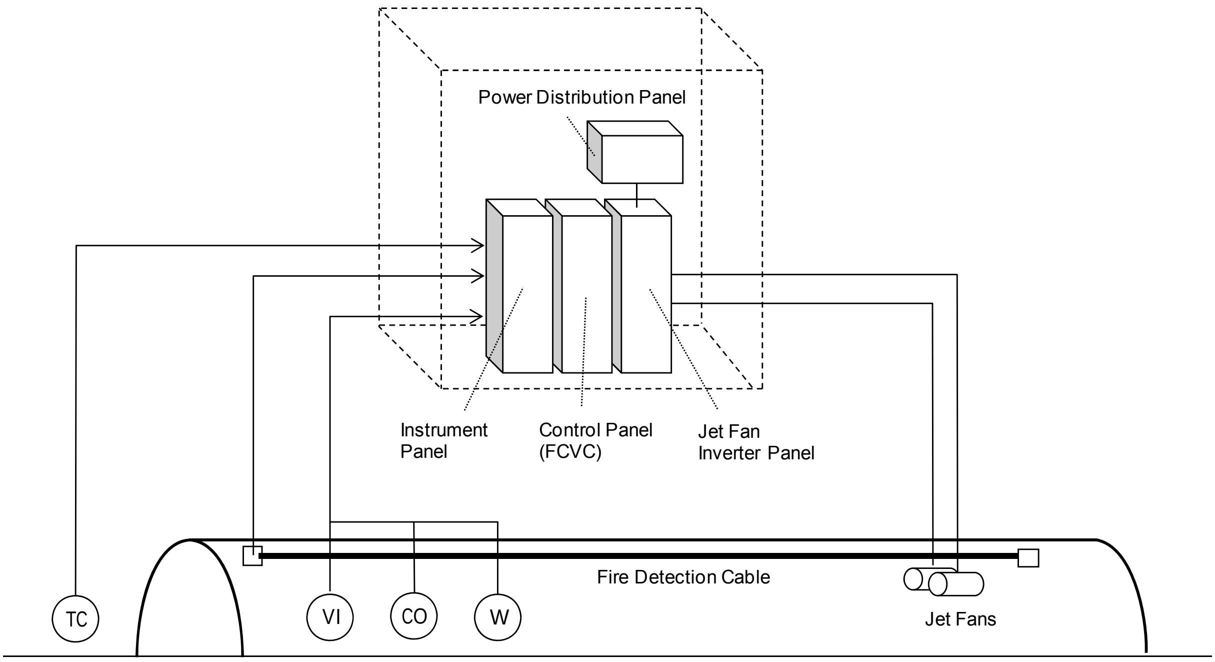

Figure 2: Tunnel equipment, sensors and controllers
(*TC = Traffic Counters; W, VI, CO = Air speed, Visibility & CO sensors*)

In Japan, the majority of existing methods of automatic control during routine operation are one of three types, namely Feedback, Feed Forward and AI Fuzzy. These may be summarised as:

- In **Feedback** control (FB), fans are activated in response to measured values of the visibility index VI. In the simplest cases, only the instantaneous value of VI is used. Alternatively, however, the control algorithm can also allow for the rate of change of VI.
- In **Feed Forward** control (FF), fans are activated according to expected future traffic conditions. This can be deduced from traffic counters upstream of the tunnel as well as from counters within the tunnel itself.
- **AI Fuzzy** control is a combination of FB and FF. That is, the adjustment process is influenced by both pollution and traffic measurements.

Although FB and FF are attractively simple, experience shows that they are not very efficient. AI Fuzzy is more effective, but it too has severe limitations and, in practice, it is difficult to configure its optimisation processes in a robust manner. In recent years, a more comprehensive system known as Model-Based Ventilation Control (MPVC) (e.g. Nomura *et al*, 2009) has been installed in several tunnels, including the longest road tunnel in Japan, namely the Kan-Etsu Tunnel. The original tunnel had two-way traffic in a single tube (e.g. Asagami & Nagataki 1988, Ohashi, *et al* 1982, Mizuno, *et al* 1985, 1988), but there are now two one-way tubes. MPVC includes on-line simulators of traffic flows and air flows and this enables it to make intelligent use of data from the various sensors. Thus, for example, measurements from VI sensors can be used to infer information about air velocity and vice-versa. Technically, it would be a good solution for the tunnels considered herein, but the proposed system (FCVC) is simpler and, for tunnels with no shafts or branches, etc, it is highly effective.

3. OVERVIEW OF PROPOSED CONTROL SYSTEM (FCVC)

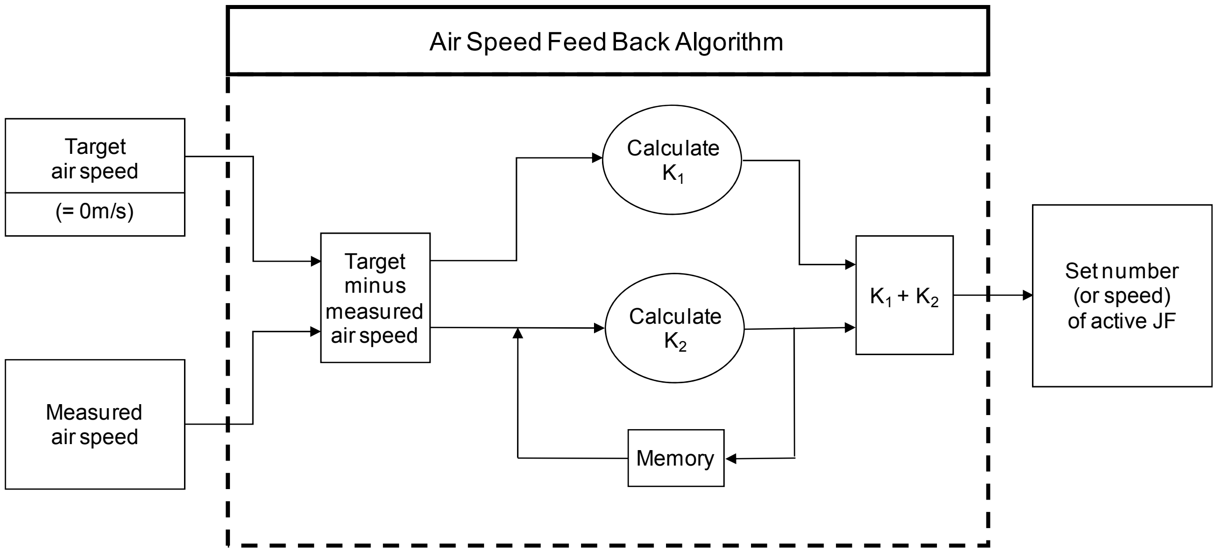

Figure 3: FCVC Flow Chart - Emergency-operation mode
(*K_1 = proportional factor, K_2 = Integral factor*)

Figures 3 and 4 depict the new control system (FCVC). In emergency operation, the only *external* input data are the target air speed and the current measured air speed. In addition, the input box labelled "Current values of FCVC air speed parameters" supplies *internal* parameters that were output at the end of the preceding control period. These parameters are important because they convey information about the historical conditions in the tunnel. They are integrated parameters describing cumulative consequences of past control actions.

The only *external* output from the FCVC algorithms at the end of each control loop is (in effect) the optimum thrust to be supplied by the jet fans. The box "Choose number/speed of active JF" converts this to either (i) an integer number of fans at full speed or (ii) the optimum speed of rotation of inverter-driven fans (see Section 4). The box labelled "Updated values of FCVC air speed parameters" receives the updated values of the cumulative historical parameters in preparation for input at the beginning of the next control period.

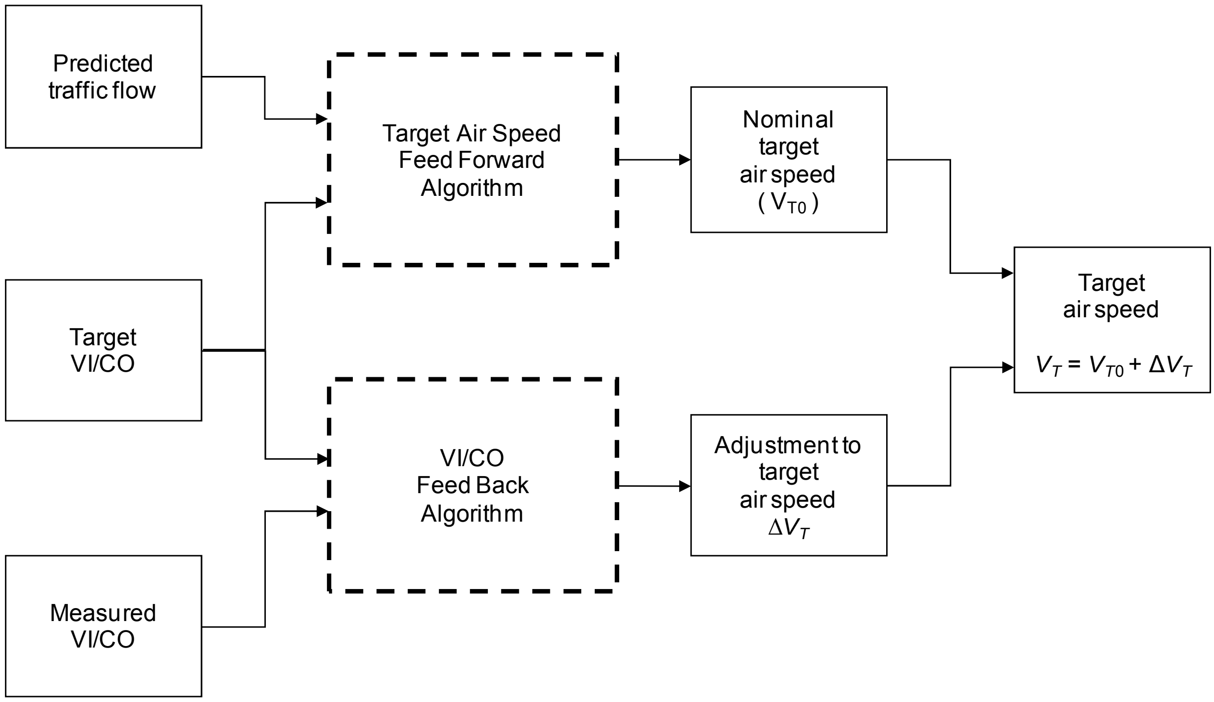

Figure 4: FCVC Flow Chart - Calculation of target air speed in Routine-operation mode

In *routine* operation, FCVC is a two-step process. First, it calculates the air speed needed to maintain acceptable concentrations of pollution. The external input data for this step are the target and measured concentrations and the external output is the desired air speed. Once again, there are also *internal* data enabling cumulative historical information to be passed from one control period to the next. The second step of FCVC in routine operation is identical to that shown in Figure 3 for emergency operation. The only conceptual difference is that the target air speed has been calculated in step-1, not prescribed a priori.

3.1. Important safety feature

The fact that the emergency-operation mode is *identical* to the second step in the routine-operation mode is hugely important from a practical standpoint. It offers a cast-iron guarantee that the emergency mode will be available and fully effective when (or if) it is ever needed. This is a really valuable safety feature. It is a big contrast with most control systems. Usually, emergency-operation modes are separate entities that need to be tested independently. With FCVC, however, the (emergency) control algorithms are, in effect, used continuously 24/7 and so are the tunnel sensors that provide the necessary input data.

3.2. FCVC algorithms

There is insufficient space in one paper to describe the details of the FCVC internal algorithms as well as to describe the overall system and its proposed operation. However, attention is drawn to two important characteristics of FCVC that distinguish it from previous control methods. The first of these is its explicit allowance for cumulative historical conditions. Very simple control systems determine the required fan thrust according to current conditions only. More advanced systems also allow for measurements of *current* rates of change of conditions. However, the authors are not aware of any other method (except model-based methods such as MPVC) that allow explicitly for historical rates of change.

A second important feature of FCVC is that it its internal algorithms focus explicitly on *differences* between measured and target conditions. The algorithms inside many control systems are designed to achieve desired absolute values of some parameter. In contrast, FCVC is designed to eliminate differences between desired absolute values and current measured values. This is not simply an academic point; it has important consequences for the error handling performance of a control system. In the case of FCVC, the target condition for FCVC is always "zero". The *first* purpose of the internal algorithms is to decide whether the control actions need to cause an increase or a decrease. The *second* purpose is to decide the required amplitude of the increase or decrease. Mathematically, of course, the two approaches are equivalent. Practically, however, the sensitivity to errors tends to be proportional to the amplitude of the target - so a target of zero has special advantages.

3.3. Response to fire

In this paper, special attention is paid to the use of FCVC in its emergency-operation mode. Since the tunnels for which it is primarily intended are remote and un-manned, the emergency-mode must itself be triggered automatically. That is, the tunnel must be equipped with a reliable method of detecting fire. In principle, any method that is robust may be chosen, with obvious preference given to methods exhibiting the most rapid responses. The selection of the most appropriate method in any particular tunnel is outwith the scope of this paper.

In addition to the importance of a reliable fire detection system, it is also crucially important that FCVC is provided with reliable information about the air speed in the tunnel. As discussed above, identical *use* of this information is made in the routine and emergency operation modes. Nevertheless, the importance of minimising error is clearly greater in the emergency case and so this is the case that should determine the provision of air speed sensors. To allow for possible failure of sensors (notably those close to a fire), it is essential to have more than one air speed sensor and highly preferable to have at least three.

In the event of a fire being detected in the tunnel, traffic signals at the portals will be set to red and vehicles already inside the tunnel will leave if possible. Nevertheless, some vehicles might remain and their location relative to the fire will be unknown. Accordingly, the most likely strategy will be to bring the airspeed along the tunnel to rest and to maintain it in that state until the emergency services have arrived. This will minimise the spread of smoke and it will maximise the time available for escape. For FCVC, this simply means that the target air speed will normally be zero even though, in principle, it could be used equally effectively with a non-zero target velocity if required.

Once a fire has been detected, the control system should seek to achieve the new target air speed as rapidly as possible. This is an important reason for the existence of the historical algorithms in FCVC. Because of them, it is possible for FCVC to "learn" very quickly indeed. Suppose, for example, that the current rotational speed of the jet fans is 30% of maximum and that the rotational speed required to maintain a steady air speed of zero is 55% (*NB: FCVC will not "know" that the ultimate condition will be 55%*). In this case, the most rapid possible change to zero air flow would probably be achieved with a short period at 100% followed by a decrease to 55%. This would be more effective than a one-step change from 30% to 55%, for example. FCVC would not achieve the optimum exactly, but its algorithms would have the same general effect (see Section 5).

4. INVERTER-DRIVEN JET FANS

In nearly all existing tunnels with jet fans, the nominal state of any individual fan at any instant is either “fully on” or “fully off”. The control system determines the minimum number of fans required to achieve the desired rate of flow. This approach is simple, effective and robust. Unfortunately, however, it also has undesirable consequences. Suppose, for instance, that the air speed is +1.5m/s when N fans are operated and that it is -1.5 m/s when N+1 fans are used. In this case, it would not be possible to control the tunnel in such a manner that zero flow is achieved. That would require the notional use of N+½ fans.

This is far from being a trivial matter. Although many humans can easily move faster than 1½ m/s for a sustained period, some cannot and would therefore be at serious risk in the hypothesized circumstances. Indeed, the risk is further increased by the fact that the leading edge of a hot smoke layer may travel more rapidly than the mean air speed.

Nakahori *et al* (2009) showed that it is possible to overcome this difficulty in a simple manner, namely by using variable-speed fans. They proposed the use of inverters for this purpose and demonstrated the effectiveness of the approach by full-scale testing. The focus of that particular paper was on the use of the inverter-driven fans to achieve major reductions in energy costs in routine ventilation as proposed previously by Bopp (1994). However, the use of inverter-driven fans is equally applicable in the response to fire and it has the major advantage of enabling zero airspeed to be achieved with high accuracy. This feature is now illustrated by means of a practical example.

5. VIRTUAL TUNNEL

FCVC has not yet been implemented in a real tunnel, but it has been tested extensively in a virtual tunnel in manner that enables its robustness to be assessed reliably. The virtual tunnel is illustrated schematically in Figure 5. In principle, it is a tunnel simulator that reproduces many features of a real tunnel – including random-like errors and uncertainties in measured data. The simulation routines predict time-dependent air speeds and pollution, etc throughout the tunnel system based on prescribed information about traffic conditions and fans, etc. The simulations yield comprehensive information about conditions throughout the tunnel system, but, in common with real tunnels, the conditions are sampled only at discrete locations. Thus, for example, air speeds are output only at locations where a flow sensor is imagined to exist. Furthermore, the output values are not output in a pure form. Instead, they are adjusted in ways that mimic measurement errors that are inevitable in real tunnels. Thus, the virtual tunnel behaves as closely to a real tunnel as is realistically possible.

5.1. Key components of the virtual tunnel

All ***input data*** for the virtual tunnel are nominally “real” values. They include such parameters as tunnel geometry, fan performance characteristics and vehicle performances characteristics as well as atmospheric conditions and the prescribed states of the traffic and fans. For obvious reasons, however, some simplifications are necessary. For example, the tunnel is regarded as a duct of uniform cross section and uniform resistance characteristics. Likewise, the vehicles are modelled as drag sources - although each of these sources moves through the tunnel independently of the others and each has its own controlled, but inherently random, variations in drag, speed and exhaust emissions.

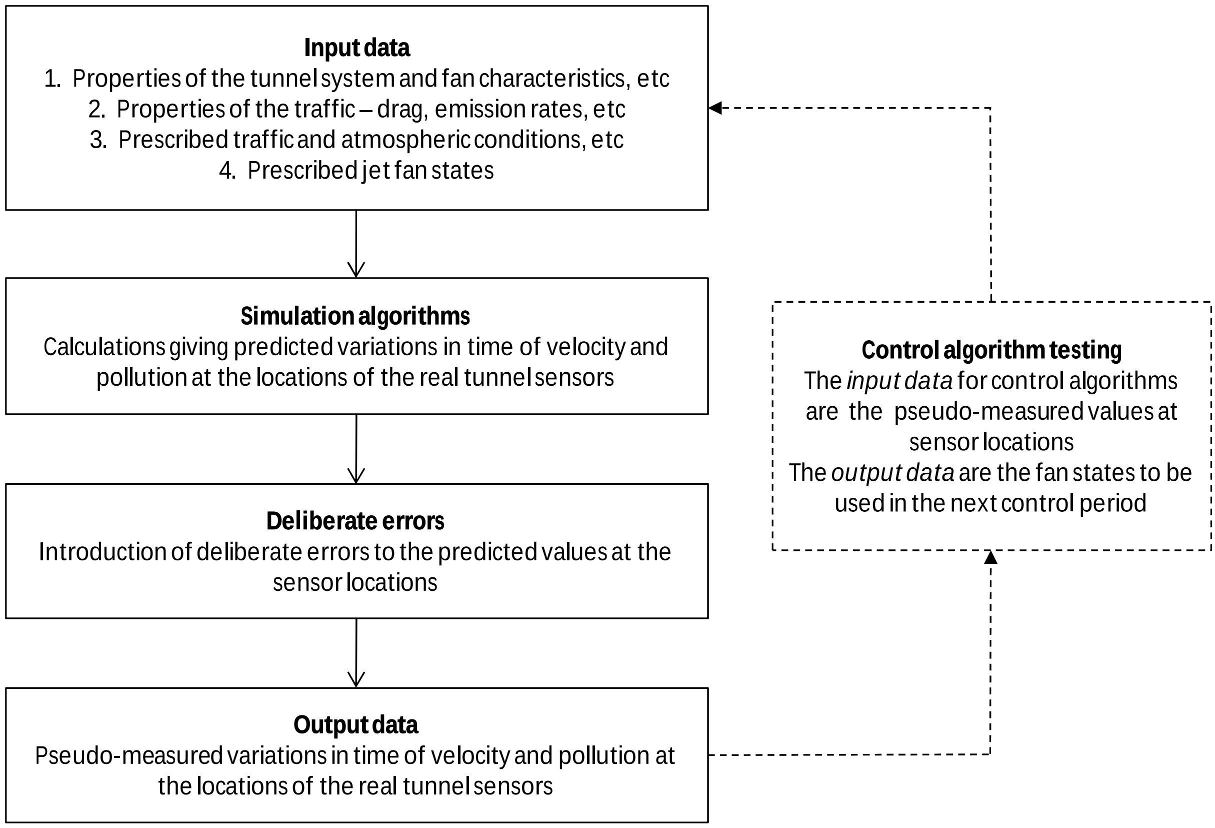

Figure 5: Virtual tunnel for testing control algorithms (e.g. FCVC)

The ***simulation algorithms*** within the virtual tunnel include a traffic flow simulator and an airflow/pollution simulator. These are designed to predict the evolving conditions in the tunnel as accurately as practicable.

The only output data from the simulation routines are the predicted conditions at the locations of hypothesized sensors (air speed, pollution, etc). These data are the simulator's equivalent of the *actual* conditions in the tunnel at these locations. In a real tunnel, however, we never know the "actual" conditions. We know only the values recorded by sensors such as air flow meters. All such measurements involve error and so the virtual tunnel has routines that introduce ***deliberate errors***. In principle, these errors are random, but, in practice, the characteristics of the errors can be controlled by the user of the virtual tunnel system. This is important because it enables the user to assess the sensitivity of any particular control system to different types of "measurement" error. These may include, for example, systematic error such as offsets and false calibrations or random errors such as those caused by noisy conditions in the tunnel or signal noise, etc. As a consequence of this methodology, a "real" velocity of, say, 3.5 m/s might be reported to the control system as 3.1 m/s at one instant, but as 3.7 m/s at another instant. Real control systems must accommodate such discrepancies and so it is important for the virtual tunnel to mimic them.

5.2. Use of the virtual tunnel

As far as is reasonably practicable, the virtual tunnel behaves in a manner that mimics real tunnels quite well. The greatest difference from a real tunnel is that the nature of the errors is known *a priori*. This should not be interpreted as a deficiency, however. On the contrary, it is an important benefit for testing purposes because it enables the sensitivity of proposed control systems to be assessed systematically. It would be much more difficult (and more costly) to do this in a real tunnel.

Initial testing of a new control system should be undertaken without introducing deliberate errors. This will enable the effectiveness of the system to be assessed for a wide range of input conditions. Common sense requires that the ranges considered should be wider than those expected in practice. Thus, for example, extremes of high and low traffic density, high and low traffic speeds, high and low emission characteristics should be considered.

Assuming that the control system passes the initial tests satisfactorily, the next step is to repeat the tests, this time with deliberate errors introduced to reflect real behaviour more closely. In addition to assessing sensitivity to errors in the pseudo-measured data at sensors, it is important to assess sensitivity to errors in initial data (tunnel, fan and traffic data, etc). The whole process should include (i) systematic errors, (ii) random errors and (iii) both systematic and random errors. It is not possible to model "real" errors exactly because these are inherently unquantifiable in detail. Nevertheless, the prescribed errors can be used to assess the control system in circumstances that are *more* challenging than those expected in the real tunnel. In this way, the eventual installation in the real tunnel can be undertaken with a high degree of confidence.

6. VALIDATION PERFORMANCE

Table 1: Test conditions (Fire incident)

Tunnel:	Length = 1500 m, Area = 64 m^2
Jet fans:	Number = 3, Diameter = 1 m, Jet velocity = 30 m/s
Initial traffic:	1008 veh/h west-bound, 432 veh/h east-bound 30% heavy vehicles, 70% light vehicles average speed 60 km/h
Incident:	t = -1 min: Collision occurs at 750 m t = 0 min: Fire starts t = 1 min: Fire detected (and control initiated)

The use of the virtual tunnel to assess FCVC performance is now illustrated. The full test programme involves many dozens of simulations and it would not be constructive to attempt to describe them all. Instead, two examples are given, both for the same hypothesized fire incident in a tunnel. In the first case, the tunnel is assumed to have fixed-speed jet fans. In the second, it has variable speed fans, all operated at the same speed.

The principal parameters for the emergency-operation example are shown in Table 1. The tunnel has two-way traffic and a vehicle collision is imagined to occur at the instant t = -1 min. Traffic that has passed the incident location continues out of the tunnel and vehicles approaching the incident come to rest on reaching the congested zone. Fire breaks out at the instant t = 0 min and it is detected at t = 1 min, at which time the automatic control system activates red traffic signals at the tunnel entrances and also activates FCVC's emergency-operation mode. For simplicity and clarity of presentation, the tunnel is assumed to be horizontal and there is no "natural wind speed" - i.e. there is no difference between the atmospheric pressures at the two portals.

6.1. Emergency operation - fixed-speed fans

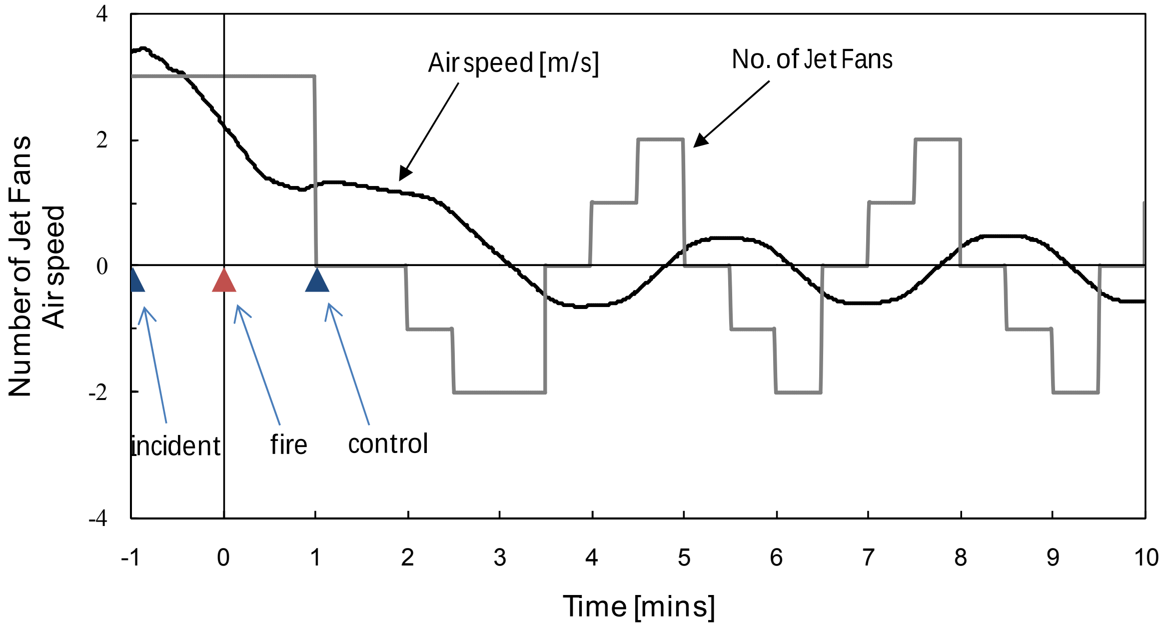

Figure 6: FCVC using fixed speed jet fans

Figure 6 shows the performance of FCVC for a case where the jet fans must be used in on-off, fixed speed mode. This is the most common case with existing installations in tunnels. By inspection, the air speed in the tunnel reduces even before the fire has been detected (i.e. before $t = 0$). The reduction occurs because of the changed traffic conditions. When the fire is detected, FCVC immediately stops all three jet fans. One minute later, when it is clear that the air speed is not decaying to zero as rapidly as desired, FCVC switches on two fans in the reverse direction. This brings the air speed to zero, but there is then an overshoot and the direction of air flow reverses. FCVC responds by switching off the fans and then activating them in the original direction. Thereafter, there is a continuous cycle of forward and reverse operation of the fans and the airflow also moves back and forth, albeit at speeds that are always smaller than 1 m/s. The apparently erratic behaviour in the early stages of the response arises because of traffic as the last of the moving vehicles leave the tunnel or come to a halt.

For this particular example, it is obvious that the air speed would eventually tend to zero if the fans were simply switched off. The disadvantage of this approach is that the time taken for the air speed to reduce to zero would be large. Also, during this period, the air would always be moving in the same direction. This is less satisfactory than moving gently back and forth. Furthermore, the possibility of simply switching off the fans arises only because the conditions assumed in this particular example are very simple. In real tunnels, the air speed would rarely tend to zero if all fans were switched off. The influence of external atmospheric conditions and smoke buoyancy, etc would be likely to cause the air to move indefinitely. As a consequence, it is much safer to allow the control system to maintain approximately zero conditions actively.

6.2. Emergency operation - variable-speed fans

Figure 7 shows the performance of FCVC in the identical scenario when the jet fans are driven by inverters and can therefore be operated at variable speed. In this case, the most appropriate method of operation is with all three fans operating simultaneously at the same speed.

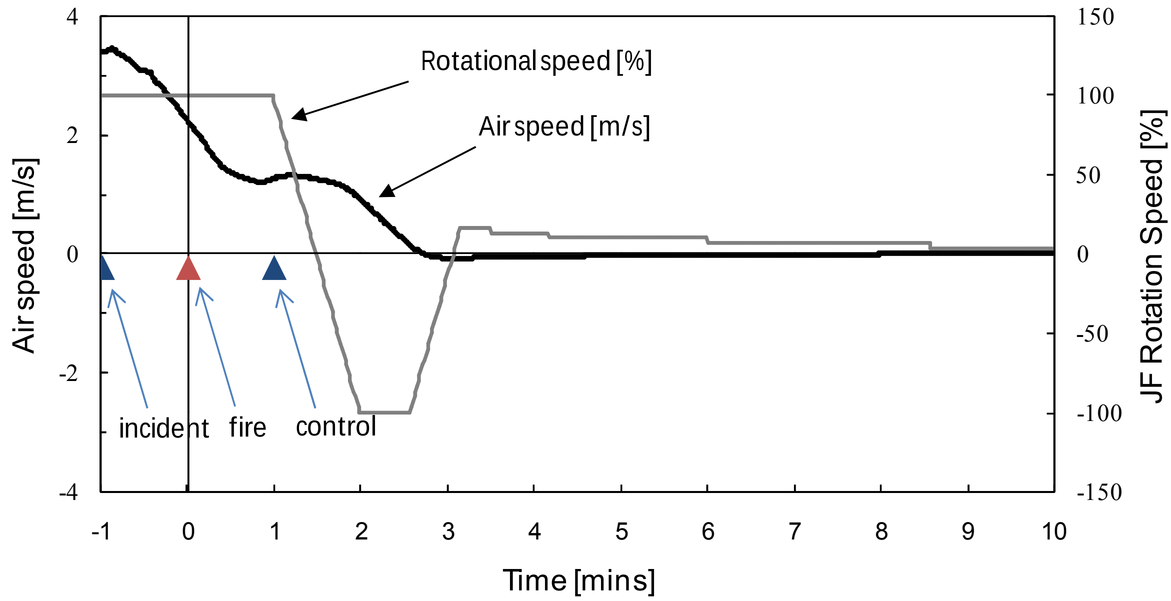

Figure 7: FCVC using variable speed jet fans

Until the incident is detected at $t = 1$ min, the conditions are identical to those shown in Figure 6. Thereafter, however, the air speed reduces to zero rapidly and is maintained continuously at that state. To achieve this outcome, FCVC initially changes the fans from 100% forwards to 100% reversed. This is done at the maximum allowable rate, which, in this instance, is full reversal in one minute. The fully reversed condition is maintained for about half a minute and the fans then revert to forwards operation, albeit at a gentle (and subsequently decreasing) rate because the airspeed is already close to zero. All of this is achieved whilst the drag from the traffic is changing as the last vehicles leave the tunnel. FCVC does not “know” what external influences are causing air to move in the tunnel. It simply responds to differences between the measured and target air speeds.

In addition to illustrating the power of the FCVC method, this example illustrates the big advantage of variable-speed jet fans in responding to an emergency. The most obvious advantage of the conditions in Figure 7 in comparison with those in Figure 6 is that the air speed is maintained very close to zero and the fans are operating at very low speed. A more important advantage from a safety standpoint, however, is that the air speed is brought to zero very rapidly, even though traffic movements are influencing it during most of the decay period. This greatly limits the speed at which smoke can move along the tunnel and hence greatly increases the likelihood that everyone involved in an incident will be able to escape safely along the tunnel.

7. CONCLUSIONS

The main conclusions drawn from this study are:

1. An effective automatic control system (FCVC) has been introduced for relatively long, two-way tunnels with longitudinal ventilation. Although long tunnels of this type are rarely built today, many existing tunnels are in this category.

2. The effectiveness of the control system has been demonstrated by using it to control the operation of fans in a virtual tunnel. In the case of operation following the detection of fire, it is able to bring the air speed close to zero very quickly.

3. The use of variable-speed jet fans has previously been shown to offer potential for substantially reduced energy costs in routine operation. In this paper, it has been further shown that they enable zero-flow conditions to be achieved closely in response to a fire, thereby offering increased safety in comparison with fixed speed fans.

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SMOKE STRATIFICATION STABILITY: RESULTS OF EXPERIMENTS

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ABSTRACT

This paper presents an experimental campaign achieved on a 1/3 scale model tunnel. Its aims at study the influence of the heat release rate, the introduction of an injector and the presence of vehicles on the smoke layer characteristics.

Firstly, two smoke layer parameters are defined to characterise the backlayering: the smoke layer length and the dimensionless thickness of the smoke layer. Secondly, the experimental results permit to determine the influence of perturbation presence on these parameters.

The analyse of the heat release rate influence shows that the scale model allows to represent correctly the backlayering comportment as in a full scale tunnel. The introduction of a jet induces a diminution of the backlayering length and the impact on the smoke layer thickness depends on the heat release rate and the velocity jet while no destratification is observed. However, the presence of vehicles does not enable to conserve visibility in the gallery, even if a thermal approach is not in accordance to experimental observation.

1. INTRODUCTION

Longitudinal ventilation in road tunnel is usually used in case of unidirectional non-congested traffic. In such case the vehicles located downstream the fire leave normally the tunnel before to be reach by any smoke. Is case of congestion, this assumption is not anymore satisfied. The longitudinal approach is not able to ensure safe evacuation conditions.

This case occurs frequently for urban tunnel that are cut and cover. The solution used is to try to obtain the stratification of smoke upstream and downstream the fire. The mechanical ventilation is then used to maintain the longitudinal airflow at a low velocity to provide favourable conditions for stratification. This means that the tunnel jet fans or the tunnel injectors are used to control the physical phenomenon occurring in the tunnel (natural ventilation, chimney effect).

However, the stratification may be disturbed by several local phenomena. The present study aims at analyse the impact of two of them. The first one is the interaction between the smoke layer and an air jet of the ventilation system. The second one is the impact of the presence of vehicles on the stratification. These two causes of stratification perturbation are almost always presents for such case of congested traffic ventilation mode.

The study has been performed using an experimental device. However, this campaign has also been design to provide data for numerical simulation calibration. The present paper is only relating the experimental campaign.

2. EXPERIMENTAL SETUP

The experimental campaign was achieved using the INERIS fire gallery (Boehm et al., 2008): a 50 m long device with a section corresponding to a 1/3 scale tunnel with a maximum cross section of 5.4 m^2. The experimental setup is schemed on **Figure 1**. This gallery corresponds to a 150 m long full scale tunnel with a maximum cross section of 48.6 m^2.

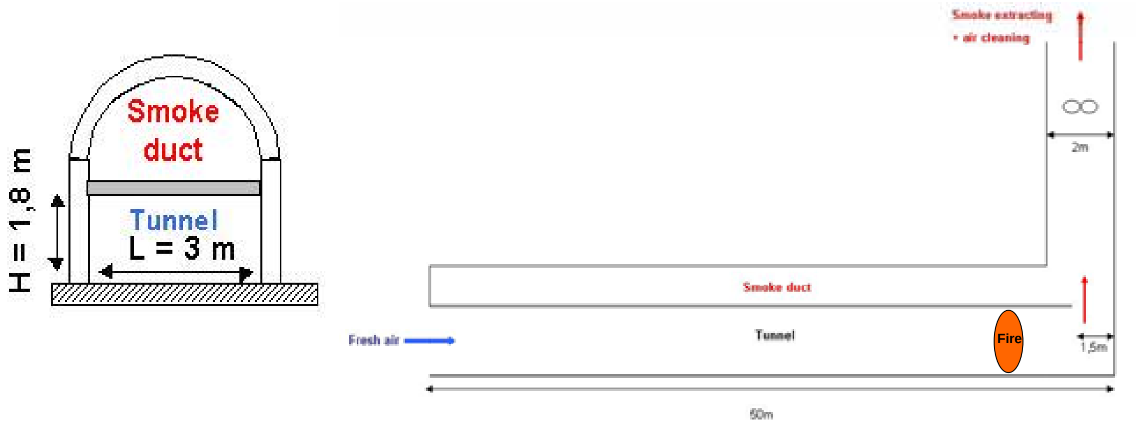

Figure 1: Scheme of the experimental setup

The gallery needs to be conferred to simulate the backlayering layer founded sometimes during tunnel fires. The smoke is extracted by a fan installed in the chimney. The fresh air could arrive by the other extremity of the tunnel. Therefore, the fire is placed at 10 m of the chimney to create a backlayering: the smoke layer flows in the opposite direction of the fresh air.

Furthermore, the longitudinal velocity needs to be around the critical velocity to allow the backlayering layer formation and avoid the propagation of the smoke out of the tunnel. For this study, the critical velocity is 1.28 m/s for the fire pool of 0.25 m^2 and 0.95 m/s for the pool fire of 0.2 m^2 (Kennedy et al., 1996). The longitudinal velocity is fixed around 0.95 m/s.

The smoke duct allows representing a transversal ventilation system but is not used in the present paper.

The Froude scaling is a mean to scale model parameters that would produce a similar flow in the full-scale tunnel. It's also necessary to scale the model results. Froude scaling enables to correctly model the thermal effect and particularly the backlayering phenomenon (Oka et al., 1995).

The fire is modelled using an heptane pool fire. The use of two different pools (0.25 m^2 and 0.2 m^2) allows simulating two heat release rates. These experiences aim at knowing the influence of this parameter on the smoke layer characteristics. The fire can be characterised by three different heat release rates: the theoretical total heat release rate calculated from the mass consumption of heptane, the total heat release rate computed from the oxygen consumption and the convective heat release rate with volumetric flow rate estimated by integration of the velocity profile measured downstream of the fire.

The difference between the two total release rates is the combustion efficiency. For the pool of 0.25 m^2, the three heat release rates are respectively: 358 kW, 303 kW and 249 kW. For the pool of 0.2 m^2, they are respectively: 266 kW, 242 kW and 184 kW. Thus, the combustion efficiency is 85% and the radiative fraction is 30% for the 0.25 m^2 heptane pool fire. The combustion efficiency is 90% and the radiative fraction is 31% for the 0.2 m^2 heptane pool fire.

3. SMOKE LAYER PARAMETERS

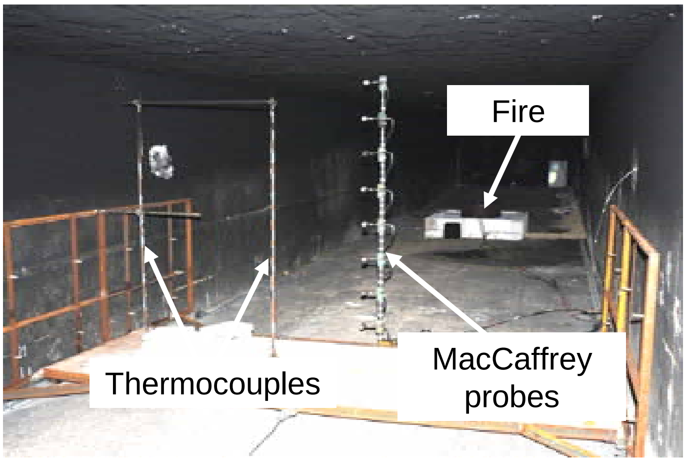

Figure 2: Photo of the device for measure

The smoke layer can be characterised by the repartition of temperature, density and velocity.

In this study, the measures of temperature are made along the backlayering layer; a device with thermocouples moves along the tunnel (**Figure 2**).

The velocities are measured at two positions on the gallery: 5.5 m and 17 m from the fire.

The repartition of density is not explored as this measure should be difficult to release in this type of experience (heptane fire in a 1/3 scale tunnel).

Two parameters for describing the backlayering are extracted of the temperature and velocity fields: the backlayering length l_b and the layer thickness δ_b.

The temperature repartition measured enables to deduce the backlayering length. The length is deduced of the position where the temperatures are equals on the vertical profile.

It is possible to compute the smoke layer thickness at two places because the temperatures and velocities profiles are required to calculate its. In fact, the smoke layer thickness is calculated using the smoke mass flow conservation (**Figure 3**).

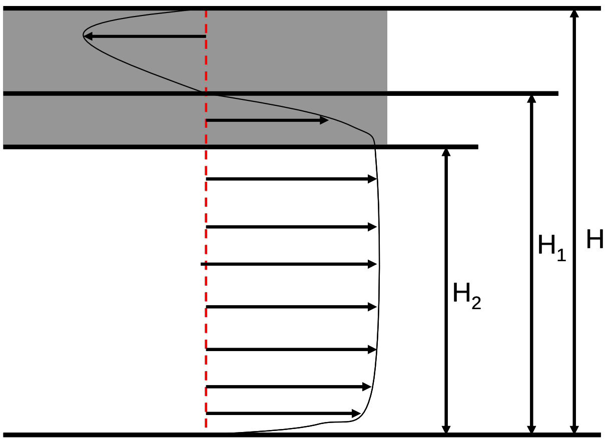

Figure 3: Scheme of the heights on the smoke layer

On the **Figure 3**, three heights are represented:
- H is the height of the gallery;
- H_1 is defined as the point where the velocity is null in the vertical profile;
- H_2 is the point at the flow of the smoke flowing on the opposite direction of the fresh air is equal to the flow of the smoke flowing in the same direction of the fresh air.

Thus the backlayering thickness is the difference between the heights H and H_2.

4. INFLUENCE OF HEAT RELEASE RATE ON THE SMOKE LAYER PARAMETERS

The length and the thickness of the backlayering depend on the heat release rate.
The smoke layer length increases with the heat release rate: 27 m for the 0.25 m^2 pool and 21 m for the 0.2 m^2 pool. In fact, the thermal energy is more important in the smoke layer for the highest fire. The equilibrium of strengths is ensured closer to the fire for the case of the 0.2 m^2 pool than for the case of the 0.25 m^2 pool.

The velocity measure was released at 5.5 m and 17 m of the fire. Thus, the smoke layer thickness is calculated at these two positions for the two heat release rate modelled. The thickness is divided by the height of the tunnel (the length parameter in this study) to create a dimensionless number.

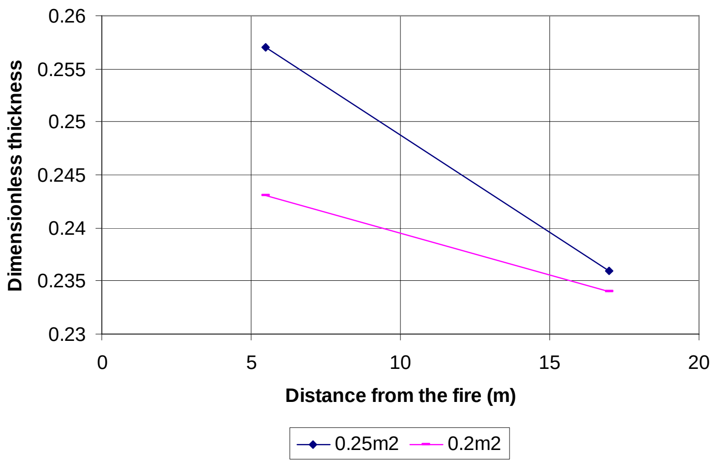

Figure 4: Evolution of dimensionless thickness along the gallery

On the **Figure 4**, the evolution of the dimensionless thickness along the gallery is represented for the two heat release rate.

The thickness decreases with the rising of the distance from the fire for the two heat release rate simulated.

Furthermore, the dimensionless thickness increases with the heat release rate. This difference diminishes with the augmentation of the distance from the fire.

These results present limitation as experience are released on a small scale tunnel. The experimental campaign of the Memorial tunnel, achieved on a large scale tunnel, provides the same conclusion for the influence of heat release rate on backlayering characteristic. A higher heat release rate leaves to a thicker and longer backlayering (MTFVTP, 1995).

5. INFLUENCE OF THE INJECTOR ON THE BACKLAYERING LAYER

In longitudinally ventilated tunnels, injectors are placed on the tunnel to generate an air flow. This presence induces a gradient on the vertical profile of velocity which should break the smoke layer stratification. This part aims at analysing the influence of this gradient on smoke layer parameters.

5.1. Experimental representation of the injector

The velocity profile gradient created by the injector is modelled by a plane jet of 0.6 m of height and 3 m of width. This plane jet is designed to avoid the rotational effect which cause complex coupled physical phenomena. The output velocity of the jet is about 3 m/s. The air fresh flow rate at the entrance is conserved with and without disturbance. In a second case, the height of the plane jet is reduced to 0.3 m with the same flow rate. Thus, the velocity of the jet is about 6 m/s. The backlayering parameters are compared for the cases without jet and with the two different jets.

5.2. Influence of jet on smoke layer parameters

The plane jet which modelled the injector creates a gradient on the velocity vertical profile. The longitudinal velocity of the fresh air is more important near the ceiling in the case with jet than in the case with no disturbance. Hence, the smoke layer length is reduced as the strengths equilibrium is insured closer of the fire in the case with jet than in the case without jet.
In fact, the lengths of the backlayering measured on the experience are reported on the table beneath.

	Backlayering length	
	Pool of 0,25 m²	Pool of 0,2 m²
No jet	27 m	21 m
Jet of 3 m/s	25 m	17 m
Jet of 6 m/s	21 m	13 m

The two jets induce a reduction of the backlayering length more important for the 0.2 m^2 pool than for the 0.25 m^2 pool.

For the case with disturbance, the thickness evolution along the tunnel is calculated for the pool of 0,25m^2. For the 0.2 m^2 pool, one position of velocity measure is outside of the backlayering and the thickness could not be calculated for this place.

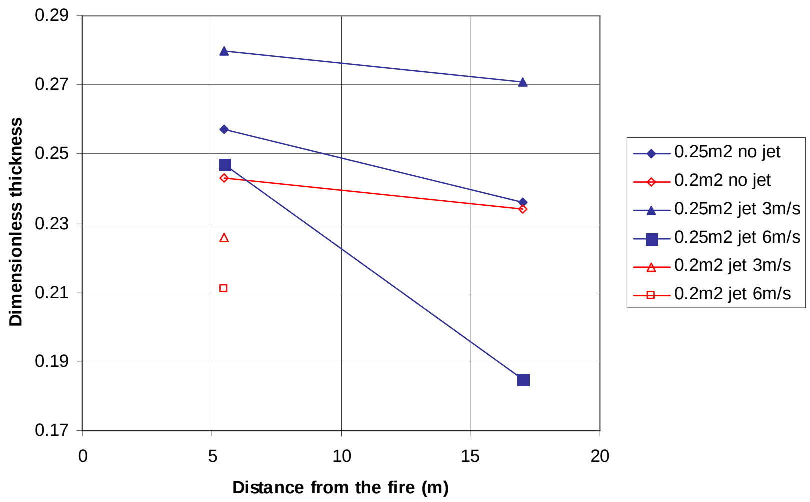

Figure 5: Evolution of dimensionless thickness along the gallery without and with jet

The evolutions of thickness for all the cases are reported on the **Figure 5**.

For the pool of 0.2 m^2, the introduction of the two jets has the same effect on the dimensionless thickness of the layer: the diminution of this parameter.

However, for the pool of 0.25 m^2 the presence of the 3 m/s velocity jet induces an increase of the thickness whereas the 6m/s velocity jet diminishes the smoke layer thickness. This diminution is more important when the distance from the fire increase.

The modification of these parameters due to the presence of a jet enables to analyse the influence of jet on smoke layer characteristics. However, they don't allow to quantify the stratification and to determine the influence of a jet on its.

6. INFLUENCE OF THE VEHICLES

6.1. Experimental vehicle reproduction

The experimental device is the one above described for studying the injector influence. Due to the third scale of the experimental device, third scale vehicles were used for studying their impact on the backlayering layer. Considering this, obstacles were built to reproduce scaled vehicles; shape and dimension of these vehicles and a visualisation are given on Figure 6.

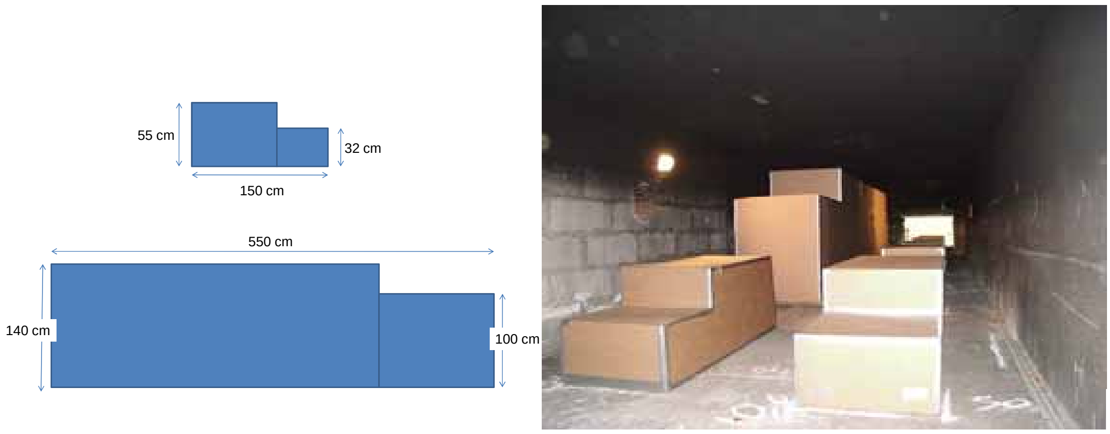

Figure 6: Schematic representation of scaled vehicles and photography inside the gallery

Truck on the right lane of the tunnel with a car on the left induces a blockage rate of 53%, this means more than the half of the tunnel section is occupied with vehicles. This represents the case of a small cut and cover 2 lanes and 2 sidewalks.

6.2. Impact of vehicles on air flow velocity

It first appears clearly that vehicles upstream the fire will have a significant influence on the backlayering layer. Such vehicles will generate a restriction and consequently a velocity increase as observed during experiment without fire. Vertical velocity profile with and without vehicles are reproduced on Figure 7.

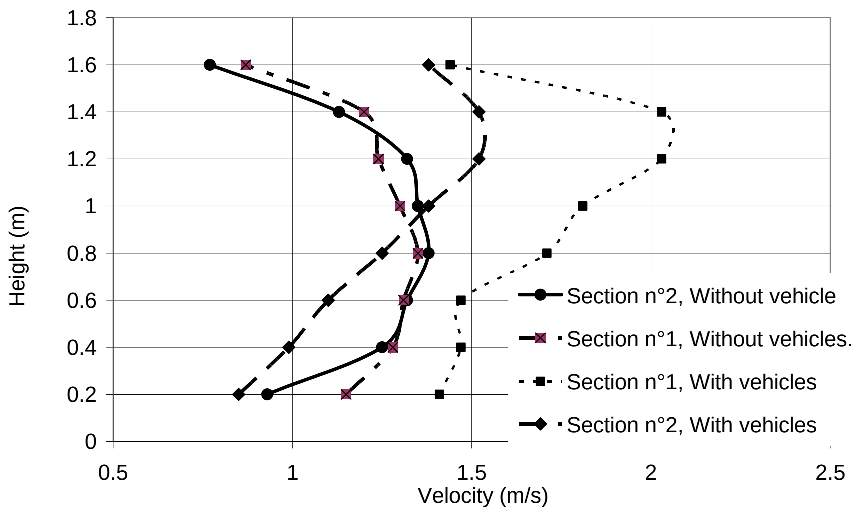

Figure 7: Vertical velocity profile with and without vehicle

Depending on the restriction factor, the local velocity can become higher than the critical one. This configuration should block the backlayering layer and disturb it. The second phase of the experimental campaign aims to evaluate vehicles impact on the backlayering layer.

6.3. Influence vehicles on smoke layer parameters

Because the velocity rise due to the restriction, the length of the backlayering layer is reduced, the velocity near truck is higher than the critical velocity. The backlayering length was measured around 10 m for the experimental case but this value highly depends on vehicles distribution upstream the fire and mainly the truck location. This first result shows that not only the ventilation governs the backlayering layer but the vehicles distribution upstream the fire too.

The experimental consequence of this layer length reduction is that only one of the two velocity measurement sections is available, the one located 6 m upstream the fire.

The backlayering thickness computed 6 m upstream the fire is 0.29 m value to be compared with the 0.25 m thickness for the reference case without vehicles. The second conclusion that appears is that the layer seems to stay stratified with an increase of its thickness around 15% from the reference case without vehicles. It is however highly important to highlight that this result depend on vehicle distribution upstream the fire and that, this increase should be different, higher or lower, for other blockage configurations.

6.4. Synthesis

The physical analysis of the backlayering layer in case of vehicles blocked upstream the fire shows that, the thickness of this shortened backlayering layer increase. It must be noted that this analysis is mainly based on a physical criterion considering that the layer is stratified and that its height is as defined in section 3. A distinction between this physical analysis and the people security in the lower part of the tunnel has to be made. Considering people safety, it is important to consider not only physical approach but pragmatic one too. Doing this implies to consider the different components of a stratified layer. Smoke effects on human beings can be spli into three aspects, two direct effects which are thermal and toxic impact and an indirect one which is visibility reduction. If the visibility diminishes, this will induce some difficulties in the tunnel evacuation but this will have no direct impact on people on the opposite of a temperature or toxic concentration rise.

In the present case, it can be shown that visibility in the lower part of the tunnel decrease, Figure 8.

Figure 8 : Video camera picture for test with vehicles

7. CONCLUSIONS

This experimental campaign is achieved on a 1/3 scale model tunnel. Consequently, it would present some limitations as the Reynolds and the Richardson numbers cannot be reproduced both. The analyse of the influence of heat release rate on the backlayering shows that a higher heat release rate leads to a longer and thicker backlayering layer as observed in large scale tunnel. The smoke layer thickness is calculated using the smoke mass flow conservation and not using only the temperature profile.

The first experimental configuration aims at determine the impact of a plane jet on the backlayering layer characteristics. The introduction of a jet implies a diminution of the backlayering layer length: this diminution rises if the jet velocity is increased. The second consequence of the jet presence is a diminution of the dimensionless smoke layer thickness for the lower heat release rate. However, for the higher heat release rate, the evolution of this thickness depends on the jet velocity: decrease of the thickness for the lower velocity jet and increase for the higher velocity jet. This influence increases with the distance from the fire as the smoke layer thermal energy diminishes when the layer spreads along the gallery.
Numerical simulations are needed to analyse more precisely the impact of the jet parameters (velocity, distance from the fire…) on the backlayering and to determine a number which permit to define the stratification stability.
The second experimental configuration, with vehicles blocked upstream the fire gives two main information. The first one is that not only the ventilation governs the backlayering layer behaviour but the vehicles have a great influence in terms of length reduction and of thickness increase. The second information mainly concerned the stratification definition. Must authors considered only the temperature profile to define the stratification criteria, considering the difference between the near ceiling temperature and near ground one (Newman 1983, Newman 1984, Cooper 1982 and Chow 2009). In this paper, a new approach is developed to computed the backlayering layer and then evaluate stratification. For both cases, this only considers one physical quantity related to one layer property, which shows some limitations in case of stratification transition regime as in case of vehicle upstream the fire.

8. ACKNOWLEDGEMENT

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TEHRAN RESALAT TUNNEL INNOVATIONS

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ABSTRACT

Due to the increase in vehicle traffic and limited real estate, the construction and complexity of road tunnels are increasing substantially throughout the world. Also, tunnels safety is very important issue.

Nowadays, most of the modern tunnels are equipped with different systems, such as: lighting, fire alarm, fire fighting, closed circuit television (CCTV), emergency telephones, Intercom, barriers, automatic ventilation, traffic counting and lane control and traffic signs.

Tehran Resalat Tunnel has been equipped with the above systems which shall be explained briefly in this paper. In order to reduce the cost of project, some innovations have been considered during the performance.

Keywords: Resalat Tunnel, innovations, Fire protection, CCTV, Cable damage

1. INTRODUCTION

Tehran Resalat Tunnel with 1800m length and two separate tubes was constructed in Tehran in 2006. Tehran is one of the most crowded and polluted cities in the world with about 10 million population and Resalat Tunnel is located at the center of the city. Because of the importance of safe transportation through the tunnel, safety systems were considered for the tunnel.

Forty eight jet fans (30 KW, single speed) were provided for ventilation of the tunnel. One 20/0.4 kV substation which is located at mid distance on top of the tunnel, feeds all of the electrical equipment of the tunnel. We were encountered two issues during tunnel cabling:

- huge number of the cables
- cables damage by vermin

To overcome the first problem and in order to reduce the number of cables, among the different methods of jet fan motor starting (i.e., on line continuous, star-delta, soft-starters and drive system), soft-starters were selected.

To solve the second issue and in order to protect cables damage against vermin, we used perforated cover plates on the cable trays, instead of using armored cables or usage of anti-termite and anti-rodent cables.

2. LIGHTING SYSTEM

Unlike almost all other exterior lighting, tunnel lighting is on generally 24 hours a day; in fact on a sunny day more light is needed in the threshold of a tunnel to give the eye time to adapt from the very high daylight illumination level down to the comparative darkness of the tunnel interior.

Among different kinds of luminaries, high pressure sodium vapour lamp projectors including symmetrical axial reflector were installed in the Tehran Resalat Tunnel. *High efficiency* and *long life* are two major benefits of high pressure sodium vapour lamps. High efficiency of the lamps causes less use of lighting fixtures, accordingly energy saving and cost.

Because of heavy traffic and high pollution of tunnel weather, the tunnel's luminaries were selected dust tight and jet proof to IP65. The body is made of aluminium, which is first heavily anodized and then powder coated to be anti-corroded in front of humidity and exhaust gas from vehicles.

Road tunnels lighting design is very important. At entry portals, drivers need to quickly adjust to the different intensities between outside and tunnel environments. Drivers must also be able to clearly distinguish other vehicles within the tunnel, which may be masked by the silhouette of larger vehicles towards the exit portal. So, according to the international standards of the CIE(Commission Internationale de Eclairage) (CIE 1984, 1990), we designed 5 lighting zones, the so called threshold zone, in the transition zone (2 zones), in its interior and in the exit one, for drivers eye easy adaption.

3. FIRE ALARM SYSTEM

Compared to tunnels for other modes of transport, fire safety problems in road tunnels are more challenging due to specific features of their infrastructure, nature of traffic using them and insufficient safety rules on vehicles.[2] As there are no international valid standards or common views of how to build fire detection systems inside tunnels, the definition of state of the art is very often the subject of individual interpretation by tunnel designers. On the other hand from a legal point of view, state of the art can be based on relevant publications and experiences which are publically known and accessible. [1]

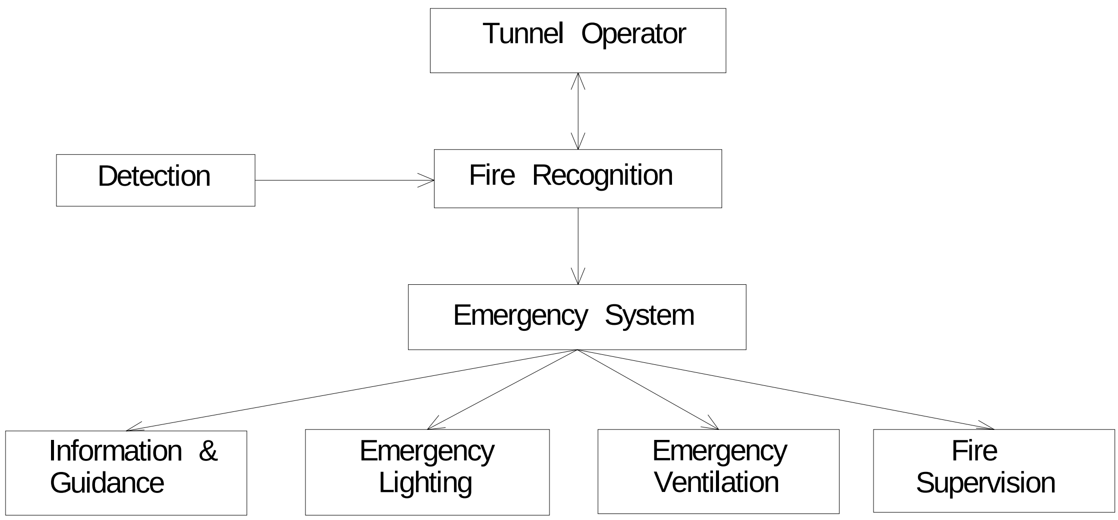

Figure 1[2]**:** Road tunnel fire protection system

Fire detection systems are an essential element of fire protection systems of road tunnels (Figure 1). Fire detectors should provide early warnings of a fire incident at its initial stage and hence facilitate early activation of emergency systems. Their role is crucial in preventing smoke spread in the tunnel, to controlling/extinguishing fires, and to aid in directing evacuation and fire fighting operations [5,7,9].

There are currently five fire detection technologies that have been used or tested for tunnel protection. They are: linear heat detection systems, flame detectors, CCTV fire detectors, smoke detection systems and spot detectors. The main features of these technologies and their applications in tunnels are listed in Table 1[4].

Linear heat detection systems are the primary detecting technology used in European tunnels, while flame detectors are mainly used in Japanese tunnels. Sprinklers, as a spot heat detector, are installed in some tunnels around the world. CCTV cameras are already widely applied in tunnels for incident prevention and management. There are significant interests in extending tunnel CCTV cameras into automated fire detection. Roadway smoke detection systems, such as smoke beam detectors and plenum and duct smoke detectors, have a fast response time to a fire incidence, however, false alarm problems associated with diesel engine and ill-maintained vehicle exhaust in tunnels seem to preclude any widespread use of these detection systems in tunnels.

Table 1[4]: Current available tunnel fire detection technologies

	Linear heat detection system	Flame detector	CCTV detector	Smoke detection system	Spot detector
Detecting principle	Heat	Radiation	Image	Smoke	Heat, smoke, gas, etc.
Detecting capability	Moderate response;	Fast response; Locating fires;	Fast response; Locating & monitoring fires	Fast response; Locating fires;	Moderate response; Locating fires;
Reliability	High	High	High	Low	Moderate to high
Availability	High	High	High	Moderate	Moderate to high

In Tehran Resalat Tunnel, linear sensor heat detectors as well as CCTV detectors have been considered for fire alarm system. Also, manual call points were installed every 100 m through the tunnel, in order to inform the operator of the control room manually by drivers of any probable fire event in case the detection system is out of order.

Sensor cables are combined heat detectors where have been installed through the tunnel in order to measure temperature rate of rise as well as absolute temperature measurement. The sensor cable is capable of operating between -40 ºC to +85 ºC. Also, aggressive exhaust fumes, salts, humidity and fog, dust and dirt, as well as vibration do not influence the functionality of the fire detection system.

4. CLOSED-CIRCUIT TELEVISION (CCTV)

The purpose of the CCTV system is to provide surveillance, security and incident control throughout the tunnel.

Full video surveillance within road tunnels longer with more than 500 m length is now mandatory in Iran. So, video surveillance system has been considered for Tehran Resalat Tunnel to ensure a highest level of safety and fast reaction to emergencies.

The surveillance system includes: fixed and motorized cameras, one switching Matrix, one operator terminal PC base, six CCTV monitors. Twenty one cameras have been installed along the northern and southern tube of the tunnel. Three of the cameras installed at the tunnel portals are mobile and the others are fixed. Each of the cameras is housed in robust, external grade housing and mounted on a locking pan tilt head.

The system is capable of automatically zooming and focusing on each of the internal emergency intercom point, when someone calls the control room. The CCTV cameras have been installed on the right wall of the tunnel at 5 m height; bellow the lights and cable trays.

All the video signals of each three or four cameras are transmitted to the local marshalling box by coaxial cables. In the marshalling box, there is an analogue/digital converter which converts analogue signals of the cameras to digital signals and transmit them to the control building through single mode fiber optic cable.

Video-image processing for fire alarm and incident applications is a major technical innovation. Resalat Tunnel CCTV system has this functionality. The smoke and fire detection with image processing technology was first put to use in 1994 by British companies. Other systems, use infrared camera with special filters in Germany. The video signal is captured and digitized with a grabber and, after this, is evaluated with algorithms for flame, smoke and incident. The image processing result is made available as a pre-alarm or alarm to a fire alarm or relevant systems and control signals are sent to CCTV system for automatic activation of specific cameras on monitors.[1]

In order to use image-processing technology in tunnels, the tunnel lighting needs to be adequate and cameras should be located no more than 100m apart.

5. COUNTING STATIONS

In order to gain information about the incident, number of vehicles, classification, speed, headway and percentage of road occupancy on each lane, the counting station system has been provided for Tehran Resalat Tunnel. The system consists of a set of magnetic loop detectors and detector controller module. The system has been housed in a waterproof enclosure and laid out in a manner that is ideal for gauging different traffic variables at a number of counting sites along the road. The detector is able to store data for at least two days long, which can be inputted into a portable computer when the communication system or main power fails.The detector controller module is a cabinet forming the counting station. This cabinet contains:

- A 19", 6U high rack, containing the different electronic cards (e.g. CPU card MER330/6, power supply card FAY-267/8, bus card BERD-457, four-channel detector card TD624ES, communication card
- A mains power module including auxiliary connections, power outlet and main protection.
- Transformer and line filter.
- Knife disconnects terminal blocks for the detectors.

Loop detector cable is a copper conductor with ethylene propylene rubber insulation and 2.5 $m\,m^2$ cross section which has been laid in a groove made in the pavement and sealed with epoxy resin bitumen.

The function of the system is so that detector controller module detects vehicle presence by means of an inductance change caused by the vehicle passing over a loop buried in the road surface.

The functional traffic parameters which are measured are as follows:

- Intensity (flow): number of vehicles on the road over a given period of time.
- Occupancy: percentage of time a vehicle remains within the metered area.
- Headway: distance between two consecutive vehicles
- Speed: average speed Kmh^{-1}

6. VENTILATION CONTROL SYSTEM

The ventilation system consists of 48 jet-fans distributed along the Resalat Tunnel which have been installed in two tunnels of different traffic direction (30 jet-fans in the north tube and 18 jet-fans in the south tube). The air flow which has to be moved, is determined by "CO emission", "opacity" and "fire".

The ventilation control system has been designed considering the following patterns:

- Keeping the tunnel environment within the traffic security criteria
- Making the power consumption and operational costs reasonably economical
- Convenient management.

The criteria of Resalat Tunnel ventilation control system design has been given in table 2.

Table 2: Criteria of ventilation control system design [6]

Traffic Situation	CO concentration (ppm) (PIARC 1995)	Extinction coefficient K ($k\ m^{-1}$) (BD 78/99)	remarks
Fluid traffic above 50 $k\ m^{-1}$	100	7	
Seldom congested	150	9	
Tunnel enclosure necessary	250	12	Within 5 min.

Environmental components used for the Resalat Tunnel operational system are as follows[3]:

- Co and Visibility (VI) Sensors
- Wind Sensors

The CO and VI sensor housing has been made of an anti-corrosive and durable material with a protection degree of IP65. Two sets of opto-electronic CO-VI detectors have been installed in each tunnel tube. Each measuring point comprises a pair of sensors mounted directly on the tunnel wall, separated by 10m. Five levels have been set to control "CO" and "Opacity" of tunnel air pollution by means of jet fans.
CO Levels:

- CO_{low} 0 PPM < CO < 25PPM
- $CO_{medium-low}$ 25 PPM < CO < 50 PPM
- CO_{medium} 50 PPM < CO < 75 PPM
- $CO_{medium-high}$ 75 PPM < CO < 100 PPM
- CO_{high} 100 PPM < CO < 150 PPM
- $CO_{very\ high}$ 150 PPM < CO < 200 PPM
- $CO_{dangerous}$ 200 PPM < CO < 250 PPM

Opacity Levels:

- OP_{low} $0\ K\ m^{-1} < OP < 4\ K\ m^{-1}$
- $OP_{medium-low}$ $4\ K\ m^{-1} < OP < 5\ K\ m^{-1}$
- OP_{medium} $5\ K\ m^{-1} < OP < 6\ K\ m^{-1}$
- $OP_{medium-high}$ $6\ K\ m^{-1} < OP < 7\ K\ m^{-1}$
- OP_{high} $7\ K\ m^{-1} < OP < 9\ K\ m^{-1}$
- $OP_{very\ high}$ $9\ K\ m^{-1} < OP < 10.5\ K\ m^{-1}$
- $OP_{dangerous}$ $10.5\ K\ m^{-1} < OP < 12\ K\ m^{-1}$

In case of fire, air speed inside the tunnel should be kept between $3\ m\ s^{-1}$ and $5\ m\ s^{-1}$, in order to evacuate the gases from the tunnel perfectly. So, jet-fans are adjusted by control system. The air speed of tunnel is measured by wind sensor. The 4-blade poly propylene propeller wind sensor has been installed in the Resalat Tunnel to measure directional air currents in the tunnel.

7. POWER SYSTEM

One 20/0.4 KV substation which has been located at mid distance on top of the tunnel, feeds all of the electrical equipment of the tunnel. The power distribution network of the tunnel is divided into normal and emergency sections. In normal conditions, all of the equipments are being fed from two 1600 KVA, 20/0.4 KV, ONAN transformers. Transformers are being fed from a 20 KV ring distribution network of Tehran. In case of any failure in normal distribution network, one 1200 KW emergency diesel generator feeds all of the necessary equipments such as fire alarm and protection systems, half of the lighting system, control and monitoring systems and a number of the jet-fans which are necessary at fire condition. Moreover, an uninterruptable power supply system (UPS) feeds some systems such as emergency telephone system, fire alarm system, CCTV, servers and part of the lighting system.

Cabling between 20/0.4 KV substation and two tubes of tunnel has been done through a cable shaft. We encountered two issues during cabling:

1. huge number of the cables
2. cables damage by vermin

7.1. Huge number of the cables

Most of the cables feed ventilation and lighting systems. In order to reduce the current consumption of the lamps, lighting fixtures have been equipped with correction factor capacitors. So, the size of cables reduced.

At starting condition, jet-fans take current 6 times more than normal operation. So, it leads to be increased the size of the cables. There are 4 methods for motor starting which are: on line continues (D.O.L), star-delta, drive system (frequency convertors) and soft starter.

Direct-on-line start (D.O.L)[8]

This is by far the most common starting method available on the market. The starting equipment consists of only a main contactor and thermal or electronic overload relay. The disadvantage with this method is that it gives the highest possible starting current. A normal value is between 6 to 7 times the rated motor current but values of up to 9 or 10 times the rated current exist. Besides the starting current there also exists a current peak that can rise up to 14 times the rated current since the motor is not energized from the first moment when starting (figure 2). High starting current leads to an increase the size of cables and switches.

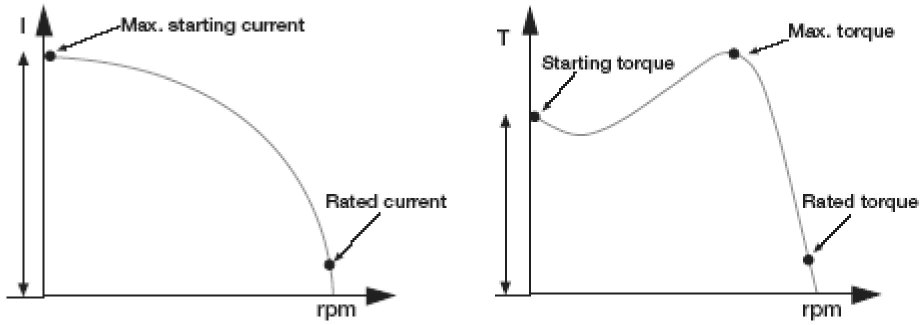

Figure 2:
a. Current curve at D.O.L b. Torque/speed curve at D.O.L start

During a direct-on-line start, the starting torque is also very high, and is higher than necessary for most applications. The torque is the same as the force, and an unnecessary high force gives unnecessary high stresses on couplings and the driven application.

Star-delta start[8]

This is a starting method that reduces the starting current and starting torque. The device normally consists of three contactors, an overload relay and a timer for setting the time in the star-position (starting position). The motors must be delta connected during a normal run, in order to be able to use this starting method. The received starting current is about 30 % of the starting current during direct on line start and the starting torque is reduced to about 25 % of the torque available at a D.O.L start (figure 3). This starting method only works when the application is light loaded during the start. If the motor is too heavily loaded, there will not be enough torque to accelerate the motor up to speed before switching over to the delta position.

To reach the rated speed, a switch over from star to delta position is necessary, and this will very often result in high transmission and current peaks. In some cases the current peak can reach a value that is even bigger than for a D.O.L start. Also, in star-delta starting, two series of cables, three cables for star- position and three cables for delta- position to be laid between electrical panel and motor. So, it leads to huge number of cables.

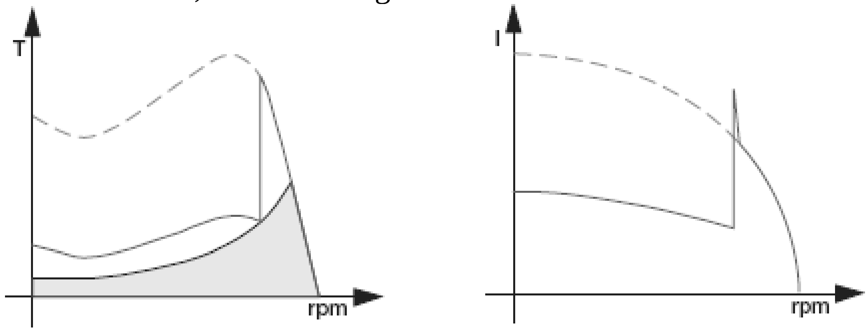

Figure 3:
a. Torque/speed curve at Star-Delta start b. Current curve at Star-Delta start

Frequency converter[8]

The frequency converter is sometimes also called VSD (Variable Speed Drive), VFD (Variable Frequency Drive) or simply Drives, which is probably the most common name. The drive consists primarily of two parts, one which converts AC (50 or 60 Hz) to DC and the second part which converts the DC back to AC (0-250 HZ). As the speed of the motor depends on the frequency, this makes it possible to control the speed of the motor by changing the output frequency from the drive and this is a big advantage if there is a need for speed regulation during a continuous run. By controlling the frequency, the rated motor torque is available at a low speed and the starting current is low, between 0.5 and 1.0 times the rated motor current, maximum 1.5 x In. Disadvantage of drive starterters is that the method is very expensive and there is no need for speed regulation during a normal run.

Softstarter[8]

A softstarter has thyristors in the main circuit, and the motor voltage is regulated with a printed circuit board. The softstarter makes use of the fact that when the motor voltage is low during start, the starting current and starting torque is also low. During the first part of the start the voltage to the motor is so low that it is only able to adjust the play between the gear wheels. In other words, eliminating unnecessary jerks during the start. Gradually, the voltage and the torque increase so that the machinery starts to accelerate (figure 4). One of the benefits of this starting method is the possibility to adjust the torque to the exact need. This method reduces maintenance costs. So, we used this method for jetfans starting for our project to balance the costs and reduce the number of cables.

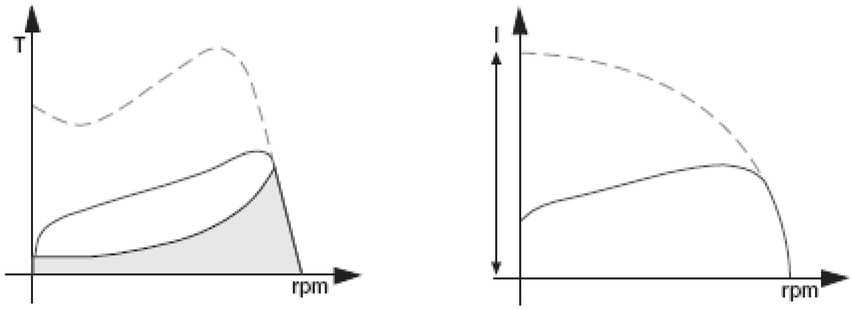

Figure 4:
a. Torque/speed curve - Softstarter b. Current curve - Softstarter

7.2. Cable damage by vermin

The common method to repel rodents and termites from cables is use of metallic armour or glass roving cables. Disadvantage of this method is that armoured cables are expensive and for the projects such as tunnels, length of the cables is very high and it leads to be an increase in the cost of the project. Also, cabling and bending of armoured cable is very difficult.
The second method is use of anti-termite and anti-rodent cables. This method is a good solution to protect cables from hostile animals. Some chemical, non-hazardous, non-toxic additives are used within the jacket polymer. Usually, for an effective anti-rodent and anti-termite, a layer of corrugated steel tape is formed between two polyethylene jackets. So, this method problem is similar to the first method.
In Tehran Resalat Tunnel project, we used un-armoured fire resistance, low smoke, halogen free cables on the cable trays. In order to protect cables against rodents, we used cover plates on the cable trays. Meanwhile, perforated cover and cable trays have been used in our project, in order to circulate the air within cover and cable tray. Use of the cover plates and un-armoured cables instead of armoured cables, decreased the cost of the project. Easier cabling was another benefit of this method.

8. OTHER SYSTEMS

Moreover, fire fighting, traffic signs, emergency telephones, intercom, barriers, over height detectors, lane control signs, speed control signs and variable control signs have been considered for the Tehran Resalat Tunnel.

9. CONCLUSIONS

In this paper, a brief explanation about the systems of Tehran Resalat Tunnel was presented. It was quoted that soft starters are the best method for jet-fan starting. Also cabling with un-armoured cables through bottom ventilated cable trays with perforated cover plates is the best solution to protect cables against rodents.

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TUNNEL TECHNICAL INSTALLATION TESTING ASSURES DEMONSTRABLE TUNNEL SAFETY

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ABSTRACT

A tunnel technical installation of a road tunnel is mainly a safety system to provide safety to travellers. Due to increasing demands and increasing dependency of software, both the chances and the consequences of malfunctioning technical installations are increasing. Typically, safety regulations contain a group of demands which have become more stringent and have given rise to the need for tighter quality assurance.

Based upon experiences and best practices, an approach for structured and risk based testing is discussed in this paper.

Keywords: testing, tunnel safety, software, tunnel technical installation.

1. INTRODUCTION

Since 2006, new laws and guidelines regarding tunnel safety regulations in the Netherlands apply to all closed road tunnels over 250 metres long. Tunnels will have to comply to these new tunnel safety regulations the latest at may 1st in 2014. Existing tunnels and new tunnels under construction are already impacted by these new regulations, because proof of tunnel safety is obligatory.

Furthermore, the number of road tunnels will rise in the Netherlands since the country is very densely populated and environmental regulations will cause parts of highways to get covered by land tunnels. This is done to reduce air pollution in populated areas. Apart from this, major infrastructural changes to road networks often include new tunnels. In fact, the number of tunnels, combined with their positions in the highway network, will lead to the situation that tunnels may become potential bottlenecks. Technical failures of a tunnel technical installation may cause tunnel shutdowns.

In all, the need for reliable tunnel technical installations which comply to tunnel safety regulations is increasing. Since the need to prove tunnel safety is demanded by law, the need for professional testing of tunnel technical installations is rising as well.

This paper elaborates a high level approach for structured and risk based testing of tunnel technical installations, called the W-model, which stems from best practices in the Netherlands.

2. TUNNEL SAFETY AND CONTEXT

This paragraph describes tunnel safety and its context as well as the dependency of tunnels and tunnel technical installations for information technology (IT).

2.1. Tunnel Safety

In the Netherlands, guideline 2004/54 of the EC, dated april 29th 2004, is worked out in a number of laws such as ‘Wet Aanvullende Regels Veiligheid Wegtunnels’ (WARVW) and ‘Besluit Aanvullende Regels Veiligheid Wegtunnels’ (BARVW), both of February 2006. These laws are the main laws regarding tunnel safety in road tunnels and contain numerous process related and product related requirements to be met, the latest in May 2014. In addition, there are guidelines by Rijkswaterstaat (RWS), the Dutch organization within the Ministry of Traffic and Waterways responsible for construction and maintenance of roads and waterways. The main guideline for tunnel safety is 'Leidraad Veiligheidsdossier Wegtunnels', dated October 1st 2007. This guideline deals among others with the obligatory set up and maintenance of the tunnel safety dossier.

Tunnel safety regulations, as described in the fore mentioned laws and guidelines, concerns the safety of tunnel users. The three main demands for their safety are:

- Facilitate 'self rescue possibilities' of tunnel users,
- Facilitate 'professional assistance squads' to do their jobs, also in the event of (major) accidents,
- Prevent escalation of incidents and accidents.

These requirements refer to the tunnel as an integral safety system and to the training of traffic controllers who operate the tunnel. Furthermore, the laws and guidelines demand proof of test results, a tunnel safety archive and a tunnel safety plan to operate a tunnel.

At Rijkswaterstaat the tunnel safety philosophy emphasizes the integral approach of tunnel safety in the following way (Mante, R., 2009):

- The tunnel system as a whole is to be considered. Not only the road, the tunnel construction, the installations, but also the organization during exploitation of the tunnel (traffic management, handling of accidents etcetera)
- The whole safety chain is to be considered, which involves pro-active measurements, prevention, preparation, risk mitigation, repression and after care.

For the purpose of this paper, we will use the following definition of tunnel safety. Tunnel safety concerns the safety of the tunnel users and:

- addresses the three main safety requirements of the ability to "save yourself", facilitating professional assisting squads and prevention of escalation,
- involves technical and organizational aspects as well as the construction and the exploitation phases,
- considers the tunnel to be an integral system and
- considers the tunnel technical installation to be primarily a safety system consisting of all hard- and software to operate a tunnel.

2.2. Availability and reliability

Requirements for availability of tunnels are high and in some cases reach over 99 percent availability, excluded for maintenance intervals. Tunnel safety and availability therefore are diametrically opposing factors. For example, in the case of technical failures of a tunnel technical installation, the traffic manager operating the tunnel, could be forced to shut down the tunnel. However, from an availability perspective, it's preferable to keep the tunnel open for traffic.

Since the introduction of the tunnel laws in 2006, technical failures in tunnel technical installations have caused major traffic congestions in main area's like Rotterdam and Amsterdam. Both cities have an encircling ring of highways and these rings contain major tunnels as well. A major traffic congestion in these cases mean that severe highway traffic jams during an entire traffic peak of three hours holds the traffic flow around the city and causes delays of one hour or more for motorists.

Because tunnel safety and availability are opposing factors, the reliability of tunnel technical installations gets ever more important. If the reliability is very high, the tunnel is able to meet both the demands of tunnel safety and availability.

2.3. Importance of information technology

A typical tunnel consists of fifty installations or more. These installations are connected by interfaces and supported by software. Moreover, the functionality of these installations as a group, is enabled by IT. This implies that the dynamic conduct of a tunnel is determined by the tunnel technical installation which relies on software for its conduct. Therefore, the importance of IT is substantial and the consequences of malfunctioning software are ample.

To put things in perspective, IT is only a fraction of the costs to realize a tunnel. New tunnel projects may cost around 500 million euro, the tunnel technical installation costs less than ten percent of this amount and the software less than one percent. However, the risks involved with IT may cause millions of damage to both society and operators of tunnels. Keeping in mind that contracts for exploitation may stretch thirty years, the expected damage because of malfunctioning software extends the investment costs for the IT-project or the software.

2.4. Demand and supply side responsibilities

The government in the Netherlands supports the view that the public sector leaves as much as possible to the private sector concerning infrastructure projects. At the end of last century the department Rijkswaterstaat was still the organization that designed and specified the tunnels in detail and the private sector constructed the tunnels as specified. This situation no longer exists. Currently, the department Rijkswaterstaat, or some other state representing institution like provinces or cities, prescribes with high level requirements the objectives for the tunnel, its surroundings, its capabilities and the private sector designs and constructs the tunnels, either with design and construct contracts or with design, build, maintain and finance contracts. The situation today could best be described as a situation where both sides, the public sector and the private sector, is still in the process of mastering the new balance in demand and supply side responsibilities. The public sector needs to direct and control the tunnel projects and has yet to achieve maturity at these aspects. The private sector for their part is still mastering the design phases, before constructing the tunnel. Enhanced tunnel safety demands have been a complicating factor in this process and to date remain a major factor.

3. TRENDS AND CHALLENGES

Tunnel demands will increase in the future. Amongst others, safety demands and availability demands will increase because of technological progress in general terms. Environmental demands will increase as well and therefore, tunnels will maintain evermore functionality in a increasingly demanding environment and society. It is to be expected that IT-complexity within tunnels will increase as well, .

The need to keep in control with regard to IT-related activities, will gain importance over the years to come. Testing, and quality assurance in general, will therefore gain significance in tunnel projects and tunnel exploitation as a prime success factor for risk mitigation.

Moreover, the change in demand and supply side responsibilities enhances the need for control of requirements management, designing, constructing and exploitation at both sides, public and private parties involved in tunnel projects, and in their cooperation to realize tunnel projects. This also implies .the need for testing and quality control in a broad sense as a key success factor.

4. EXPERIENCES

In the last four years experiences at seven tunnel projects in the Netherlands, including three investigations, several points of attention for testing can be drawn up.

- Test maturity levels are low compared with the risks involved with tunnel technical installations and the needed test attention.
- Adequate test environments are essential to test tunnel technical installations during the construction and the exploitation phase.
- During the project phase of tunnel realization, relatively little attention is given to maintenance and exploitation with respect to testing. The capability to assess the status of the entire tunnel technical installation during the exploitation phase is lacking in many cases.
- System architecture; the interfaces between systems, subsystems and installations are not always clear in the design documents. Therefore the test base for integral testing of functions and scenarios aimed at the dynamic behavior of the tunnel is insufficient.
- The main processes should be worked out at the beginning of each tunnel project. This is important for a successful cooperation between the sponsor and the contractors and is the base for the contractor to elaborate the required design documents.
- During the construction phase, the emphasis is at technical tests of separate installations, rather than integral tests at the functional level or the level of scenarios or main processes. With the emphasis at technical tests, the prove of complying to tunnel safety requirements is lacking.
- Moment of involvement for IT with regard to architecture, design, realization and testing. This moment is lagging behind other disciplines like civil engineering. Ideally, the systems engineering involves the enabling functions of IT right from the beginning of tunnel projects.
- At the one of investigated tunnel projects, methods of testing are not standardized in practice although required by the used standards for systems engineering. Therefore it was unclear what executed tests have demonstrated. More specific:
  - test objects during testing remain less defined,
  - test scripts don’t determine precisely which tests have been executed,
  - descriptions of test data and test data is lacking,
  - traceability of tested requirements is lacking in most situations.
- Tests aren’t always repeatable in an easy manner.
- In the tunnel projects where certified test specialists were involved, the traceability aspects and the structured approach of testing was evident.

The main conclusion is that the significance and the need for structured risk based testing is underestimated at the demand side as well as the supply side. Nevertheless, the need for structured risk based testing during the entire life cycle of an tunnel technical installation is evident and awareness is growing.

5. PROPOSED SOLUTION, W-MODEL

From an IT perspective, several solutions are possible to solve issues with the IT-delivery processes involving the construction of a tunnel technical installation. One solution is using systems engineering with standards like J-STD-016 or MIL-STD-1521. However, prescribing systems engineering with acknowledged standards is already common practice in tunnel engineering and yet, timely delivery of an adequate tunnel technical installation remains problematic in the Netherlands. Therefore testing adds value to the processes constructing a tunnel technical installation by measuring progress and demonstrating the status.

In our view, testing throughout the construction and the exploitation phases of a tunnel is a key success factor. Therefore, a model to test tunnel technical installations, based upon our experiences in tunnel projects and test experience in the Netherlands, is presented.

5.1. Requirements of the model

The following is taken into account for the presented model.

- It should be easy to understand because common practices within the IT-industry may be unfamiliar to engineers involved in construction of tunnels.
- It should be relatively easy to apply the model in practice.
- In general, it should be a framework for all tunnel projects.
- It should ensure demonstrable tunnel safety or other requirements.
- It should be cost effective throughout the entire lifecycle of a tunnel.
- The division in demand and supply responsibilities of sponsor and contractor should be incorporated in the model.

The presented model is called the W-model and is elaborated in the next paragraphs.

5.2. W-model overview

The W-model is graphically shown in the next model overview.

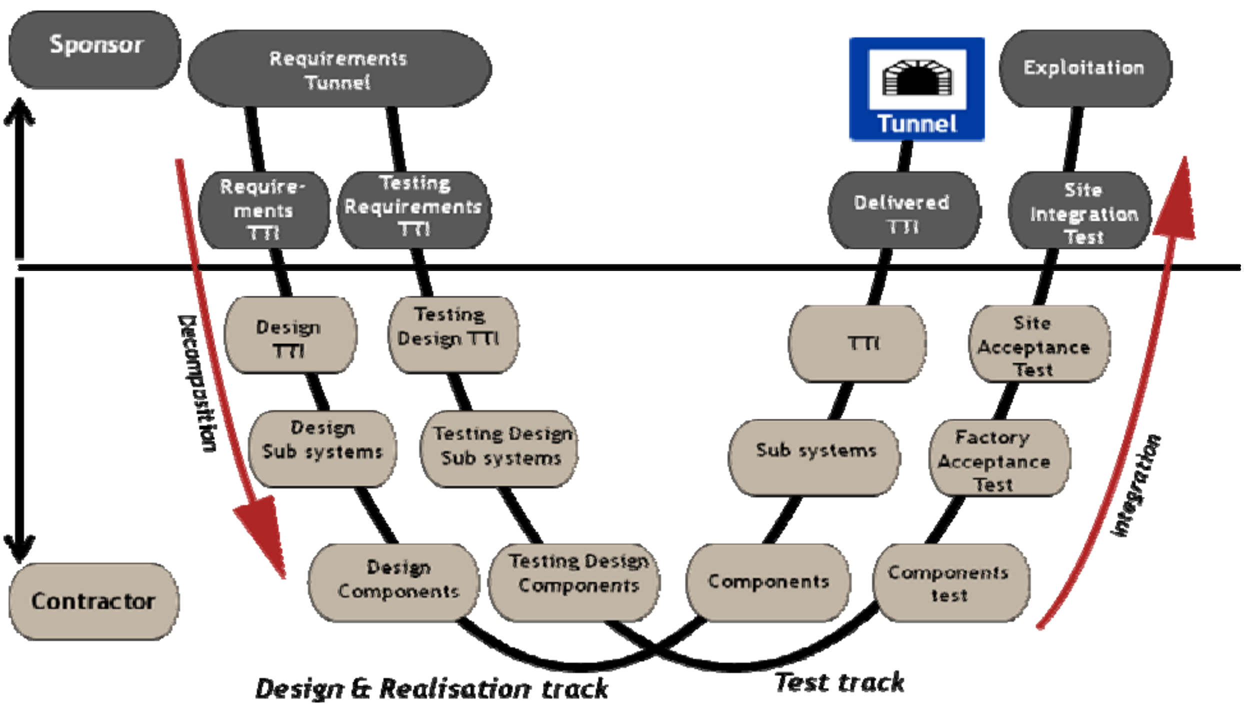

Figure 1: Graphical overview of the W-model.

First of all, the W-model is derived from the V-model (Koomen, T., 2006). This V-model exemplifies the following among others:

- The construction of (information) systems comprises a process of decomposition of high level requirements to detailed designs and a process of integration to construct bottom up the required system based upon the designs.
- The referred V-model is a way to control a software delivery process. The decomposition and integration steps enable control in terms of progress and quality.
- Each 'block' within the V-model contains an identified piece of work.

The W-model is based upon these principles since the model consists of two interlinked V-models. One for the design and the realisation of the tunnel technical installation and one for the corresponding test activities.

The horizontal line divides the responsibilities for these two tracks between the sponsor and the contractor. The 'blocks' above the horizontal line are the responsibility of the sponsor, below the horizontal line are the responsibility of the contractor. However, cooperation is necessary since both parties are taking part in the same tracks.

Furthermore, the model overview clearly shows that testing parallels designing and realisation. It is emphasized that testing starts the moment requirements analysis starts and that testing goes on until the tunnel technical installation is at the end of its lifecycle. In the model overview the exploitation phase is omitted. However, the result should be that testing capabilities to validate tunnel requirements are preserved.

5.3. Objectives and testing conform the W-model

The W-model aims to deliver a test approach and a test method to ensure timely and demonstrable delivery of the needed quality of a tunnel technical installation.

Testing relies on a test strategy and the two main components of a test strategy are:

- the phasing of testing and
- the test coverage of the risks which need to be addressed.

From a different perspective, these two main components represent on a high level structured risk based testing as meant by the test method TMap®.

To explain more detailed the test phases, the test levels in the model are briefly described:

- Testing as shown in the left hand side of the test track with the test levels 'testing requirements TTI', 'testing design TTI', 'testing sub systems TTI' and 'testing design components'. One objective is to trace the development of business requirements in user requirements and in system requirements and the development of these requirements in the corresponding design documents. The result of tracing is amongst others the degree to which can be demonstrated that the tunnel technical installation is safe for the tunnel user. Moreover these tests focus on completeness, accuracy and, consistency of the requirements and the design documents.
- The 'components test' is basically the technical test for all separate installations. The test for a single component is done solitarily. The test has to prove whether the component under meets the requirements and whether the component may be part of the tunnel technical installation together with other components.
- The 'factory acceptance test' (FAT) is a test for sub systems like 'energy supply', 'air supply', 'directing and handling'. The tests are executed at a test environment at the site of the contractor. This environment has to be maintained throughout the design and realisation phase and during the exploitation phase of the tunnel. In all, the sub

systems of the tunnel technical installations are tested separately as well in interaction with each other. This means that the tunnel technical installation is tested as an integral system as well. The FAT may be split in two separate test levels to divide the tests for the sub systems and the integral system.

- The ‘site acceptance test’ (SAT) is a representative sub set of the FAT, complemented with at least a small portion of newly designed tests based upon the experiences and the remaining risks of the FAT. The test environment is a production like environment at the tunnel site with interfaces to its surroundings. There is a redundancy between the FAT and the SAT and the test strategy for the entire test project should determine the level of redundancy.
- The ‘site integration test’ (SIT) is to prove at the process level whether the tunnel technical installation meets the process requirements and whether the organisation can operate the tunnel. This is done because tunnel safety laws demands it as well. The three top demands for tunnel safety are explicitly tested in the SIT. The test environment is production like and no interfaces are simulated Furthermore, the SIT may be split into a test level aimed at the processes and a test level aimed at the interaction between travel managers, firemen, policemen and other rescue workers.

This proposal for phasing the test project secures a controlled way of verification and validation of the tunnel technical installation

The risk based component of testing is encapsulated within the W-model as well. A typical test project initially delivers a test master plan containing a division of risks over test levels. Since the “test track” parallels the “design and realisation” track, the status of tunnel technical installations is constantly available. This information provides the basis for risk assessment and risk management.

In the figure underneath this is illustrated graphically.

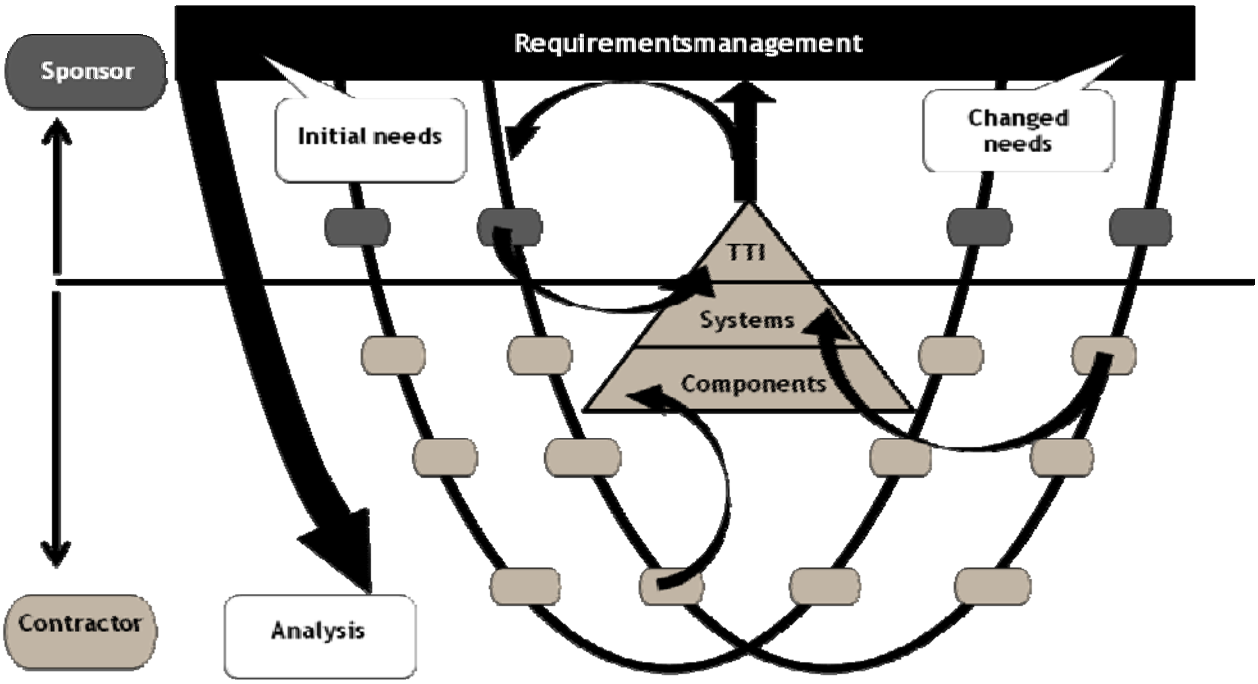

Figure 2: Iterations with risk based testing

Deviations are detected by testing and need to be addressed at the requirements management level. If a requirement is altered, corresponding design documents and (sub)systems are altered subsequently. In other cases requirements remain the same but the corresponding design documents and or (sub)systems need to be changed.

The iterations involved with risk based testing are a main tool for controlling and directing and the entire project of constructing the tunnel technical installation.

A single iteration typically consists of:

- Testing and in this manner finding defects and assess progress.
- Analyze single defects or grouped defects and assess risks involved with it.
- Determine the needed adjustments. This concerns requirements and the system or the system alone.
- Deliver the adjusted requirements and system or the adjusted system.
- Start retesting.

The whole process starts with the initial requirements analysis at the level of business requirements, followed by user requirements and systems requirements.

Summarizing, the W-model contributes to timely delivery of tunnel technical installations and at the required quality level and assures demonstrable tunnel safety. It is a structured and risk based approach based upon the global test method TMap®. It takes into account that in the Netherlands public institutions remain at the demand side of tunnel construction and the private sector for the main part design, constructs and sometimes finance and maintain the tunnels. Moreover, the model also takes into account that IT-complexity will rise and that an approach to direct and control the IT-delivery processes is needed.

6. PRACTICES SO FAR

The model is currently in use at a tunnel project in the Netherlands, called “Kanaalkruising Sluislkil”, which will become approximately 1.000 metres long and will be built in the province of Zeeland. The process to select a contractor is currently underway and the candidate contractors are obliged to organize test processes in line with the testing principles as described in this paper. Furthermore, a presentation at a national road congress in the Netherlands was given on the same subject (Boersen, P., 2009).

7. RELATED DEFINITIONS

Testing is a quality measure and is one of the measures available for quality assurance. In this sense, what does quality mean? “Quality is the totality of features and characteristics of a product or service that bear on its ability to satisfy stated or implied needs” (Koomen, T., 2006) What is testing? “Testing is a process that provides insight into, and advice on, quality and the related risks”. (Koomen, T., 2006) Other related terms are the terms ‘verification’ and ‘validation’. Verification is about testing whether a test object meets the requirements properly. Validation concerns testing whether the testobject suits the operational organisation.

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SAMPLING AT INTEGRATED TESTS IN TUNNELS

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[1]Amstein + Walthert Progress AG, CH

ABSTRACT

The proper operation of the safety equipment in road tunnels is verified with periodic integrated tests. These tests contain verification of the correct operation and interaction of the safety equipment in case of an incident (reflex tests) or special situations (power failure etc.). Because of time pressure often reduced test effort using a sampling methodology is chosen. The analysis of the sampling results is used to assess the quality of the entire system. The statistical analysis in this article show that for the entire system the significance of sampling results is very limited. Therefore adequate test methods are required to get reasonable results for a significant assessment about the safety condition of a tunnel.

Keywords: integrated tests, sampling, error probability, confidence level

1. INTRODUCTION

The term "integrated test" is not precisely defined. However, the term has largely established in the construction and engineering industry and includes those tests that are executed across an overall system, which ensure interoperability between different systems with the required or expected manner.

The main focus of integrated tests is on examination of interfaces, junctions, correct forwarding of alarms and messages and their proper visualisation. Such tests are therefore a prerequisite for a safe tunnel operation.

For operational and safety equipment in tunnels integral tests can be defined as follows:

- Cross-system testing to verify the correct functioning of the overall system and to validate the security requirements:

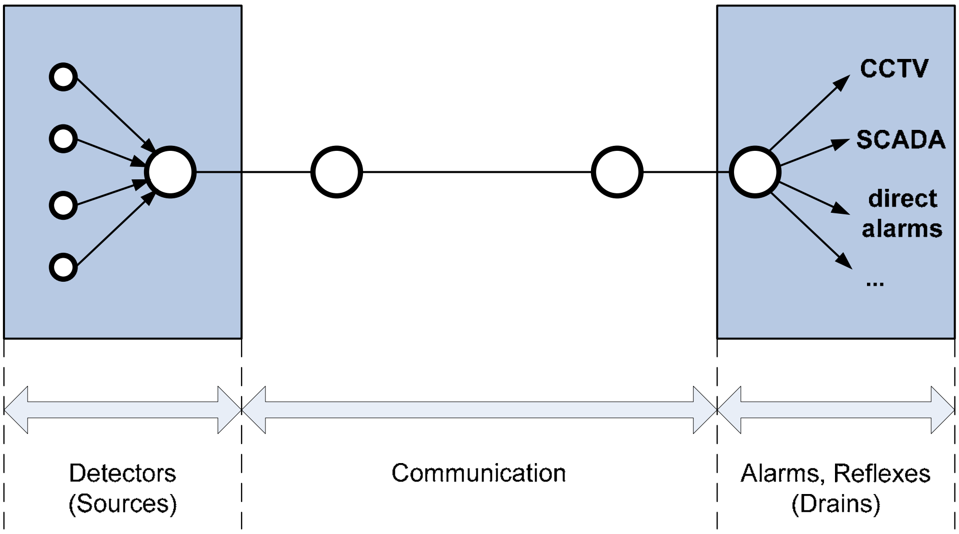

Figure 1: Example of a detection system with alarms and reflexes

The typical elements of integrated tests can be divided into three groups:

- Reflex tests: Examination of the interaction of the different safety systems (e.g. fire test)
- Performance tests: The equipment will be tested on full load
- Special tests: Other tests needed for safe operation (e.g. electricity blackout test)

In terms of reducing the testing effort integrated tests are often executed with a sampling methodology. This means only a random selection of all items (e.g. fire detectors) is tested. Afterwards, the analysis of the test results is used to assess the quality of the entire system. In practice, if the sample is found to be free of malfunctioning items a positive conclusion is drawn for the entire system. However, this has found to be critical because the significance of the sampling results is very limited for the overall system. The statistical analysis of sampling approach can quantify the significance of the test results for the entire system and can indentify the weak spot of sampling at integrated tests.

2. DIFFERENTATION SYSTEM TESTS / INTEGRATED TESTS

Along with integrated tests, system tests play a crucial role for getting significant results for the complete system. In *integrated tests* the interdependencies of the different systems shall be tested with priority. The *system tests* are defined as tests focussing on a single system without considering interfaces and adjacent systems or components. The system test of a detection system contains all detectors including the alarms on the respective control unit. The entire system tests are often ensured by self-monitoring systems.

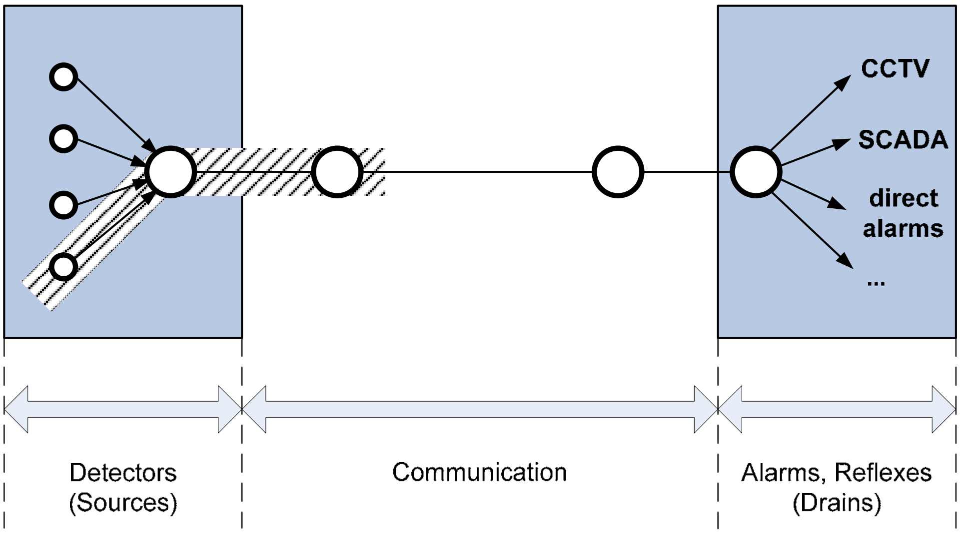

Figure 2: System tests (shaded) as prerequisite for integrated tests.

3. SIGNIFICANCE OF SAMPLING RESULTS

3.1. Sampling tests

Sampling means that out of a more or less large number of items only a selection (a "sample") is tested. The analysis of the sampling results is finally used to assess the quality of the entire system.

Within the probability theory, the binominal distribution is one of the statistical approaches for understanding the effects and the correct application of sampling tests. The binominal distribution describes the probability of identical an independent experiments with only two possible outcomes. The integrated tests of safety equipment conform to this characteristic. For the statistical consideration the error probability respectively the confidence level of the binominal distribution is relevant.

The statistical theory shows that the significance of results from randomly tested units for the entire system depends on the number of all system elements, the true failure rate and the sample size. For the entire system the significance of sampling is very limited. Therefore, its use is not appropriate for detection systems in tunnels. This will be made clear in the following.

3.2. Error probability / confidence level

Error probability means the probability of drawing a wrong conclusion from the sample test. The confidence level is 100% minus the error probability, which means the probability of drawing a right conclusion. Among others the probability depends on the total number of units to be tested.

The following table shows the relationship between the total number of system elements and the error probability with a constant failure rate of 10% and a constant relative sample size of 10%:

Total elements	Number of defective elements	Sample size	Number of defective elements in the sample	Error probability
10	1	1	0	0.9
50	5	5	0	0.59
100	10	10	0	0.349
150	15	15	0	0.206
200	20	20	0	0.122
250	25	25	0	0.072
300	30	30	0	0.042
400	40	40	0	0.015
500	50	50	0	0.005
750	75	75	0	0.00037
1000	100	100	0	0.000027

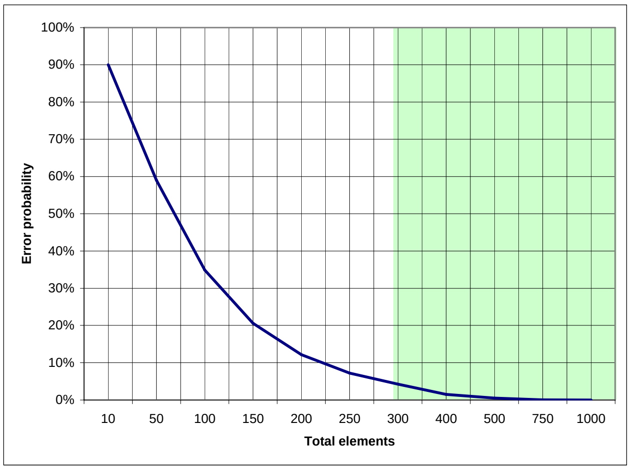

Figure 3: Decreasing probability of error with increasing number of elements (constant failure rate of 10% and constant relative sample size of 10%)

The error probability decreases by considering systems with higher total number of elements (having the same failure rate and the same relative sample size). The error probability should be less than 5% in order to achieve a 95% confidence level, which is a widely accepted and reasonable safety level (shaded area in figure 5).

Up to a total number of elements of about 300 the error probability is higher then 5%. Under these circumstances this way of testing would be inappropriate. If the number of elements exceeds 300, a sufficient level of confidence over 95% can be achieved.

At a constant total number of elements and a constant level of confidence the expected failure rate defines the necessary sample size. This means, if the failure rate decreases the sample size has to be increased.

3.3. Example: Emergency telephones

There are 20 emergency telephones in a tunnel, which are to be tested using a sample size of 3 telephones. The test principle is as follows: If there is no malfunctioning telephone in the sample, no further tests are made. In this case we assume that the all of the 20 telephones are working correctly. In case of any telephone in the sample working incorrectly, all telephones will be tested.

The following table shows the probabilities for one, two or three defective telephones among the 20 for the test procedure described above (shaded the probability to find no malfunctioning telephone in the sample):

Total elements	Number of defective elements	Sample size	Number of defective elements in the sample	Probability
20	1	3	0	0.857
20	1	3	1	0.143
20	2	3	0	0.729
20	2	3	1	0.243
20	2	3	2	0.028
20	3	3	0	0.614
20	3	3	1	0.325
20	3	3	2	0.057
20	3	3	3	0.003
20	3	10	0	0.197

Figure 4: Problem of sampling (shaded the probability to find no malfunctioning telephone in the sample)

If there is among 20 emergency telephones one defective unit we will not find it in a sample of 3 with a probability of 0.857. In this case, the probability of error is 85.7%. If there are 2 telephones in the same test working improperly, this value is 72.9%. In case of 3 telephones with malfunction the probability of error is 61.4%.

The benefits (less effort for testing) cannot be justified due to the high probability of error. Even with a sample size of 10 and 3 defective telephones, the probability of error is still 19.7%.

3.4. Example: Fire alarm cable with sensor chips

A fire alarm cable with sensor chips should be randomly tested. The test principle is as follows: If there is no defective chip in the sample, no further tests are made. In this case we assume that the whole system is working correctly. In case of any chips in the sample working incorrectly, all chips will be tested.

The following table shows the error probability for different sample sizes to find no defective chip in a total of 100 containing 5 defective ones:

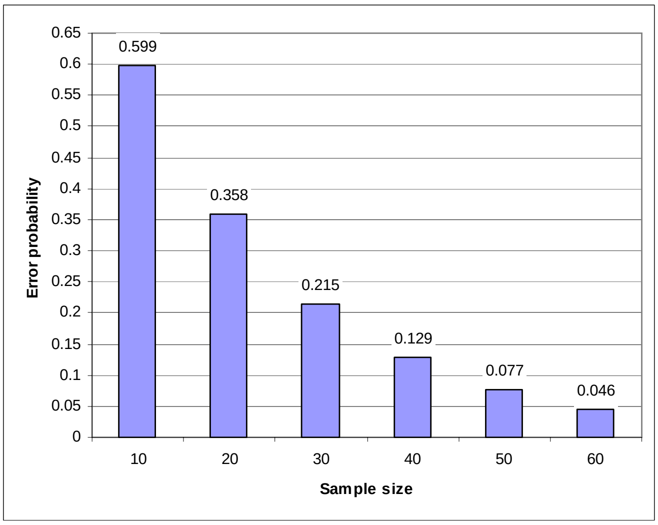

Figure 5: Error probability for different sampling sizes to find no defective chips (for 100 chips containing 5 errors)

The probability to find no defective element in the sample (error probability) decreases with increasing sample size.

For this example the sample size must exceed 50 chips out of 100 to achieve a sufficient level of confidence (over 95%) respectively a sufficiently low error probability (below 5%).

3.5. Conclusion

There are not many technical systems in tunnels, which allow sampling test methods due to the limited number of units to be tested. It was outlined that a confidence level of 95% is necessary for evaluation of safety systems – and, that this level can be hardly reached. 300 test units are required to reach significant results by a failure rate of 10% and a sample size of 10%. If the expected failure rate is smaller then 10%, the sample size must be increased.

4. ADEQUATE TEST METHODS

4.1. Principle

As outlined above, integrated tests shall focus on the interaction between different systems and should not be system-oriented. However, the test methodology has to base on the weakest and most crucial link in a chain. Hence, a statement about the safety condition of a tunnel is only possible with an adequate test methodology for each individual component.

This means that critical elements of the test chain, such as fire detectors, emergency telephones, video detectors, etc. must be thoroughly tested. Due to a lack of time and limited maintenance staff capacity, other test methods are necessary, such as combined processes with single tests and sampling tests.

4.2. Sampling combined with evidence of system tests

The maintenance staff executes and records single system tests within a defined time span or monitors precisely results of self-monitoring systems, if available. The results of these tests shall be audited and documented carefully and may give evidence for a proper system function. Basing on this data, integrated tests can be executed with a sampling methodology as outlined above.

Finally, for the overall validation of the integrated tests the evidence of successfully executed system tests must be included in the test record. The combination of the results from the system tests and integrated tests allows a proper assessment about the overall system and the safety condition of a tunnel.

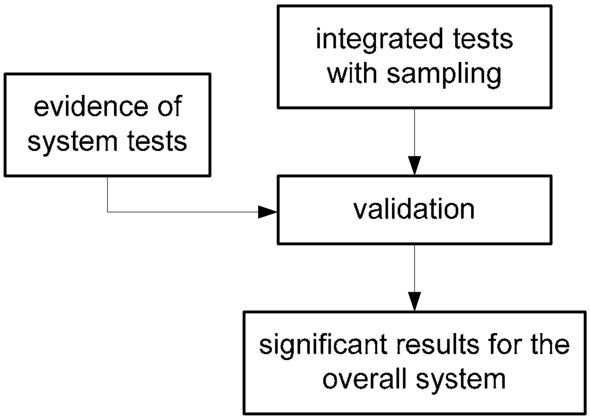

Figure 6: Test method of sampling combined with evidence of system tests

4.3. Test of the entire system

If no records of single system tests exist, sampling at integrated tests is not reasonable. Therefore, the integrated tests must ensure that all elements (detectors) are included in the test range. This means, the system tests must be executed in the integrated tests. Otherwise, the results do not allow a proper assessment about the entire system or safety condition of a tunnel.

5. CONCLUSION AND RECOMMENDATION

Integrated tests are increasingly important for tunnel safety procedures. Safety officers have learned that a carefully worked out test program and respective test records are mandatory. However, test records are of limited value, if the test method does not follow the simple laws of probability.

The statistical theory shows that the significance of results from randomly tested units for the entire system depends on the number of all system elements, the true failure rate and the sample size. It depends on the specific safety system characteristics (number of detectors and expected failure rate) if sampling tests can be applied with a reasonable sample size.

If such sampling tests are not feasible, 100%-testing is necessary. Further a combination of the two test methods shall be considered, it may be more efficient. Nonetheless, performing of tests is time-consuming and costly – and test results do not simply reflect the safety standard of a tunnel. A careful adaptation of the methodology to each technical system is required.

LEACKAGES IN EXHAUST DUCTS OF TRANSVERSE VENTILATED ROAD TUNNELS

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ABSTRACT

In tunnels with concentrated smoke extraction systems the under pressure in the exhaust ducts are relatively high and leakages into the exhaust ducts cannot be avoided. Those leakages can have a significant impact on the efficiency of the ventilation system and must be considered in the design.

Currently very few established bases to quantify leakage of flows are available. For this reason a Swiss research project has been initiated to extensively investigate leakage of flows into exhaust ducts in road tunnels. The main part of the research covers in-situ leakage measurements in several road tunnels then analysing the data to draw concrete conclusions. The leakage measurements have been carried out using the well-proven tracer gas (SF_6) method. In order to acquire a comprehensive set of data, a total of 16 tunnel tubes of different type (age, refurbished/new, construction) have been measured.

This paper gives a brief overview of the leakage problem, discusses the measurement results and presents a method to easily predict leakages.

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

1. NOMENCLATUR

L:	length [m]
x:	coordinate in exhaust duct direction [m]
A:	cross-section area [m²]
D_{hyd}:	hydraulic diameter [m]
U:	perimeter [m]
λ:	wall friction factor [-]
ζ:	pressure loss coefficient [-]
Δp_{stat}:	static pressure difference [Pa]
Δp_{dyn}:	dynamic pressure difference (Staudruck) [Pa]
ρ:	air density [kg/m³]
u:	exhaust air velocity [m/s]
Q:	volume flow [m³/s]
δQ:	volume flow measurement uncertainty [m³/s]
ΔQ:	leakage volume flow [m³/s]
Δq:	specific leakage volume flow [m³/s/m]
ω:	dimensionless volume flow ratio [-] ($\omega = Q_1/Q_0$)
f*:	effective leakage area [mm²/m²] (effective geometric ratio of the leakage area compared with the duct surface area)
K:	parameter 1 [-]
$\bar{t}$:	parameter 2 [-]
Π_0 :	dimensionless pressure [-]

Indices

0:	beginning of the exhaust duct (tunnel)
1:	end of the exhaust duct (fan)
AK:	relating to the exhaust duct
BK:	relating to the damper
δ	uncertainty
Δ	Difference

2. INTRODUCTION

The ventilation system is a major part of the road tunnel's safety system. The fundamental goal is to help tunnel users to escape from the tunnel in the case of a fire by preventing smoke from spreading over the trapped vehicles and keeping routes to the emergency exits smoke-free.

In longer tunnels most countries demand a system for locally extracting the smoke from the traffic space near the fire (see **Figure 1**). Because of the under pressure in the exhaust duct and the fact that the duct and the dampers are not completely airtight, leakages into the duct along its length cannot be avoided. These leakages can have a significant impact on the efficiency of the ventilation system such as:

- Reduced extraction flow from the fire location
- Inaccurate control of the longitudinal flow in the tunnel, particularly if the air velocity sensors are installed in groups near the tunnel portals.

According to guidelines such as *ASTRA* (2008) and *RVS* (2008), the leakage along the exhaust duct must be considered in the design. The main difficulty today is to actually quantify the expected leakage flow into the exhaust duct because very few established data are available.

In 2007 the *Swiss Federal Road Office* (ASTRA) initiated a research project to extensively investigate leakages into exhaust ducts in road tunnels. The project is well advanced and should by completed by mid-2010. The principal objective of the research work is to create a comprehensive basis to better understand the leakages into smoke exhaust ducts. The research work has been articulated in five phases: 1) Literature search, 2) Leakage measurements, 3) Data analysis, 4) Development of a method to extrapolate the measurement data to arbitrary tunnels and 5) Recommendations regarding prevention (e.g. reduction of leakages) and intervention (e.g. increasing ventilation capacity).

This paper focuses on phases 3 and 4. Further leakage associated aspects such as measurement methods, duct sealing, duct friction values, pressure loss over open dampers and damper leakages have been investigated in the research project but are not or just very briefly discussed in this paper.

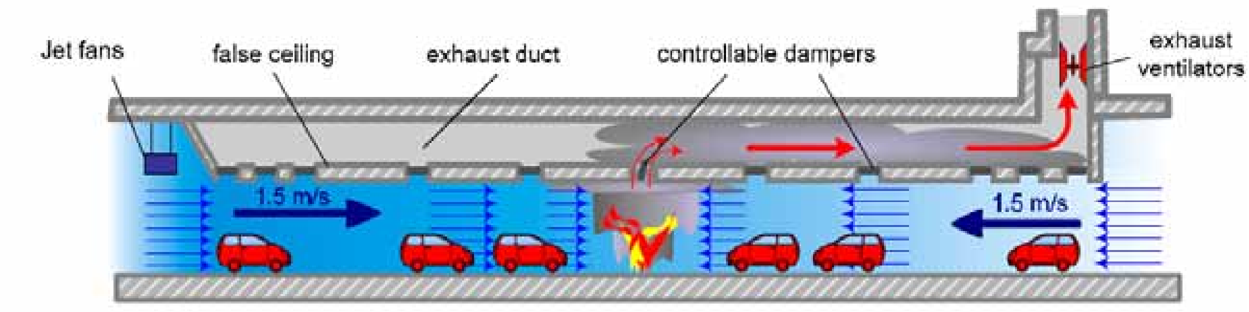

Figure 1: Typically tunnel with a smoke extraction system

3. MEASUREMENTS

3.1. Tunnels

Between August 2007 and September 2009 a total of 16 leakage measurement campaigns in 10 different Swiss tunnels were carried out. In order to acquire a comprehensive set of data the tunnels cover a wide range of types considering geometry, age, construction and topology. In **Table 1** all the measured tunnel tubes are briefly described. The "Type" indicates if the tunnel was originally built with a concentrated exhaust system (type A, generally newer tunnels) or if the concentrated exhaust system has been added later (type B, generally older tunnels). The "Position of the ventilation station" refers to the arrangement of the ventilation station(s): L = ventilation station at one portal, U = ventilation stations at both portals, T = ventilation station in the middle of the tunnel.

Table 1: Measured tunnel tubes

Nr.	Tunnel	Tube	Type and Opening	Position of the Ventilation station	L_{Tunnel}	A_{AK}
1	Flimserstein	-	A / 2007	T	2’922m	11.5m²
2	San Bernardino	Süd	B / 1967*	U	6’600m	11.0m²
3	San Bernardino	Mitte	B / 1967*	U	6’600m	11.0m²
4	Giswil	-	A / 2000	L	2’066m	11.2m²
5	Raimeux	-	A / 2007	T	3’211m	9.9m²
6	Leissigen	-	B / 1994	T	2’200m	9.5m²
7	Aescher	Basel	A / 2009	T	2’142m	10.2m²
8	Aescher	Chur	A / 2009	L	2’175m	10.2m²
9	Stägjitschuggen	-	A / 2008	L	2’302m	12.4m²
10	Üetliberg	Basel	A / 2009	T	4’439m	16.7m²
11	Üetliberg	Chur	A / 2009	T	4’499m	16.7m²
12	Kirchenwald	Nord	A / 2009	L	1’530m	13.0m²
13	Aescher	Basel	A / 2009	L	2’175m	10.2m²
14	Aescher	Chur	A / 2009	L	2’142m	10.2m²
15	Islisberg	Luzern	A / 2010	U	4’950m	8.5m²
16	Islisberg	Zürich	A / 2010	U	4’950m	8.5m²

* refurbished 1991 – 2008

3.2. Measurement method

For the evaluation of the leakages into the exhaust ducts the volume flow and the under pressure in the exhaust duct must be identified at different locations. The measurement of the under pressures in the exhaust duct is done using standard pressure measurement devices. The leakage measurements are more complex.

The leakage measurements have been carried out using the well-proven tracer gas method with constant emissions using SF_6 as the tracer gas. The concept of this method is to inject a constant mass flow of SF_6 into the exhaust air at the open dampers. After about 60 hydraulic duct diameters downstream the tracer gas is well mixed with the exhaust air and the volume flow can be calculated from the measurement of the concentration of the tracer gas. The measurement uncertainty for the volume flow is in the order of 5%. A detailed description of the method can be found in *Frei* (2008).

All the measurements reported here have been carried out by “*Hochschule Luzern – Technik & Architektur”* which is an ISO 17025 accredited laboratory.

4. QUANTIFICATION OF THE LEACKAGE

4.1. Discussion of the measurement results

The outcome of the measurements is a set of 159 data-triples (Δp, Q, ρ), 127 for A-type and 32 for B-type tunnels. These raw data are not appropriate in themselves to quantify the leakage but they do indicate important trends. The measured leakage values are very chaotic:

- For the majority of tunnels the leakages vary over a wide range even for the same pressure difference.
- For some tunnels the leakage increases approximately proportional to $\Delta p^{0.5}$, for other tunnels the leakage increases approximately proportional to Δp.

- Even for the same section and operation point, the results can be significantly different.
- Normally the leakage for the same section increases with increasing under pressure, but sometimes the reverse could be seen.

Although the reasons are not completely understood, the author assumes that the measurement uncertainty, the inhomogeneity of the exhaust duct and the structure-flow interaction (deformation) are the most important:

- With a measurement uncertainty of about 5% from the volume flow, the leakage uncertainty increases quickly to be of the order of magnitude of the leakage itself, due to the flow difference in the denominator ($\delta(\Delta Q)/\Delta Q \sim 2^* \ \delta Q \ /\Delta Q$). The problem increases for higher exhaust flows and/or lower leakages.
- Numerous inspections confirm the inhomogeneous exhaust duct tightness and material deformation due to pressure differences. Visible leakages such as drainage cabling between the exhaust duct and road level, doors or manholes are arbitrary distributed along the duct. Furthermore there is always a risk that doors and traps are not correctly closed or equipment is not correctly installed during the measurement and can distort the results.

Based on this knowledge one can conclude:

- A single measurement is not very representative to generally quantify the leakage flow. More representative is an overall treatment considering numerous measurement data.
- Leakage measurements and guideline values must be considered as fuzzy and hence used as bandwidth.
- The accuracy of leakage measurement is mainly dependant on the exhaust flow (better for low flow) and the leakage (better for high flow). The reliability depends mainly on the length of the section and the number of measurements.

Figure 2 shows the specific leakage as a function of the pressure difference (scaled to a pressure difference range of 200 Pa) for tunnel type “A” (127 data points) and tunnel type “B” (32 data points). The specific leakage is defined as the leakage per meter of exhaust duct. The numbers below the data points refers to the number of data points per pressure range.

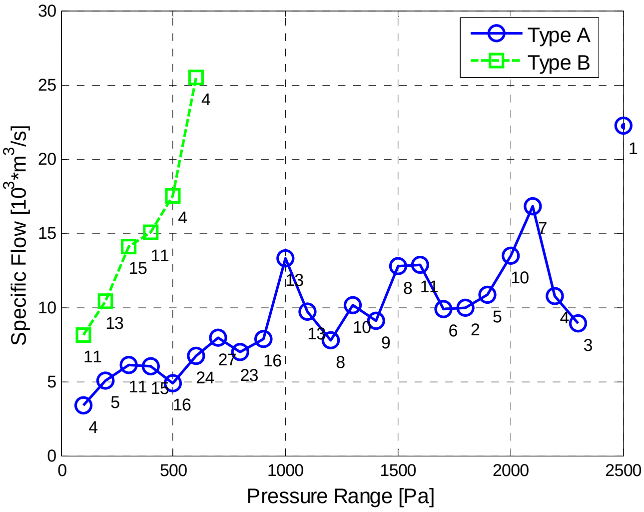

Figure 2: Specific leakage vs. pressure difference for tunnel types “A” and “B”

4.2. Approach to quantify the leakage with a dimensionless number

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

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

To describe the volume flow and the under pressure in the leaky exhaust duct, two equations are required. One equation describes the momentum balance in the main flow direction and the other describes the leakage flow perpendicular to the main flow direction. The second equation associates the under pressure with the leakage flow through the false ceiling. For this relation different approaches are possible and have been tested. From a physical point of view turbulent ($\Delta Q \sim \Delta p^{0.5}$), laminar ($\Delta Q \sim \Delta p$) or a combined approach must be considered.

The perfect approach, i.e. one which fits all measurement data very well, could not be found. The best compromise could be achieved with the turbulent approach, especially for typical pressure differences less than 2’500 Pa. Furthermore, this approach is well proven and convenient for practical application. On must consider that this approach is a compromise and for some tunnels the laminar approach could be more accurate.

The basic differential equations for the turbulent approach are shown below (Eq. 1 & Eq. 2). A detailed described and the derivation is given in “*ISETH Mitteilung Nr.39”* (1978). The unknown parameters in these equation is f* which is a dimensionless value and can be deduced from the leakage measurements.

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

$$\frac{du}{dx} = \frac{U}{A} \cdot f^* \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho}} \qquad \text{Eq. 2}$$

4.3. Definition of f*

According to the approach described above, f* is a parameter independent from the geometry and the pressure, which describes only the tightness of the exhaust duct. Hence f* should be constant for arbitrary ducts with comparable tightness.

Figure 3 shows a similar plot to that in **Figure 2** but with f* instead of the Δq. For tunnels of the type “A”, the f*-value is relatively constant for all pressure ranges. For tunnels of the type “B”, this behaviour is less distinctive. Although the pressure dependency of f* is much lower compared to that with Δq, the f*-value increases considerably with increasing pressure.

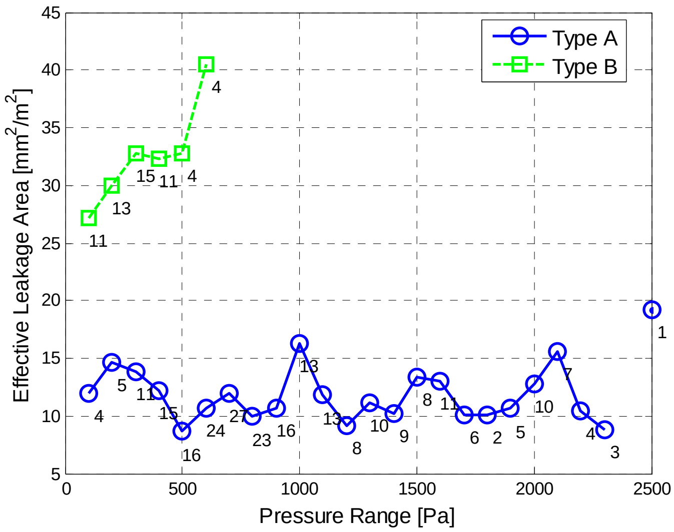

Figure 3: Effective leakage area (f*) vs. pressure difference for tunnel types "A" and "B"

This indicates that the used approach is relatively accurate for tunnels of type "A", but is not suitable for tunnels of type "B". We assume that for tunnels of type "B" the under pressure in the exhaust duct results in an increase of the leakage area due to material deformation (structure-flow interaction). Tunnels of the type "B" were not originally built for today's typically high under pressures.

Even though the present approach is not completely accurate, it is now possible to define reasonable values for f* for specific types of tunnels. These values are shown in **Table 2** for tunnel types "A" and "B". For type "B" tunnels a further differentiation considering the quality of the exhaust duct sealing was applied. The sealing type "good" refers to "state of the art" sealing where no openings are visible, while "poor" refers to a duct without or just very sparse sealing where openings are visible.

Table 2: Typical values for f*

Tunnel type	A	B	
Sealing of the exhaust duct	good	good	poor
f* [mm^2/m^2]	12 – 14	20 – 30	30 – 35

5. METHOD FOR PRACTICAL APPLICATION

For practical application, a method has been developed which enables the leakage into the exhaust duct to be quantified using a dimensionless number based on a well known approach described in "*ISETH Mitteilung Nr.39*" (1978). With this method it is possible to quickly calculate the volume flow (Q_1) and the under pressure (p_1) at the end of the exhaust duct. With these values it is then straightforward to estimate the ventilator operation point and the required power.

For the basic differential equation system (Eq.1 & Eq.2) an implicit solution for a dimensionless flow ratio (ω) can be found. This solution is not very convenient for practical application; therefore a graphical solution for ω has been created and is shown in **Figure 4**. With two parameters (K and $\bar{t}$), the dimensionless flow ratio (ω) can be directly read from the diagram. The definition of ω and the corresponding parameters are given in the following equations (Eq. 3, Eq. 4, Eq. 5 & Eq. 6)

$$\omega = \frac{Q_0}{Q_1} \quad \text{Eq. 3}$$

$$K = 8 \cdot \lambda \cdot f^{*2} \cdot \left(\frac{L \cdot U}{4 \cdot A_{AK}} \right) \quad \text{Eq. 4}$$

$$\bar{t} = 2 \cdot \sqrt{\Pi_0} \left(\frac{f^*}{\lambda} \right)^{1/3} \quad \text{Eq. 5}$$

$$\Pi_0 = \frac{p_{stat0}}{p_{dyn0}} = 1 + \frac{\varsigma_{BK} \cdot A_{BK}^2}{A_{AK}^2} \quad \text{Eq. 6}$$

The reference values for K are typically between 0.01 and 0.1 and for $\bar{t}$ between 0.2 and 0.8. If no specific data for f* are available the typical values from **Table 2** can be used. After defining the dimensionless flow ratio (ω), the under pressure at the end of the exhaust duct can be calculated using Eq. 7.

$$p_{stat1} = p_{dyn0} \left(\frac{\lambda}{8 \cdot f^*} (\omega^3 - 1) + \Pi_0^{3/2} \right)^{2/3} \quad \text{Eq. 7}$$

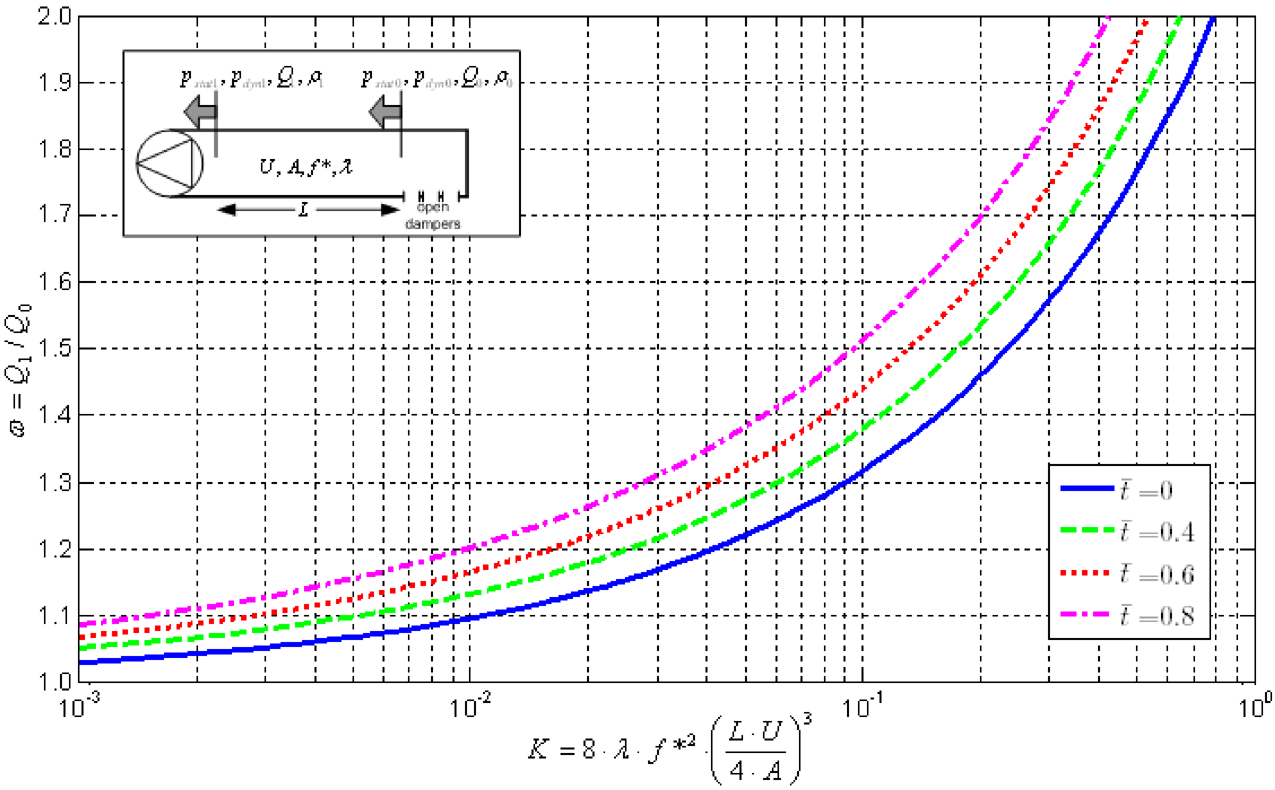

Figure 4: Diagram to estimate the exhaust duct leakage

6. CONCLUSIONS

Leakages into the exhaust duct can have a significant impact on the efficiency of a ventilation system and must be considered in the ventilation design. However to quantify leakages very few established bases are available. Therefore a research project has been initiated to extensively investigate leakage into exhaust ducts in road tunnels. The most important results of the research are:

- Data of in-situ leakage measurements in 16 tunnel tubes could be gained.
- Results of leakage measurements can be very chaotic; hence a single measurement is not very representative.
- Measurement uncertainty, inhomogeneity of the exhaust duct and the structure-flow interaction are important aspects regarding leakages.
- A method to quantify the leakages into exhaust ducts with a dimensionless number (f*) has been developed. This method enables the leakage and the under pressure at the end of the exhaust duct to be quickly quantified.
- Typical values for f* have been defined for different types of tunnels. These values must be considered as orders of magnitude and used as bandwidth.

7. ACKNOWLEDGEMENT

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"FROM THE CLASSICAL FIRE-FIGHTING WATER SUPPLY TO STRUCTURE AND SMOKE-GAS COOLING, TAKING THE "GLEINALM TUNNEL" AS AN EXAMPLE, PART I

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1. INTRODUCTION AND OBJECTIVE

Classical fire-fighting water supply systems have not been able to prevent disasters in road tunnels. The first 10 to 15 minutes are crucial in fighting fires. However, the persons involved are normally not capable of becoming active in initiating fire-fighting measures on scene. Moreover, activating hydrants and handling the equipment requires expertise and training. Against this background, there are considerations for the use of water-spray systems, etc. as a first means to quench the fire. After giving an overview of the currently existing fire- fighting water supply systems, this option will be discussed based on these systems. In the Gleinalmtunnel, smoke-gas cooling by injecting fine dripped water mist is being implemented to protect air extraction facilities. (see presentation by Helmut Kern).

Classical water supply systems are imperative for fire brigades in combating fires and in mitigating their consequences. Naturally, avoidance of the outbreak of any fire is the overarching goal. In the event of a fire, recognizing and localizing the incident have absolute priority. The same applies to the ventilation system, which has to be adapted to the fire incident to minimize the spread of the fire and the development of smoke. If the fire is not detected early enough and if no immediate action to extinguish it is taken, it must be safeguarded that the victims are able to reach the exit, escape adits or emergency bays via the shortest route. Another absolute requirement to protect humans and material in tunnels is to provide and to keep clear the access routes for professional fire fighters.

2. FUNDAMENTALS, GUIDELINES AND STANDARDS

2.1. Scope of application

Applicable to existing and planned road and railway tunnels, not to subways, etc.

2.2. Terminology, definitions, etc.

- Mountain tunnels
- Underground passages (flat land tunnels)
- Underwater tunnels
- Short tunnels up to 800 m
- Tunnels of medium length: 800 to 2.400 m
- Long tunnels 2.400 to 9.600 m
- Extremely long tunnels > 9.600 m
- Twin-bore tunnels
- Single-bore tunnels
- Cross passages
- Escape tunnels / exploratory tunnels
- Longitudinal ventilation
- Transverse ventilation
- Fire extinction bays
- Parking bay with rescue and waiting area

2.3. Guidelines, standards, etc.

- RVS (Austrian Guidelines and Regulations for Road-based Infrastructure)
- Guidelines for fire protection, guidelines and standards for the planning, construction and operation of water-supply systems, etc.

3. DESIGN PRINCIPLES AND COMPONENTS OF A CLASSICAL FIRE-FIGHTING WATER SUPPLY SYSTEM ACC. TO RVS

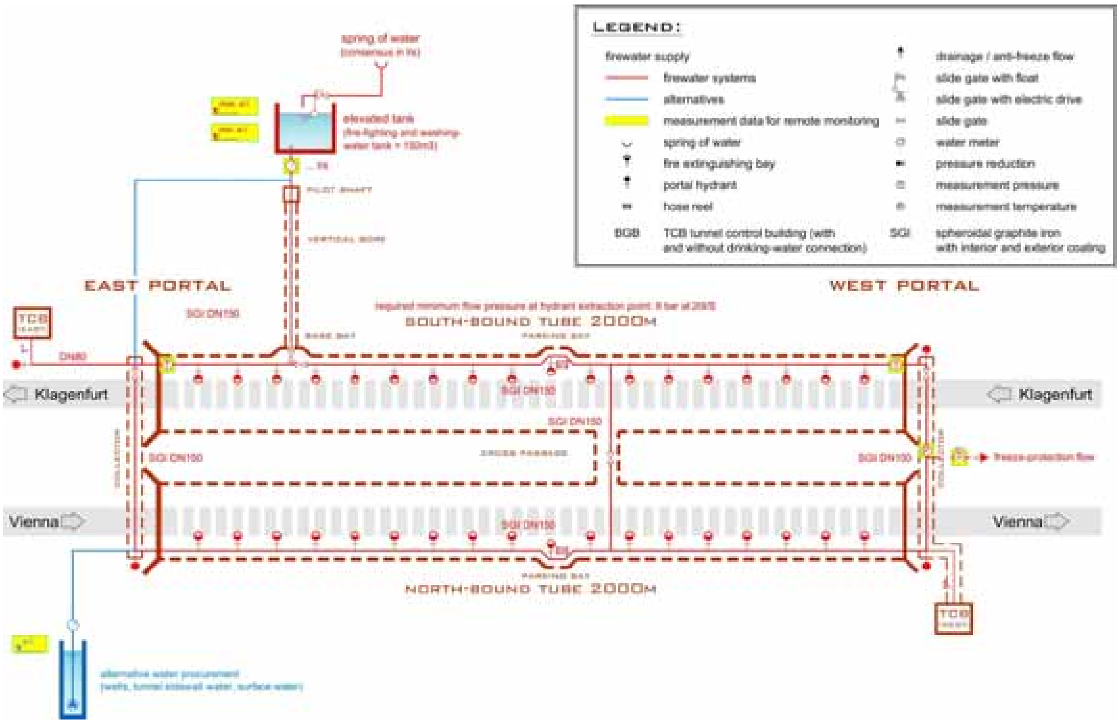


Fig. 1: Classical fire fighting water supply system

3.1. Water requirement, supply pressure, bay equipment, etc.

According to RVS, hydrants must be able to deliver 1,200 l/min at a flow pressure of 6 to 12 bar for a period of 1.5 hours. Experience has shown that this quantity is sufficient for the conventional method of fire-fighting via hydrants. Pressures above 6 bar should be avoided as handling hoses at such admission pressures may be dangerous. When determining the admission pressure and the water quantity, the equipment available in the bays and in the tunnel itself as well as the equipment of the fire protection staff needs to be considered, too. It should be noted at this point, that in long tunnels large water extraction volumes and high admission pressures require lines of a diameter of DN 200 to DN 250. The equipment of fire brigades is usually at a standard which allows water quantities and pressure to be increased to the required level via mobile pumps anyway. The use of foam could be optimized.

3.2. Availability of water resources and water procurement

Basically, there a 3 common ways of water procurement in Austria:

a) Obtaining water from an existing water-supply company (municipal water supply, water cooperative or association, individual water supply companies)

b) Building a separate water procurement system (spring water, ground water, surface water) – see photo 1

c) Using the tunnel's sidewall water
Even though drinking water quality is not required for fire-fighting water supply systems, their water quality must be similar in its physical and chemical properties to drinking water since, for example, corrosion and depositions may have adverse effects on fire-fighting water supply systems, too (pipe ruptures, service life, …). Moreover, a part of the fire-fighting water supply system is also used to provide tunnel operation facilities with drinking water, so that drinking water quality is a requirement in this case.

From a hydraulic-economic point of view, water procurement facilities which are located at altitudes above water storage facilities are to be preferred as this eliminates the need for pumping. On the other hand, considering the low annual consumption, the water transport costs are not really an issue for fire-fighting water supply systems.

Fig. 2: Surface water intake (by Markus Gutjahr, Asfinag)

When extracting the tunnel's sidewall water, it must be borne in mind that in case of karst catchment areas the water may turn very turbid after precipitations, rendering it partly or completely unsuitable for use. Another problem which may arise under special circumstances is sintering and the vanishing of the sidewall water, particularly if it is subject to strong fluctuations. In this case it may dry up almost completely at low water. This problem does not usually occur when the bedrock is crystalline; however, this water is mostly highly aggressive. In both cases, appropriate measures must be taken to prevent corrosion and deposits. If water is obtained from public utilities, these concerns are unfounded.

3.3. Water storage (see photo 2)

RVS specifies that 108 m^3 of water must be available for a period of 1.5 hours and that this volume must be replenished within 24 hours. This means that an inflow of approx. 1.2 l/s is required. Taking into account the quantities needed for cleaning and for tunnel operation facilities, the storage volume is normally designed for a capacity of 150 m^3. If water is available in greater abundance, the storage volume can be reduced accordingly.

As a matter of principle, twin-chamber elevated tanks are to be preferred as this safeguards the security of supply even in case of power failure. Theoretically, the water for the purpose of fire-fighting could be supplied directly by a third-party utility without the need of building one's own water procurement system and one's own storage facility. This is probably the reason why a provision is included in RVS requiring dual supply, as the security of supply might not be guaranteed if one relied on the direct source of supply alone. Such a situation could arise, for example, if the tunnel were connected to a utility operating with ground tanks. In the event of a power failure, the fire-fighting water supply would fail as well.

Based on his own experience, the author would recommend installing a separate fire-fighting water tank for the sake of the necessary security of supply. Whenever and wherever elevated tanks are not possible, an adequate water supply must be safeguarded by ground tanks, which must be provided with an appropriate pumping system. In long tunnels, the pumping station must be protected from power failure (emergency power generator).

Fig. 3: Water storage basin (by Markus Gutjahr, Asfinag)

3.4. Pipelines

For reasons of fire protection, the only eligible material candidates are cast iron and steel lines, which, however, should not be coated with material containing PVC. Cast iron and spheroidal graphite iron have proved their worth in numerous tunnels, and their benefit versus steel pipes is their wall strength. In Germany and Northern Europe GRP pipes are used as well. However, in my view these pipe materials should be investigated further via fire tests to collect further data and, based on these, choose the right material. As already mentioned , a diameter of 150 at a minimum and of 200 at a maximum ought to be sufficient.

Hydrants must be placed at distances of 100 to 150 m as well as at the portals. The equipment of the bays should be coordinated with the fire brigade. Hose systems, foam and fire-fighting tubes may be stored in the bays as well, if required. Time and again discussions arise on how to design and equip the bays as temporary shelters. The author would rather recommend the provision of parking bays at distances of 500 m and equipping these with rescue and waiting rooms. This would be desirable in long single-bore tunnels, whereby the bays should be provided on both sides, but always at half the distance, so that in essence there would be a parking or rescue bay every 250 m. These bays must be provided with air via a compressed-air system, which may also be used to control valves and gates (e.g. in case of power failure). In twin-bore tunnels, closed-loop connections must, of course be established via cross passages, etc.

3.5. Technical safety equipment, especially in the hydrant bays (see photo 3)

The equipment depends on the length of the tunnel, on the distances between the bays and on the hazard classification of the tunnel.

The basic equipment should include:
- hoses and hose drum with dimensionally stable hose
- foam with admixing device, steel pipes, etc.
- various hand-held fire extinguishers, etc.

The fire extinguishing bays are marked by an appropriate signaling system, which must switch to flash mode in case of a fire. The author strongly suggests that training how to behave in case of fire should become mandatory for learners at driving schools.

Barendrecht Tunnel / railway tunnel in the Netherlands

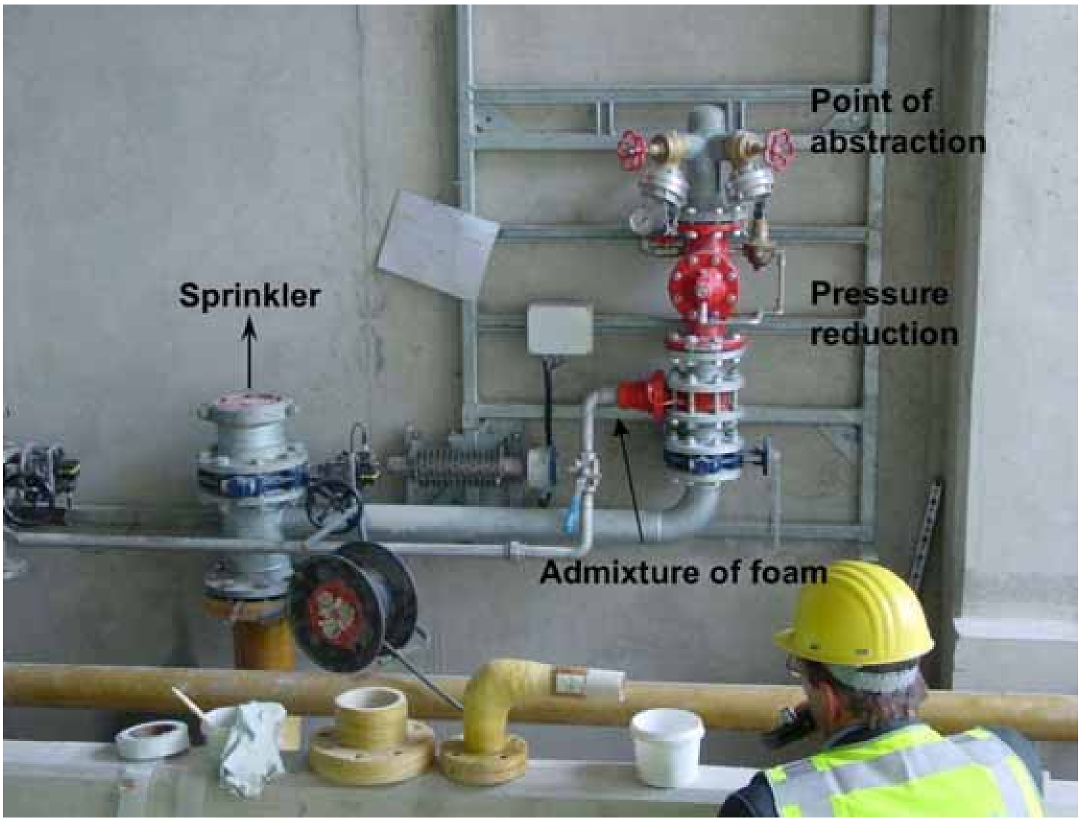


Fig. 4: Hydrant bay with downpipe to sprinkler system

3.6. Control and operation

Normally, hydrants are operated by trained personnel. According to RVS, there are lines which are permanently filled with water and so called dry-lines which are filled in case of a fire. It would be important to clarify whether these so-called dry lines will be filled automatically at the outbreak of a fire or on activation by the fire fighters on site. For operational reasons the author would favor wet lines. To detect any problems in the fire-fighting system as early as possible, selected parameters should be permanently monitored, such as the water level in the elevated or ground tank and electrically driven components of the system (pumps, valves etc.). Collecting these data and transmitting them to a permanently-staffed tunnel control center is an absolute requirement.

At regular intervals the overall systems should be inspected for reliable performance by the tunnel staff. This applies, in particular, to the mobility of gates and of shut-off and reducing valves, which should be checked, as well as to the equipment in the fire extinguishing bays. Moreover, the fire brigades should have knowledge of other possible ways of water procurement existing in proximity to the portal area (e.g. rivers, reservoirs, etc.). Special attention must be paid to the metallic parts of the fire-suppression lines, which must be properly grounded to prevent the risk of electric shocks. The annual and routine checks including remarks, in particular as regards damage and repair, should be recorded, and these records should be collected and evaluated throughout Austria.

A problem which must not be underestimated is the removal of the consequences of a fire, in particular the possible discharge of fire-extinguishing media into the road drainage and, further on, into ground water protection zones and receiving waters. At any rate, precautions must be taken to prevent extinguishing media and the resulting chemical compounds from entering the natural cycle.

4. EXPANDING AND IMPROVING FIRE PROTECTION BY SPRINKLER AND SPRAY SYSTEMS

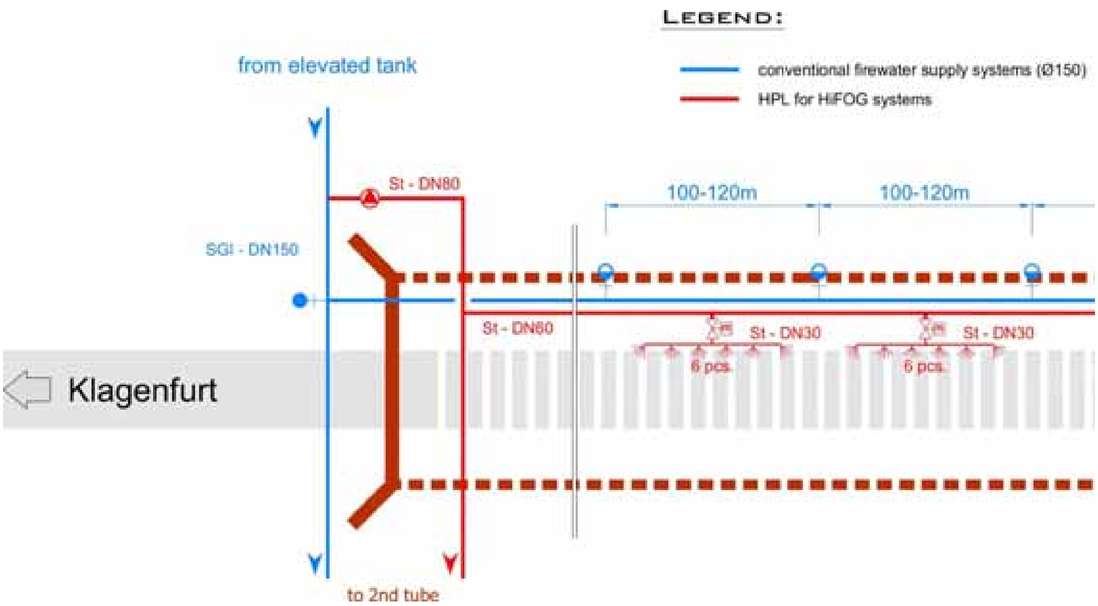


Fig 5: Principle of a sprinkler system

Sprinkler and spray systems have proved to be very efficient in commercial and industrial buildings, so that their use in tunnels should be considered as well. Sprinkler or spray systems could be positioned on the roof or on the sidewalls of the tunnel between the bays and connected to the fire extinguishing line. If required, they could be activated, for example, for certain tunnel sections. Tests should be performed to investigate whether this would limit the rise in temperature to levels which would not only protect humans, but prevent damage to objects as well. We all know only too well how time-consuming and costly it is to repair concrete structures.

The advantage of sprinkler and/or water spray systems operating at high pressure is that they disperse very small water droplets across long distances, thus counteracting efficiently the spread of heat and fire. Marioff provided the following data on the systems:

A water mist system was applied in the exhaust air duct of the Gleinalmtunnel in order to cool down fumes in case of a fire. A detailed description of this system can be found in the paper “From Classical Fire Fighting Water Supply to structure and smoke gas cooling taking Gleinalmtunnel as an example” of Mr. H. KERN; AQUASYS Technik GmbH, Linz Austria

	Typical drop size range (mm)	Number of droplets per litre of water	Surface area (m²)
Conventional sprinkler / water spray	1...5	15 thousand to 2 million	1...6
Low-pressure water mist	0.2...1	2 million to 250 million	6...30
※HI-FOG®	0.025...0.2	250 million to 150 billion Superior cooling and local inerting	30...250 Superior blocking of radiant heat

Fig 6: Comparison of a sprinkler and spray systems

5. SOME REFLECTIONS ON TUNNEL SAFETY AND PROPOSALS FOR IMPROVEMENT

5.1. The cardinal sins committed during the Kaprun disaster (from “ Blaulicht” 12-2002)

- Carriage doors and windows could not be opened from inside.
- No automatic safety doors that would open automatically in case of an incident.
- No safety hammers to smash the window panes.
- No fire extinguishers mounted in the passenger compartments.
- No tunnel illumination and no emergency lights.
- No after-glowing rescue information and signs, neither in the tunnel nor in the train.
- No rescue stairs in the tunnel. The existing stairs were merely service stairs for maintenance work and not at all suitable for rescue operations!
- No rescue or safety caverns in the tunnel.
- No sprinkler system in the tunnel or in the train.
- Tunnel lock at the top station open, presumably due to the destruction of the energy source by the fire (dead-man circuit). Thus, strong chimney effect.

5.2. Escape and rescue routes and exiting and rescue times

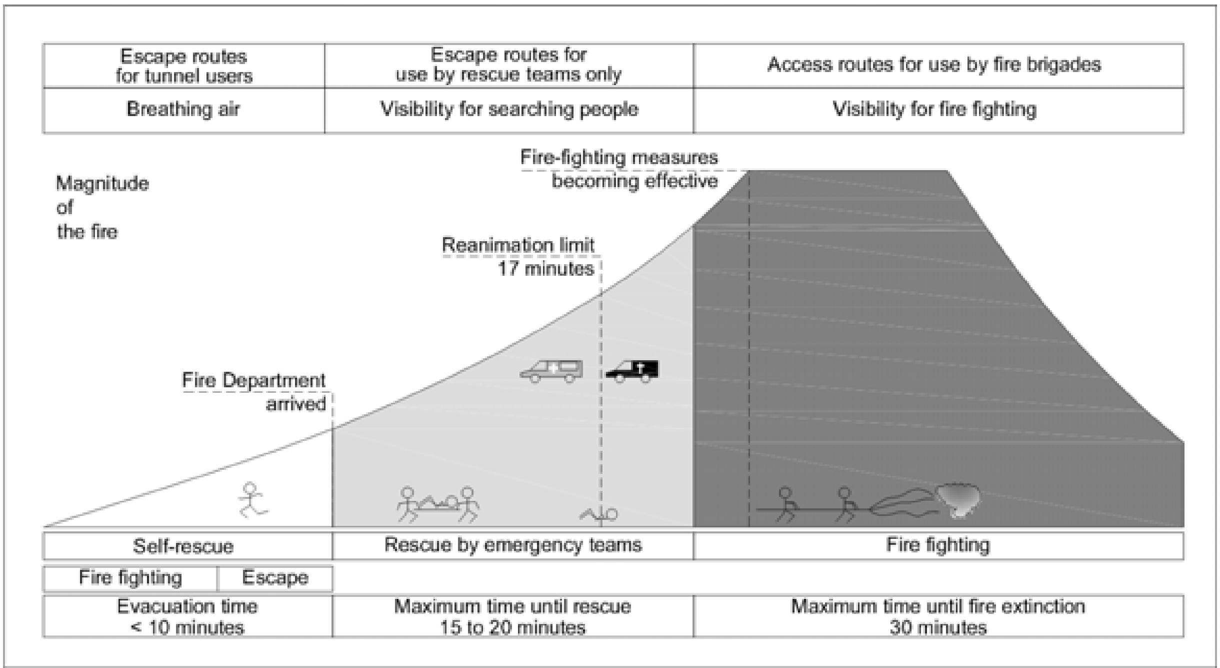
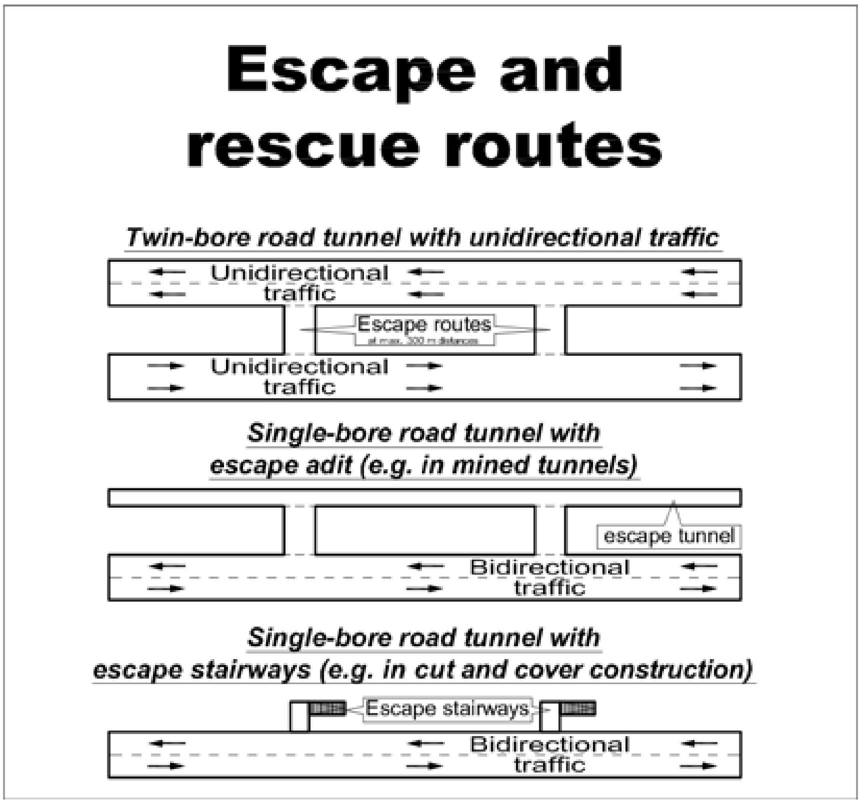


Fig 7: Allocation of the escape and rescue times

Phases of the fire and necessary protection for people
From: Leitfaden Ingenieurmethoden des Brandschutzes vfdb TB 04-01, issue May 2009



By courtesy of Univ.-Lecturer Dr. Otto Widetschek

Fig 8: Overview of escape and rescue routes

FROM THE CLASSICAL FIRE FIGHTING WATER SUPPLY TO STRUCTURE AND SMOKE GAS COOLING TAKING GLEINALMTUNNEL AS AN EXAMPLE; PART II

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ABSTRACT

Traditionally fire fighting in tunnels is done by the fire brigade with aid of the existing fire fighting equipment such as fire hydrants or hose reels in emergency cabinets. This means seem to be sufficient for smaller car fires but recent catastrophic fires have shown that the fire brigade cannot access the scene when a fully loaded truck is involved, as the temperatures in the tunnel exceed live threatening limits in just a few minutes after the incident. Based on these facts, stationary fire fighting systems which are instantly available after the detection of the fire and which are able to cope with large scale fires have been developed. These fire fighting systems can either be sprinkler or water mist systems installed in the traffic area, or smoke gas cooling systems installed in the tunnel exhaust ducts for limiting the temperature of the smoke gases. The aim of both systems is to protect the tunnel by limiting the temperature of the structure to an acceptable level during a large scale fire in the tunnel.

Keywords: water supply, fire fighting, water mist, tunnel ventilation, smoke gas cooling

1. INTRODUCTION

Several catastrophic fires during the past years did change the design of the tunnels to make them more durable against these incidents by enhancing the ventilation system, installing stationary fire fighting means or change the concrete composition of the tunnel structure.

In the project described in this document, the ventilation system was upgraded to cope with the new requirements, which included extracting hot smoke gases from the tunnel traffic area. Rather than replacing the existing ventilation fans by high temperature resistant units, it was decided to implement means to cool the hot smoke gases to a level where the existing fans can be further used to extract the then cooled smoke gases over the required period of time.

This smoke gas cooling system works on the principle that fine water mist droplets are injected in the smoke gas stream upstream the ventilators where the heat energy from the smoke gases is withdrawn by evaporation of the water droplets.

2. SMOKE GAS COOLING IN THE GLEINALM TUNNEL

2.1. The Project

The Gleinalmtunnel is situated on the highway A9 between Graz and Linz and belongs to the highway network of the ASFINAG. The tunnel has one bore with bidirectional traffic and has a length of 8.320m. The tunnel is equipped with a transverse ventilation system.

The Gleinalmtunnel was opened in 1978 and since then several upgrade programs where undertaken to adopt the safety of the tunnel to the evolving standards.

One of the major improvements was the installation of 84 exhaust air flaps in the intermediate ceiling to the exhaust duct, and the installation of fresh air flaps in the intermediate ceiling to the fresh air duct in 2002.

With this modified ventilation system only one exhaust air flap is opened in case of a fire in the tunnel. This may result that in case of a fire the temperatures near the ventilators can raise very quickly to rather high values.

When the ventilators were designed to the former specifications, they had to withstand a temperature of 250°C over 60 minutes. The current guidelines – RVS – call for a temperature resistance of 400°C over 2 hours for all constructions, which are in contact with the exhaust air or smoke gas respectively.

Therefore, to further improve the safety of the tunnel and to prevent the ventilators from high temperatures, there is a need to cool the extracted smoke gas by means of a smoke gas cooling system.

Figure 1: View of the North portal of the Gleinalmtunnel

The employer of the project is ASFINAG. The basic planning of the ventilation system was performed by FVT, Graz University of Technology, and the planning of the water supply was done by Kaiser & Mach ZT GmbH. AQUASYS was responsible for the smoke gas cooling system on a turn- key basis.

2.2. Ventilation System of the Gleinalmtunnel

The Gleinalmtunnel is a one bore tunnel with a length of 8.320 meters and operated with bi-directional traffic. The tunnel is equipped with a transverse ventilation system, consisting of six ventilation sections. Each section is equipped with a fresh air and an exhaust air ventilator, both designed as axial flow fans. Two ventilation sections are operated through the portal buildings whereas the remaining four sections are operated through the north cavern or the south cavern respectively. Each cavern is connected to a vertical air shaft where fresh air is drawn in and exhaust air is expelled.

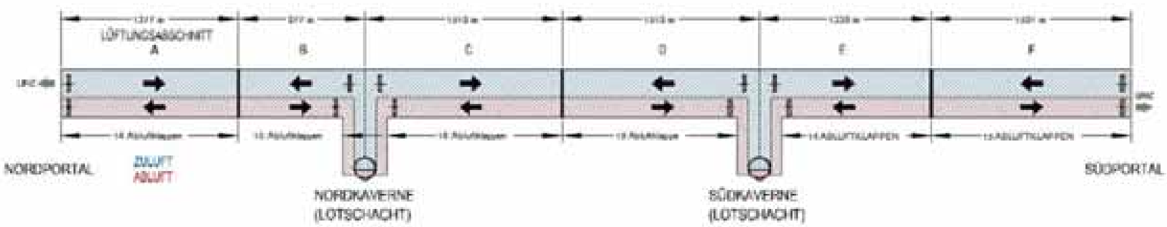

Figure 2: Ventilation Sections of the Gleinalmtunnel

The Gleinalmtunnel is equipped with an intermediate slab and a separated fresh air and exhaust air duct above the traffic area. In the exhaust duct air flaps are installed approximately every 100 meters, which are capable to extract the smoke gases in case of a fire. Through smaller flaps in the fresh air duct, fresh air is injected during normal traffic operation.

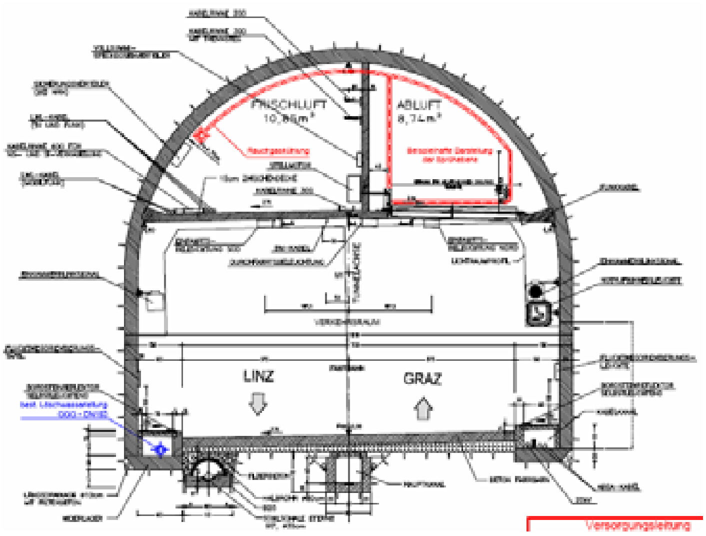

Figure 3: Cross Section of the Gleinalmtunnel

2.3. General Design of the Smoke Gas Cooling System in the Gleinalmtunnel

As mentioned earlier the Smoke Gas Cooling System shall be capable of reducing the temperature of the hot smoke gases during a fire in the tunnel to a level that the axial fans of the ventilation system are capable to operate for a duration of 2 hours in this environment as specified in the current RVS guidelines.

This temperature reduction is achieved by injection of fine droplets water mist into the smoke gas stream in the exhaust air duct. The water mist droplets evaporate and withdraw the temperature energy from the smoke gas in the equivalent of the energy which is needed to evaporate the water droplets. Based on this effect the temperature of the smoke gas is reduced to a level where the ventilation fans can operate for 2 hours.

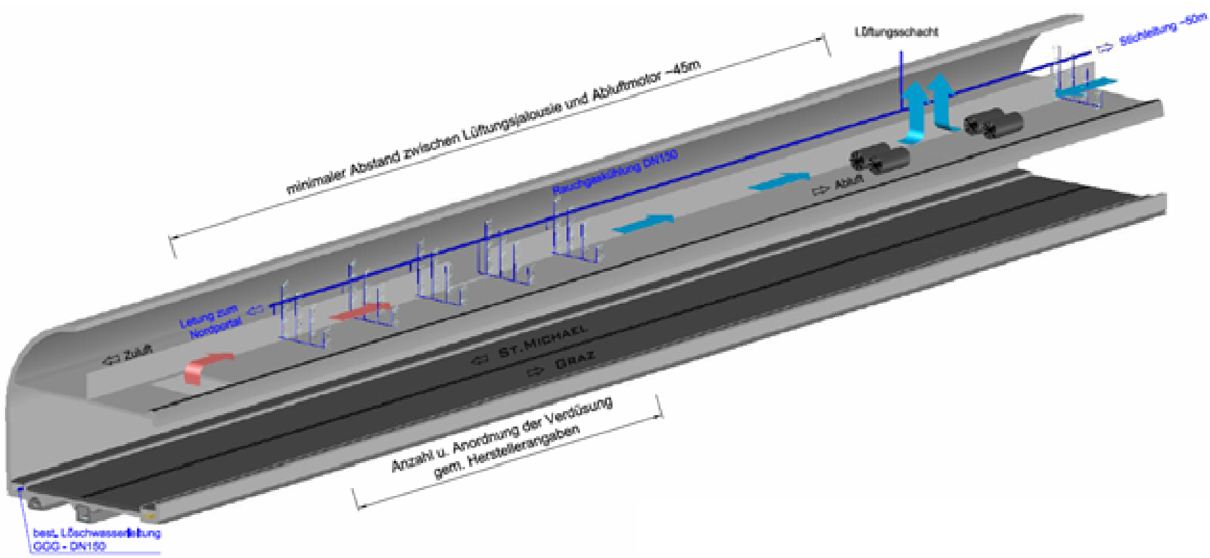

Figure 4: Principle of Smoke Gas Cooling System in the Gleinalmtunnel

For designing the smoke gas cooling system the following parameters have been specified:

- Maximum Temperature of the extracted smoke gases upstream the gas cooling system is 400°C
- Maximum Temperature of the smoke gases downstream the gas cooling system and upstream the ventilation fans is 150°C
- Maximum smoke gas flow rate in each ventilation section is approximately 150 m³/s
- The velocity of the smoke gases in the exhaust air duct is approximately 18 m/s
- Maximum distance between ventilation fan and closest exhaust flap is 20 m
- Maximum available water flow rate 20 l/s
- Minimum operation time 120 minutes

Based on above parameters the smoke gas cooling system has been designed as follows:

Thermal energy for reduction of temperature of smoke gas from 400°C to 150°C

$$Q_p = m_p * c_{pm} * (T_2 - T_1) = 40.000 \frac{kJ}{s}$$

Evaporation energy of water

$$Q_v = 2.250 \frac{kJ}{kg}$$

Amount of water for smoke gas cooling (including efficiency)

$$Q_w = 20 \frac{l}{s}$$

Maximum available time for evaporation of water droplets in exhaust duct

$$t = \frac{A}{v} = \frac{20m}{18\frac{m}{s}} = 1{,}1s$$

With this figure the Water Mist Droplet Distribution was selected to $D_{v0,9} \leq 100\mu m$

Water pressure to produce water mist by means of water mist nozzles $p \geq 25bar$

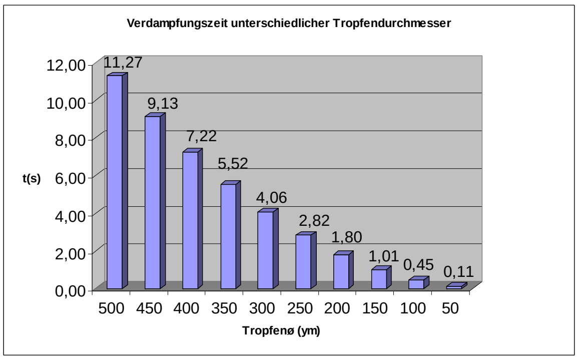

Figure 5: Evaporation time of water droplets versus size of water droplets

2.4. System Design of the Smoke Gas Cooling System in the Gleinalmtunnel

The Smoke Gas Cooling System for the Gleinalmtunnel consists of four independent stations to supply the six ventilation sections.

- One portal station with underground water reservoir and high pressure pump for ventilation section A – north portal
- One portal station with underground water reservoir and high pressure pump for ventilation section F – south portal
- One station in cavern north with elevated tank ΔH = 365 m for ventilation sections B + C
- One station in cavern south with elevated tank ΔH = 285 m for ventilation sections D + E

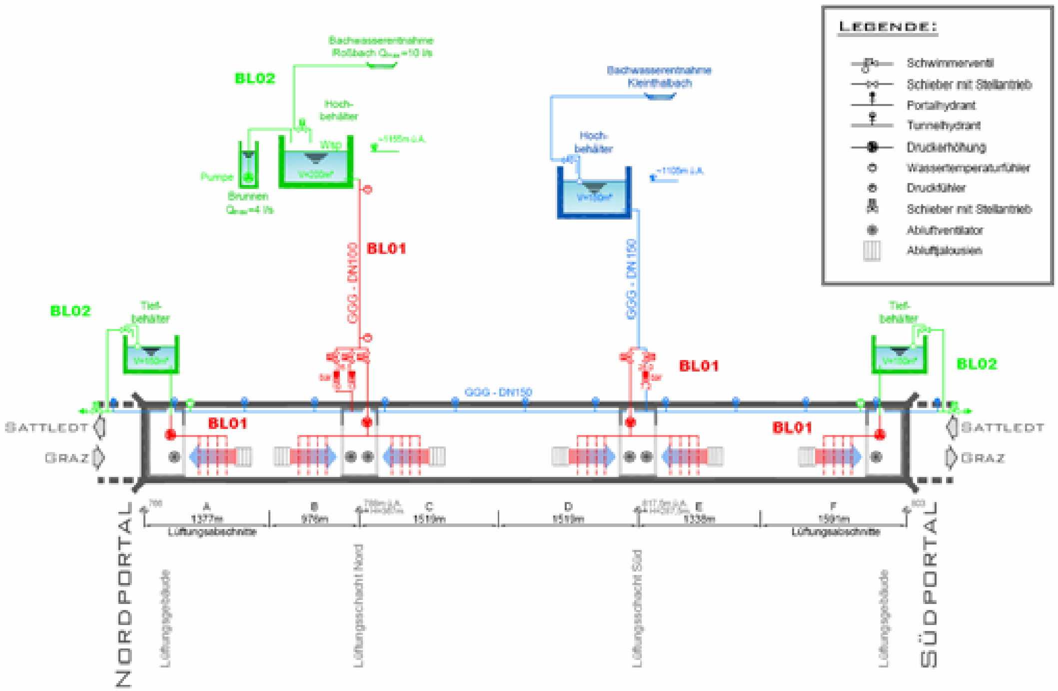

Figure 6: Schematics of Smoke Gas Cooling System in the Gleinalmtunnel

In the portal stations the water is stored in underground reservoirs with a volume of 150 m³. Booster pumps supply the water to the main high pressure pumps which produce a water flow at a rate of 20 l/s at 30 bar. From these main pumps the water is transported through high pressure pipes to the four nozzle rings in the exhaust ducts. Depending on the required water flow rate, the water is expelled through a number of water mist nozzles into the smoke gas stream in the exhaust duct where the fine water droplets evaporate and subsequently cool the smoke gas.

In the cavern stations the water is stored in elevated reservoirs at 365 m respectively 285 m above the tunnel. The water is transported in a vertical pipe through the fresh air inlet shaft to the cavern stations, where water control valves are situated to direct the flow rate to the nozzle rings. Likewise to the portal stations, the water is then expelled through a number of water mist nozzles into the smoke gas stream in the exhaust duct where the fine water droplets evaporate and subsequently cool the smoke gas. As the water reservoirs for the cavern stations are situated 365 m respectively 285 m above the tunnel, the geodetical pressure of 36 bar respectively 28 bar is used to drive the water through the nozzles without the need of an additional pressure pump.

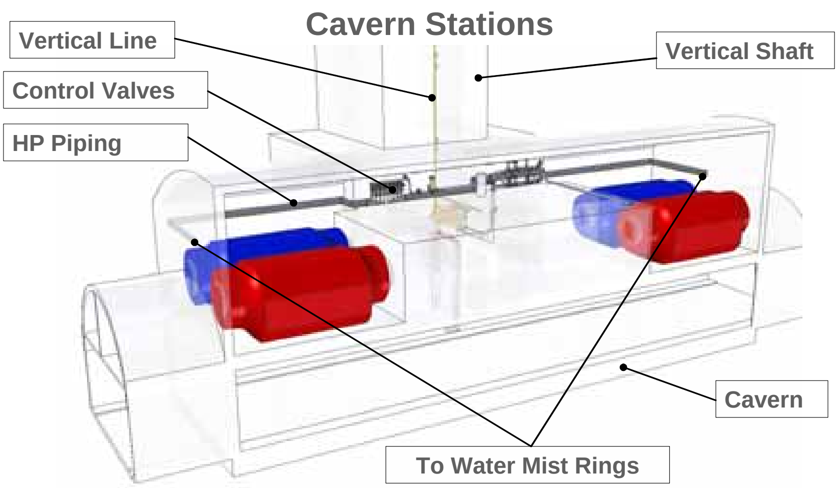

Figure 7: Cavern Stations of Smoke Gas Cooling System in the Gleinalmtunnel

2.5. Control System for the Smoke Gas Cooling System in the Gleinalmtunnel

During normal operation of the Gleinalmtunnel the Smoke Gas Cooling System is on stand by and monitors all relevant states of the system and constantly reports it to the main tunnel control system.

For each ventilation section respectively for each ventilation fan three temperature measuring grids are installed.

The system is activated when the smoke gas temperature in the exhaust duct exceeds 175°C. Then the system controls the water flow rate such that the temperature at the ventilator inlet is kept between 150°C and 175°C regardless of the smoke gas temperature which could reach a temperature up to 400°C.

In normal operation the system works fully automatically. However for emergency or maintenance operations the system can be controlled through touch panels directly at the control stations.

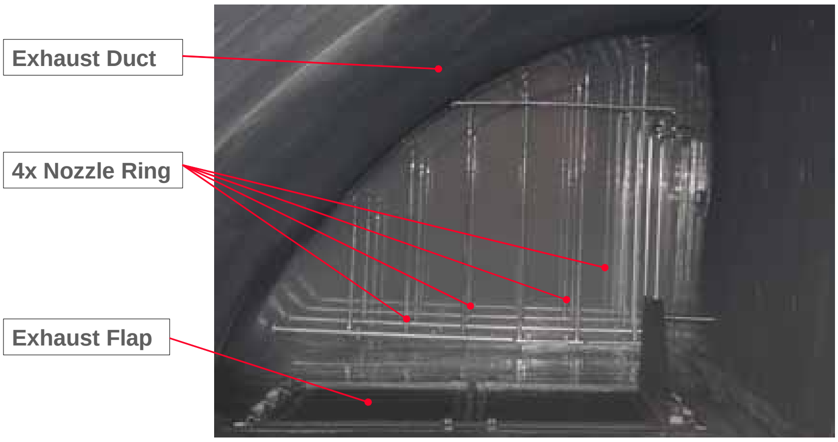

Figure 8: Nozzle Rings of the of Smoke Gas Cooling System in the Gleinalmtunnel during operation

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Figure 2, Tender Document RGK GlTu ASFINAG
Figure 3, Drawing 6 398_TuRQS ASFINAG
Figure 4, Drawing Kaiser & Mach ZT GmbH
Figure 5, Table AQUASYS
Figure 6, Drawing 1 398_Schema_06 ASFINAG
Figure 7, Drawing AQUASYS
Figure 8, Photograph AQUASYS

DIGITAL VIDEO SURVEILLANCE IN ROAD TUNNELS

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ABSTRACT

This paper proposes a new digital hardware architecture for video surveillance in road tunnels. Digital video has significant advantages compared to analogue video, which is the standard today. Studies recently carried out by us showed that digital cameras would have major impacts such as allowing a larger distance between the cameras without any consequence for video processing and reduction of false alarms of the video processing software due a better image quality. The new architecture envisages the integration of camera communication and low level image processing by a video cross-bar which offers bi-directional access to the cameras over TCP/IP thus offering video surveillance vendors a flexible and open standard way to control the cameras and to process video. Furthermore, the cross-bar provides a trigger signal over the interface to the cameras which allows the time synchronisation of all cameras. The cross-bar's computational capabilities allow basic real-time image processing such as image resizing, image cropping, colour conversion and video compression. These functionalities enable variable bandwidth and thus access to camera images whatever device is used from smart phones, over embedded devices to personal computers.

Keywords: *road tunnel surveillance, video surveillance, cross-bar, intelligent transportation systems.*

1. INTRODUCTION

Tunnels play a crucial role in the importance of the transport sector for Europe’s economy. Austria is one of the leading countries in Europe when it comes to the total number and length of street and motorways tunnels. Tunnel safety is a challenging task with very serious requirements, due to special tunnel conditions and a tight timeframe for recognition purposes and reaction of tunnel operators. Effective incident management completely depends on fast incident detection and fast incident verification. Thus, it is required that operators pay careful attention during the monitoring task, and tunnel monitoring has to be resolved by them within a very tight timeframe. Besides, the tunnel control centre has to coordinate the incident detection and verification, utilization of emergency response actors and on-scene actions, traffic management, and evacuation. As consequence, tunnel operators have a high degree of responsibility on tunnel monitoring and emergency management. Many road tunnels are

already equipped with video systems, mostly analogue CCTV-Systems. Such systems allow operators the supervision of tunnel activities and the guidance of emergency activities.
Hardware technology grew exponentially (Moore, 1965), (Kryder, 2005). Especially, advances in digital equipment and connection between different devices allow data transmission and data change easily. Digital video has significant advantages compared to analogue video, which is the standard today. Studies carried out by us (Pflugfelder, 2005), (Schwabach, 2006) showed that digital cameras would have three major impacts: (i) Assuming a constant camera's depth of focus, the higher resolution allows a larger distance between the cameras without any consequence for video processing. (ii) Assuming constant camera parameters, the higher resolution allows recognising smaller objects, and (iii) progressive-scan and less transmission noise gives a better image quality which results in fewer false alarms of the video processing software.

This paper proposes a new digital hardware architecture for video surveillance in road tunnels. The organisation of this paper is as follows: Section 2 summarises the proposed architecture explaining its characteristics, the innovation and benefits related to. Section 3 presents results of a prototype using several video sequences recorded in a real scenario. Conclusions are drawn in Section 4.

2. ARCHITECTURE

2.1. Motivation

It was mentioned that many road tunnels are already equipped with video systems for purposes, surveillance and security. Tunnel video systems are mostly conventional analogue CCTV-Systems. Such systems are based on analogue components such as cameras, coaxial cable and necessary interfaces.

Analogue cameras generate an analogue signal which is typically transmitted by coaxial cable. After transmission, the signal is digitised for monitoring, recording and image analysis. Due to the conversions from analogue to digital and vice versa, and material resistance the quality of the original video is degraded. In case of long transmission distances, it might be necessary to add power and inputs/outputs complicating this situation. In case of digital systems, images are digitised once and they remain digital during all related processes, i.e. transmission, processing, monitoring or recording. Therefore, no unnecessary conversions are necessary and no image degradation happens. In case of a typical analogue camera, it is not easy to control the camera parameters. In case of a digital one, the commands to control the camera and its parameters are being sent over the network or/and the optical fibre. Thus, the signal can also be bidirectional. Commands like synchronisation between cameras are also possible which means increased functionality and integration potential. Finally, unlike analogue systems, digital video streams can be routed through a network without loss of information.

2.2. Innovation

The proposed architecture envisages the integration of camera communication and low level image processing by a novel video cross-bar which offers bi-directional access to the cameras over TCP/IP thus offering video surveillance vendors a flexible and open standard way to control the cameras and to process video. Camera control means either the control of the camera lens or in case of pan, tilt and zoom cameras the control of the pan, tilt and zoom unit. For the first time, the video processing could directly control the cameras in real-time. Furthermore, the cross-bar provides a trigger signal over the standard interface to the cameras, either Camera Link (CL) or Gigabit Ethernet. Such technology allows the time synchronisation of all cameras and provides fast transmission of the data without loss of information. Figure 1 shows both approaches. The cross-bar's computational capabilities allow basic real-time image processing such as image resizing, image cropping, colour conversion and video compression. These functionalities enable variable bandwidth and thus access to camera images whatever device is used from smart phones, over embedded devices to personal computers. Integration and communication with both systems, existing and future are main components of this architecture. Clear and pre-defined interfaces also play an important role.

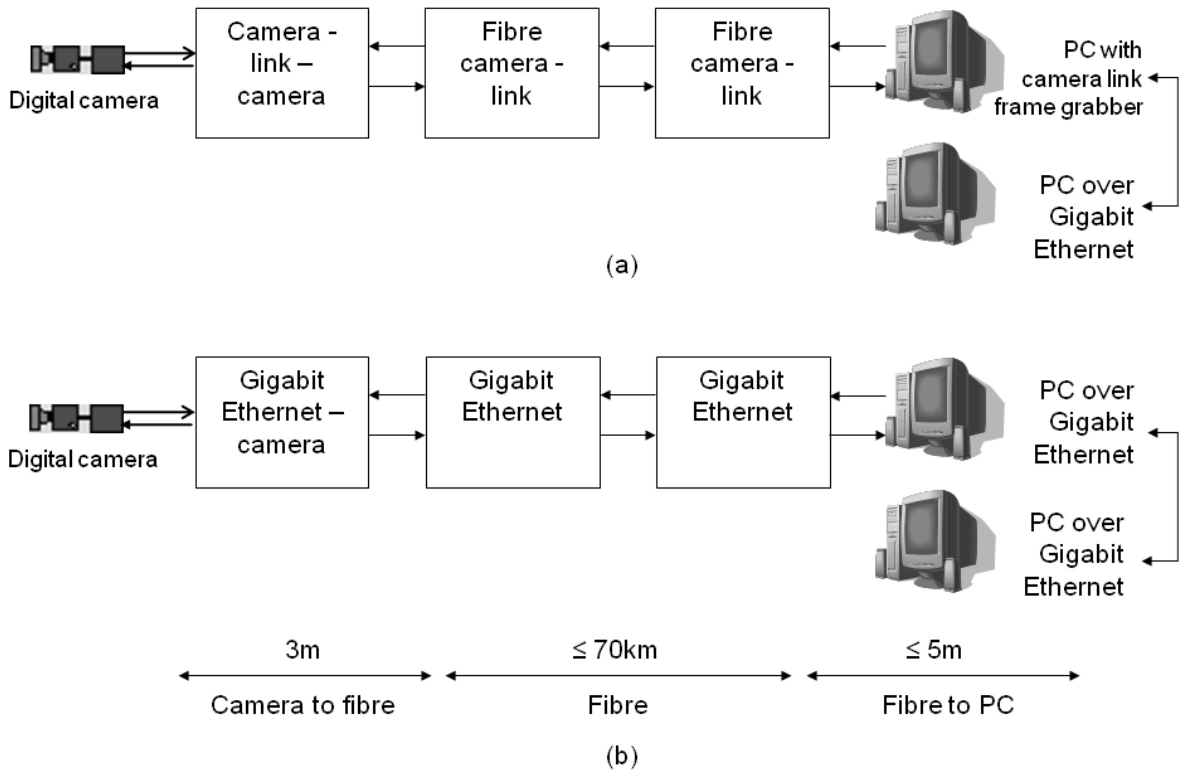

Figure 1: Possible data transmission between camera locations and central of processing (a) Camera Link approach, (b) Gigabit Ethernet approach

2.3. Benefits

Considering the characteristics mentioned in Section 2.1 and Section 2.2, by using aforementioned architecture following benefits can be pointed out:

- Costs for digital video will be competitive to analogue video with the digital crossbar.
- Digital video offers better image and image processing quality.
- A digital crossbar offers a flexible and standardised interface for third party vendors. By using low-level image processing services of the crossbar, third party vendors could use all their computational resources for high-level image understanding, thus the overall performance of video surveillance is likely to increase substantially.

- A digital crossbar offers multi-camera image processing and thus new applications. For example, multi-camera vehicle tracking would then be possible which could foster new innovations in application fields such as section control or the tracking of vehicles transporting hazard goods.
- Critical low-level image processing, such as vehicle detection and object tracking could be certified and embedded as a service that every vendor must use which would assure a lower bound of expected quality of image processing in the future.

2.4. A practical example

The main aim of VITUS project was to build and implement a prototype for an automatic video image analysis system in order to increase safety in tunnel roads (Schwabach, 2006). To achieve their objectives, VITUS was divided into two subprojects called VITUS-1, and VITUS-2 respectively. VITUS-1 was a feasibility study about video image analysis in tunnels, and it defined a concept mainly based on automatic incident management based on digital video image analysis. VITUS-2 addressed the implementation of the prototype and evaluation of the system. During VITUS-2 project, five digital cameras were installed in Plabutsch tunnel. The farthest camera was installed more than 3 km of distance of the tunnel control room. Data acquired by the digital cameras was transmitted along optical fibre to the tunnel control room. The received signal was further sent via a Camera Link interface to PCs where a camera link frame grabber was installed. Note that *all steps are digital*, thus we get the data and transmit them through the tunnel more than 3 km *without loss of information*. Figure 2 depicts part of the installed hardware.

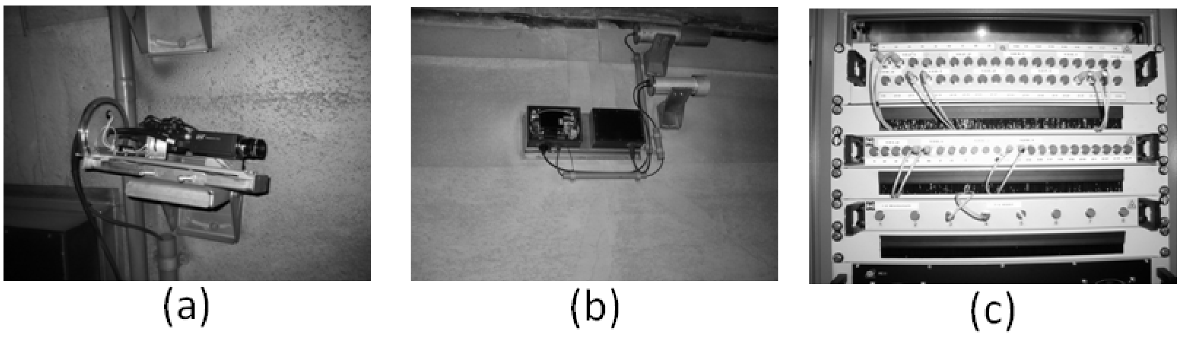

Figure 2: Installed digital components. (a), (b) Digital camera and its interface in tunnel; (c) Digital interface in tunnel control room

3. RESULTS

During VITUS project many sequences were recorded for testing purposes. Used scenes cover sequences recorded during normal operation of the tunnel, and simulated dangerous situations like traffic in wrong direction, presence of persons, lost cargo. Scenes using low illumination in the tunnel and wet road were also recorded.

Lost cargo sequences were recorded using diverse objects, which were thrown from cars running in tunnel. The objects were thrown at specific distances of the camera. Used objects were four polystyrene cubes, one carton box, one cone, and a plastic bag containing rubbish.

These objects are not part of any standard, because to the best of our knowledge no such standard currently exists. However, these objects were suggested by the users as objects of interest to be detected. Figure 1 depicts results obtained by lost cargo detection. Outer square indicates where the object was located. Inner squares indicate the detection of such objects. Table 1 compares the performance of lost cargo detection using different types of cameras.

In case of traffic in wrong way direction, Table 2 shows the detection time of traffic in wrong way direction. Such experiments were carried out under different conditions (for example, dry road and wet road) during project VITUS-2.

Figure 3: Lost cargo detection

Table 1: Results of lost cargo detection

Object	Camera distance (meter)	Object detection (%)	
		Analogue	Digital
Cube 500	40	33,33	100
Cube 300	105	0	66,67
Carton Box	130	0	66,67

Table 2: Wrong way driver detection

Sequence	Distance of detection from the camera (metres)	Detection time (seconds)	
		Analogue	Digital
Dry road, car runs to the camera	125	0.440	0.280
Wet road, car turns around	80	1.080	0.760
Wet road, car runs to the camera	125	Not detected	0.560

4. CONCLUSION

This paper has described a digital architecture for video surveillance in road tunnels. Benefits of such architecture were summarised. Basic image processing operations such as colour conversion, image resizing and image cropping are supported by the cross-bar's computational capabilities. These functionalities enable variable bandwidth and thus access to camera images whatever device is used from smart phones, over embedded devices to personal computers. Besides, the advantages of a digital common interface and benefits on the expanding area of Computer Vision applied to Intelligent Transport Systems are foreseen. Results on two real problems (lost cargo detection and wrong way driver detection) were presented showing the application of such technology.

It is hoped that this work will provide a basis for future applications by using digital technology in tunnel safety.

5. ACKNOWLEDGEMENT

We are very grateful to ASFINAG, ASTL and tunnel operators of Plabutsch tunnel for their cooperation. Current paper does not constitute a standard, specification, or regulation.

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VIDEO DETECTION OF DANGEROUS GOODS VEHICLES IN ROAD TUNNELS

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ABSTRACT

We present a solution for the automatic detection and classification of dangerous goods on trucks. Dangerous goods are labeled by an orange dangerous goods plate and/or a dangerous goods symbol sign. The acquisition system consists of a camera and dedicated illumination setup. A computer vision system processes the images by localizing and reading the dangerous goods number. The proposed system can be installed on both ends of a tunnel, thus raising awareness of all dangerous goods currently within the tunnel. To demonstrate the system, we show qualitative and quantitative localization/recognition results on real world data.

Keywords: dangerous goods plates, automatic detection and recognition, trucks

1. INTRODUCTION

Tunnels as closed rooms implicate significantly limited air ventilation as well as limited escape exits in the case of an emergency in conjunction with the limited range of sight resulting from fire/smoke/fumes in the tunnel. As for all closed rooms flammable materials show a severe hazardous potential. This is especially true whenever dangerous goods are involved in a tunnel accident due to the high temperatures and toxic fumes that can occur. For instance in May 1999 due to an accident in the Tauern Tunnel (Austria) 12 people were killed and 50 injured, as a truck loaded with paintings caused a rear-end collision. The freight exploded and the fire flashed over to 24 additional vehicles in the tunnel [9].

To avoid such accidents or to settle the right steps in case of an accident, particular attention in conjunction with dangerous goods needs to be given to road tunnels [8]. Thus, the aim would be to automatically identify dangerous good trucks before entering a tunnel. According to the European Agreement concerning the International Carriage of Dangerous Goods by Road, commonly known as ADR[1], a dangerous goods vehicle has to carry two orange-colored dangerous goods plates in front and rear of the vehicle. This is illustrated in Figure 1. These plates having a size of 40x30cm are either void (mixed transport), or contain two codes: the class/hazard-identification (e.g., 3 or 33 for flammable liquids) and the UN number (e.g., 1202 for diesel fuel or heating oil) [14].

1 ADR = Accord européen relatif au transport international des marchandises Dangereuses par Route. The last amendment entered into force on 1 January 2009. A revised consolidated version was published as document ECE/TRANS/202, Vol.I and II ("ADR 2009") [14].

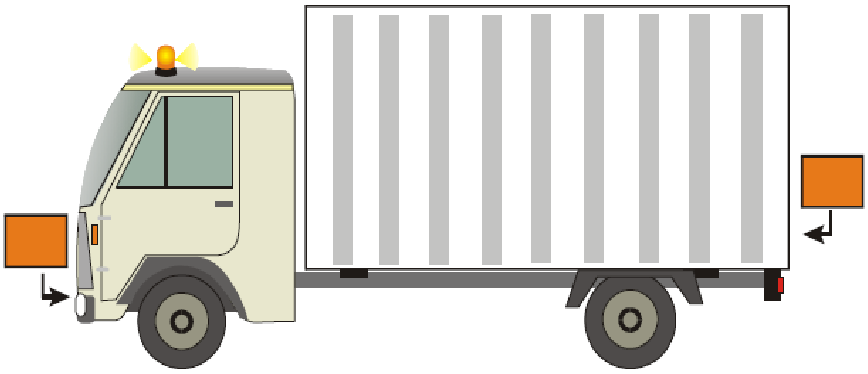


Figure 1: Markings on dangerous good trucks [15]

Thus, the goal of this work is to identify dangerous good trucks by extracting the information from these dangerous goods plates. We achieve this goal by means of video surveillance, i.e., acquiring a series of images of trucks and automatically analyzing those images. In particular, we apply a detector to localize these plates and an Optical Character Recognition to read the hazard-identification number (HIN) and the UN number, which we demonstrate on a real world data set.

The rest of this paper is structured as follows. First, in Section 2, we will briefly show a relation to the recognition of dangerous good plates on railway wagons, which inspired this work and has been the starting point. In Section 3, we outline the processing chain and its components. Qualitative and quantitative results for localization of dangerous good plates as well recognition rates for the hazard-identification number and UN number are given in Section 4.

2. RELATED WORK

The starting point for our work is the detection of dangerous good plates on railway wagons, where the wagon images are acquired by a line-scan camera and dedicated illumination unit thus resulting in a multi-megapixel image per wagon. Figure 2 shows a typical wagon image in conjunction with the automatically located orange plates on the side. Because of this image acquisition setup the data quality is different than for trucks where we need to obtain an image of the front and rear of the truck primarily. The dangerous good plates on trucks, however, follow the same conventions and are also composed by a hazard-identification and UN number. Hence, similar processing steps can be carried out.

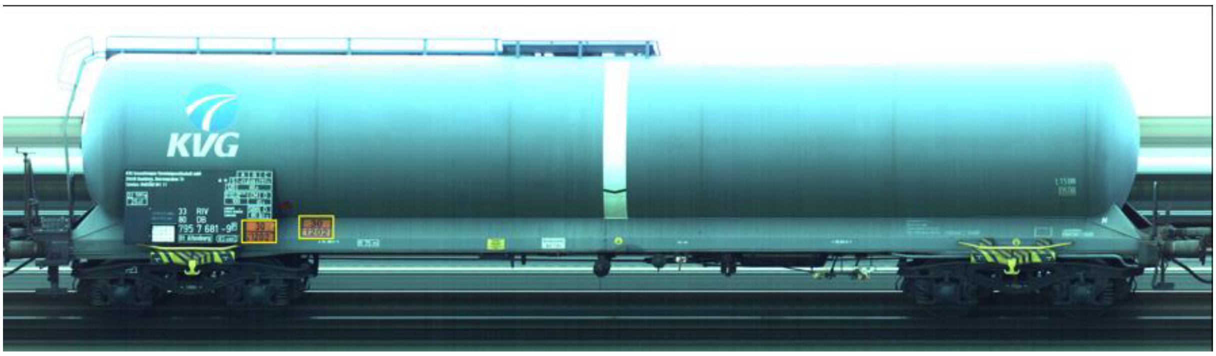


Figure 2: Siemens WaggonID

The recognition of dangerous goods plates can be seen in the context of text reading in natural scenes (e.g., [1,2]) or in particular with automatic number plate detection (ANPR, e.g., [4,7,11]). The main steps in such processing queues can be described as localization (of the plates) and the Optical Character Recognition (OCR). The most prominent way for the localization (detection) is to apply a sliding window technique (e.g., [13, 3]). A previous learned model - typically a discriminative model estimated from positive samples (i.e., the plates) and from negative (i.e., all possible backgrounds) – is applied on the image, and all locations that are consistent with the model are reported. Once the location is initialized the OCR is applied to extract/read the text.

3. AUTOMATIC DANGEROUS GOODS PLATE DETECTION

For our task, however, the processing queue described Section 2 is infeasible for two reasons. First, due to the large image sizes for the localization 100,000s of locations would have to be analyzed resulting in insufficient run-time. Second, since the dangerous goods plates can mainly be described as homogenous regions it is quite hard to discriminate them from similar regions that can be found on trucks or even on the road resulting in an unacceptable number of false detections.

Thus, in the following we propose a five-stage approach overcoming these problems. In particular, to reduce the detection time we perform a *segmentation* to identify possible candidate regions and run a *detector* on the identified regions. In an *enhancement step* the contrast in the detected plate is increased to improve the classification using an *Optical Character Recognition* (OCR). Finally, these results are checked versus a given database in the *Lookup* step. The whole processing queue is illustrated in Figure 3.

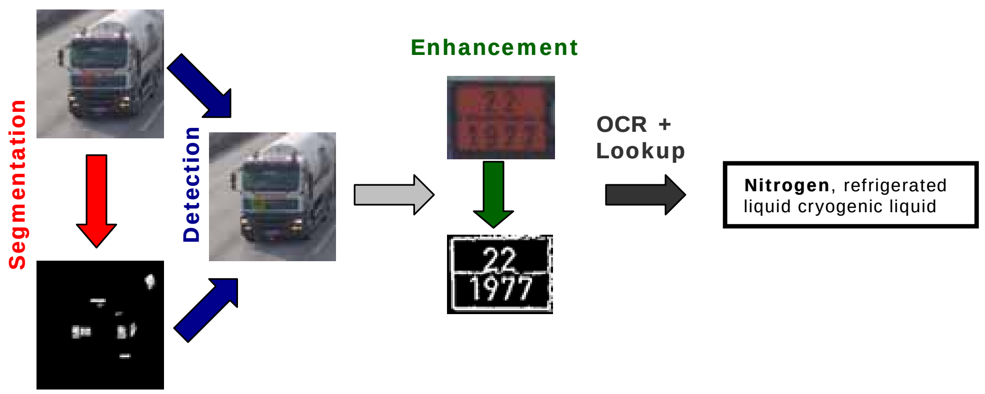
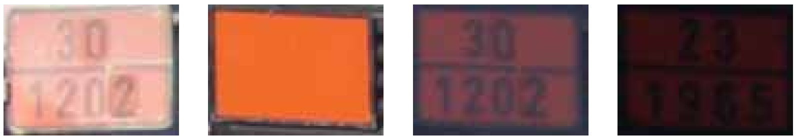


Figure 3: Dangerous plate detection/recognition processing queue consisting of (a) a segmentation, (b) a detection, (c) an enhancement, (d) an OCR, and (e) a lookup step

3.1. Region-based Segmentation

Having in mind that all plates have to be orange, it would be obvious to use color information for segmentation, i.e., to search for orange regions. However, due to the large variability in color appearance resulting, e.g., from different illumination conditions, shadows, or dirt this is infeasible in practice. This is illustrated in Figure 4 for correctly identified plates: the color ranges from “light orange” over “carmine” to “dark gray”, which clearly shows that color is an insufficient information cue for our segmentation task.



(a) (b) (c) (d)

Figure 4: Examples of real-world dangerous goods plates showing that due to the high variability a simple color model is insufficient to get a stable classification

Figure 4, however, also reveals that the plates are mainly characterized by homogeneous regions, which can perfectly be described by a region-based segmentation. In particular, in our system we build on the Maximally Stable Extremal Region (MSER) algorithm of Matas et al. [10], which has proven to be one of the best interest point detectors in computer vision (i.e., it is invariant to affine transformations, allows for multi-scale detection, etc.).

The MSER method belongs to the family of watersheding algorithms [12], which generate a binary image $\boldsymbol{B}$ from an intensity image $\boldsymbol{I}$ by considering all possible thresholds ϕ:

$$\mathbf{B}_{\phi}(x) = \begin{cases} 1 & \mathbf{I}(x) \geq \phi \\ 0 & \text{otherwise .} \end{cases} \tag{1}$$

A maximally stable extremal region (MSER) is then a connected region in $\boldsymbol{B}_{\phi}$ which is stable over a large number of thresholds ϕ. To estimate the MSERs first all pixels are ordered by their intensity (i.e., {0,…,255}). Then, iteratively by increasing the threshold ϕ the corresponding pixels are added to the binary image and a list of connected components is returned.

The original formulation was limited to gray-scale images, however, for our application color would still provide valuable information. Existing methods of Forssen [6] and Donoser and Bischof [5] either proposed to detect regions that are stable across a range of time-steps in an agglomerative clustering of image pixels based on proximity and similarity in color [6] or proposed to estimate a color-space transformation using a multivariate Gaussian distribution of the original RGB[2] values to order the pixels by their Mahalanobis distance to this Gaussian distribution [5]. However, the approach of Forssen is computationally too expensive and the approach of Donoser and Bischof would require a Gaussian distribution, which cannot be estimated from the given data. Thus, similar to [5], we perform a simple color-space transformation – from RGB to R color-space, which covers the most essential information for our task, obtaining an intensity image that can be processed by the standard MSER method.

3.2. Plate Detector

Once we have detected the MSERs within the image, as illustrated in Figure 2, we use this information to reduce the computational effort when running a sliding-window-based detector. Thus, the model is estimated only for image locations that were identified during the segmentation process. In particular, to increase the detection performance we run three detectors in parallel: one for void plates, one for plates containing numbers, and one covering

[2] RGB: red-green-blue

both cases. In general, any classifier-based detector can be applied, but in particular in our system we apply the HOG-Detector of Dalal and Triggs [3].

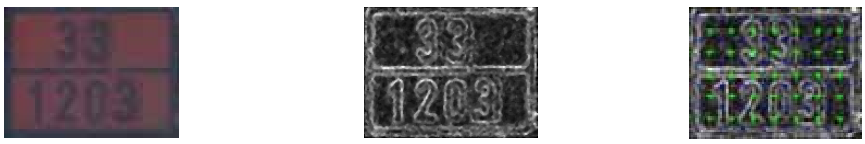
Histograms of oriented gradients (HOGs) are locally normalized gradient histograms, which are estimated as follows. Given an image ***I*** the gradient components $g_x(x,y)$ and $g_y(x,y)$ for every position (x,y) the image is filtered by 1-dimensional masks $[-1,0,1]$ in x and y direction. The magnitude $m(x,y)$ and the signed orientation $\Theta_S(x,y)$ are estimated by

$$\begin{aligned} m(x,y) &= \sqrt{g_x(x,y)^2 + g_y(x,y)^2} \\ \Theta_S(x,y) &= \tan^{-1}\left(g_x(x,y)/g_y(x,y)\right) . \end{aligned} \tag{2}$$

Next, to get an orientation invariant representation, only unsigned orientations Θ_U are used:

$$\Theta_U(x,y) = \begin{cases} \Theta_S(x,y) + \pi & \Theta_S(x,y) < 0 \\ \Theta_S(x,y) & \text{otherwise} . \end{cases} \tag{3}$$

As illustrated in Figure 5, to create the HOG descriptor, the image is divided into non-overlapping 10x10 cells. For each cell, the orientations are quantized into 9 bins and weighted by their magnitude. Groups of 2x2 cells are combined in overlapping blocks and the histogram of each cell is normalized using the L2-norm of the block. The thus obtained descriptors (extracted from training samples) are then learned using a Support Vector Machine. During the evaluation for all image locations pre-selected by the segmentation step a HOG descriptor is estimated and checked versus the previously learned model.



(a) (b) (c)

Figure 5: HOG descriptor: (a) input image, (b) gradient image, and (c) descriptor

3.3. Enhancement

As can be seen from Figure 6(a) the detected regions cannot directly be used as input for the OCR, which requires images of high contrast. Thus, as a pre-processing step we binarize the potential plate regions by generating a color model in which the plate's orange background can be discriminated well from other colors. Since, due to lighting conditions and noise the variability of the background is very high, we use Support Vector Regression on a combined *[R,G,B,cos(H),sin(H),S,V]* color-space[3] to obtain a robust measure for "orangeness". By applying the model onto an input image, we get a likelihood map and derive a binarized version showing the letters and the frame of the plate by a convolution with a Laplacian of Gaussian filter, resulting in an excellent segmentation as shown in Figure 6(b).

(a) (b)

Figure 6: The original input images are insufficient as input for the OCR - a pre-processing step is required: (a) original and (b) pre-processed data

[3] HSV: hue-saturation-value

3.4. Number Recognition

After we estimated the location of potential dangerous goods plates the task is to extract the contained information, i.e., the hazard identification number (HIN) in the first row and the UN number in the second row. For that purpose we use a standard OCR software (i.e., Tesseract OCR[4]). After removing the edges the upper and the lower text line of the plate can be extracted by region grouping and can be used as input for the OCR. Prior to the actual character recognition, the contrast is enhanced and the images are binarized as described in Section 3.3. For feature extraction the OCR uses a polygonal approximation of the connected components of the binary image. The extracted features are used to match to a set of allowed prototypes. To minimize the error rate and to speed up the text extraction, we reduced the allowed character set to numbers and the letter “X”, which indicates a dangerous reaction of the substance with water.

3.5. Lookup in Database

Finally, after running the OCR the obtained results are checked versus the UN database containing all possible number combinations. Moreover, in this step errors of the OCR can be compensated due to restrictions given by the database entry. The unique 4-digit code allows direct inference on the hazard identification number (HIN). The HIN and UN are checked vice-versa for correspondence and this information can be used to detect and correct errors of the independent number recognition results. The errors are mostly based on mixed up digits (e.g., 8 instead of 0) or clutter that resembles a digit in a similar geometric configuration. For instance, if the UN and the HIN were recognized as “1202” and “38”, respectively, the HIN can be corrected to “30”.

4. EXPERIMENTAL RESULTS

To demonstrate our system, we generated a real-world data set consisting of 54 images showing trucks with and 177 images showing trucks without dangerous goods plates. The data set is challenging since it covers different realistic problems such as changing illumination conditions, shadows, cluttered background, polluted plates, and low contrasts.

First of all, we evaluate the plate detection, where we show the results obtained by the three classifiers discussed in Section 3.2. The obtained results are summarized in Table 1 showing the recall (i.e., the percentage of correctly detected plates) and the false positives per image (FPPI) as a measurement for the precision.

Table 1: Detections performance for combined segmentation/detection process

	recall	FPPI
all plates	**94.44%**	**0.12**
pates with numbers	96.66%	0.01
void plates	79.16%	0.06

It can be seen that for the combined classifier for a recall of 95% only 1 false positive is reported per 10 frames. This is especially an excellent result since the void plates do not contain any informative structure and can easily be mixed up with other homogenous regions in the images. Moreover, if reducing to plates containing numbers (which are the interesting

[4] http://sourceforge.net/projects/tesseract-ocr

ones), for a recall of more than 96% only 1 false positive per 100 images is reported. These results are illustrated in Figure 7. From Figure 7(a) it can be seen that even under difficult varying illumination conditions accurate detections can be obtained. In contrast, as shown in Figure 7(b), misses mainly result from highly polluted plates and low contrasts. In both cases the segmentation fails and no detections are reported. The false detections shown in Figure 7(c) are detected as void plates, which is plausible considering the appearance.

(a) (b) (c)

Figure 7: Illustrative detection results: (a) correctly detected plates, (b) missed plates, and (c) false positives

Finally, we evaluate the recognition performance for both the HIN and the UN number. For that purpose all plates that were detected were used as input for the OCR and the Lookup step. Table 2 shows these results, separated into plates with and without numbers. For the plates containing a dangerous goods information around 95% of all plates are classified correctly whereas for all void plates also a void response was returned, i.e., none of these plates were wrongly classified! Hence, even if the detection step returns a small number of false detections (mainly void plates) this would not harm the overall system, since no (wrong) information is extracted. Thus, applying the combined classifier is a considerable tradeoff.

Table 2: Recognition performance on detected plates

	plates with number	void plates
HIN	94.45%	100,00%
UN	96.36%	100,00%

5. CONCLUSION

In this paper, we tackled the problem of automatic dangerous goods plate detection, which can be of considerable interest for tunnel safety. In case of accidents knowing which dangerous goods are close to the accident location could help to take the necessary steps. In particular, we propose a five-stage method: segmentation of salient regions (to reduce computational costs), detection of dangerous goods plates, contrast enhancement, text extraction, and a lookup in the database. For all of these steps we apply proven and widely used methods assuring the required stability. The qualitative and quantitative results, which were obtained on a challenging data set, show that the approach works quite robustly, even in realistic scenarios. Future work would include locating and recognizing the diamond-shaped dangerous goods symbol sign and reading the license plates by means of ANPR. The image acquisition setup needs to be revised to allow for a front-, rear- and side-view image acquisition to cover mixed transports. We will strive for optimizing the raw input image quality for instance by experiments with different spectral channels (i.e. NIR).

ACKNOWLEDGEMENT

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DETECTION OF RISK BEARING VEHICLES BEFORE ENTERING TUNNELS

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ABSTRACT

Tunnel safety can experience an innovative advance due to an increased awareness of dangerous goods vehicles and the monitoring of potentially dangerous overheated vehicles before the tunnel entrance. The overhead 3D vehicle classification system with laser scanners and conventional digital and infrared cameras enables the automatic generation of highly accurate and reliable data on risk bearing vehicles for the first time. Various installations in Germany and Switzerland have shown that complex applications can be solved with an all-in-one system without intrusion into the road surface. The 3D model-based vehicle information provides comprehensive traffic and safety information which supports tunnel management authorities and emergency services.

Keywords: dangerous goods recognition, hotspot detection, overhead vehicle classification

1. INTRODUCTION

The increase in traffic volume on roads and motorways and in heavy goods vehicles in particular highlights the need for new traffic management and monitoring solutions. High traffic density, especially in road tunnels, requires automatic sensor systems for the detection and monitoring of risk bearing vehicles in order to prevent possible incidents. These systems enable the emergency services and traffic management authorities to provide an immediate and appropriate reaction in case of an event. Tunnel safety can experience an innovative advance due to an increased awareness of dangerous goods vehicles and the monitoring of potentially dangerous overheated vehicles before the tunnel entrance.

Furthermore, the latest guidelines in various European countries require a risk and safety assessment for tunnels. Substantial high quality statistical data on risk bearing vehicles provides the information required for a long term tunnel safety evaluation.

The newest sensor technologies permit the automatic acquisition of highly accurate data on risk bearing vehicles with an overhead system based on laser scanner technology in combination with conventional digital and infrared cameras. Without any intrusion into the road surface, information about traffic flow and composition, overheight monitoring, dangerous goods vehicles and vehicle hotspots can be generated from a single system which will be presented below. This comprehensive traffic data is transmitted and visualized in the tunnel management headquarters in order to conduct an efficient and safe tunnel operation.

2. OVERHEAD VEHICLE CLASSIFICATION WITH LASER SCANNERS

Laser scanner technology using the time of flight measuring principle provides precise traffic information and vehicle specifications (Hirst, 2009). A 3D model of each vehicle, representing the vehicle's outline is generated and permits the derivation of traffic data such as speed, vehicle class, travel direction and distances between vehicles (see **Figure 1**).

In addition to standard vehicle classification systems (e.g. inductive loops), precise information on the vehicle's height, length and width can be measured leading to an overheight monitoring and detection system. Lane changing vehicles are identified and correctly classified thus providing accurate traffic statistics for a given cross-section.

Figure 1: Overhead vehicle classification with laser scanners on the A99 motorway in Munich and the 3D model of a vehicle on the right

The 3D model classification differentiates between 28 vehicle classes which can be assigned to the standardized TLS8+1 classes. The classification results obtained on the four lane A99 motorway in Munich satisfy the requirements of the TLS2002 norm with level A1 for the TLS8+1 and F1 for the TLS5+1 classification, including all lane changing vehicles.

Due to the precise vehicle speed measurement, the classification system is especially suitable for "stop and go" traffic on city motorways with heavy traffic during rush hours. The self-calibrating system can be mounted over a four lane motorway within less than one hour allowing fast relocation of the classification sites.

The overhead vehicle classification system with laser scanners represents the basic detection system which can be combined with other sensors for further and more sophisticated applications in a fully modular approach (e.g. travel time forecast, dangerous goods detection, hotspot detection, weigh-in-motion, axle counting, etc.).

3. DETECTION AND MONITORING OF DANGEROUS GOODS VEHICLES

As a large part of heavy goods traffic transports dangerous materials it is becoming more important to acquire reliable data throughout the transport infrastructure but especially in hazard areas like tunnels (Feldges et al., 2009).

Vehicles carrying dangerous goods by road must attach an orange dangerous goods plate in accordance with the UN directive (The European Agreement concerning the International Carriage of Dangerous Goods by Road – ADR 2009). The plate contains a UN code and a dangerous goods code which identifies the goods being transported. If several different hazardous goods are transported on the same vehicle, the orange plate will be blank (see **Figure 2**).

Figure 2: Numbered and blank dangerous goods plates

Standalone automatic sensor systems which have been developed in the past (e.g. video surveillance) have not been able to produce sufficiently accurate data for the detection of dangerous goods vehicles to be useful to tunnel management authorities. Since the dangerous goods plates represent a highly inhomogeneous data set because of different weather conditions, mounting positions and plate types, either the detection rate or the false detection rate were not satisfactory with regard to the previous systems. In addition to this, a solitary OCR (Optical Character Recognition) sensor system is not able to read blank dangerous goods plates which constitute up to 40% of all plates. Furthermore, so-called A-plates which indicate waste transportation vehicles and which have the same dimensions as dangerous goods plates must not be detected.

These reasons are leading to a new multi-sensor approach using the overhead 3D vehicle classification system together with a conventional OCR camera. This offers more possibilities of reaching higher detection rates required to satisfy the high expectations of the tunnel management authorities (see **Figure 3**).

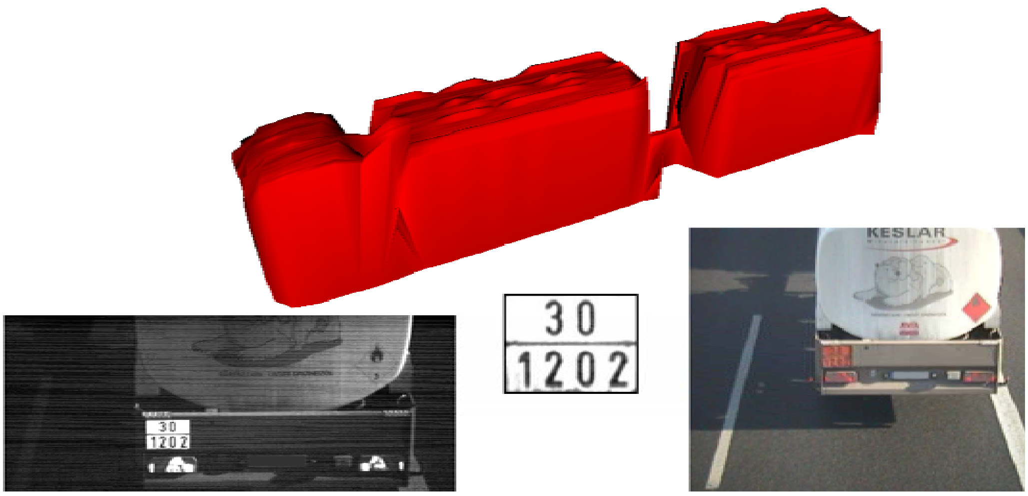

Figure 3: 3D model of a vehicle with the identified dangerous goods plate

Both, blank and numbered plates are automatically identified and read with high accuracy by this new dangerous goods plate identification system. It is based on laser scanner technology in combination with a camera and an OCR algorithm which identifies the UN codes. The laser scanners deliver the exact position and speed of each vehicle at a given time and thus are used to precisely trigger the camera and the infrared flash. The images are assigned to the corresponding vehicle without ambiguity and the additional information from the vehicle classification together with the 3D model is used in further validation algorithms.

Each vehicle's data set, including a coloured overview picture, can be transferred to the tunnel management headquarters in real time, enabling emergency services and traffic management authorities to react to an incident in an appropriate and timely manner.

The practical results obtained in January 2010 at three independent locations, one lane each, on the A99 city motorway in Munich before the entrance to the Allach tunnel show very satisfactory results despite the difficult weather conditions during the measurement campaign. The detection rate (detected plates over actually present plates) is 84% together with a false detection rate below 5% (falsely detected plates over all detected plates). The read rate reaches 97% (correctly read plates over all detected plates).

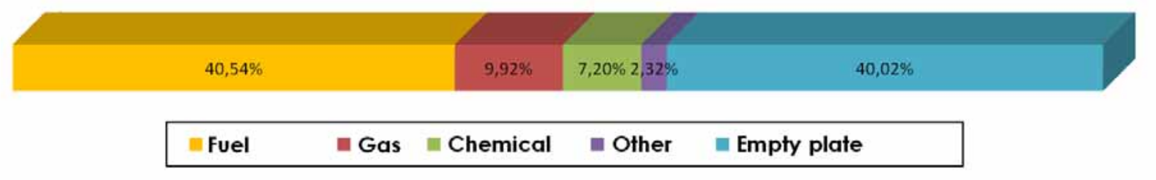

Figure 4: Distribution of dangerous goods being transported in one week (1300 vehicles)

Figure 4 shows an example of the statistical distribution of the dangerous goods transported during one week on the A99 motorway in Munich. The analysis of the time gap between two successive dangerous goods vehicles has shown that in 13% of cases this gap is below one minute and in 2% of cases it is even below five seconds, representing an increased safety risk. This high quality statistical data on dangerous goods vehicles provides the information needed for a long term tunnel safety evaluation.

4. DETECTION OF OVERHEATING VEHICLES

Vehicles with potentially dangerous hotspots such as overheated wheels, axles and exhausts represent a high risk to the transport infrastructure, especially to tunnels. Potentially risk bearing vehicles must be detected before entering a tunnel in order to prevent a possible fire incident caused by temperature violations on vehicle parts.

The difficulties for a hotspot detection system reside in the correct hotspot localisation and assignment to the corresponding vehicle which resulted in presenting a major problem for solitary infrared cameras.

Figure 5: 3D model with the vehicle's temperature distribution on the right

The hotspot detection system combines measured temperature data from a thermal imaging camera with the 3D model from the overhead vehicle classification system with laser scanners (see **Figure 5**). An additional side scanner provides detailed 3D information on the wheel zone of each vehicle enabling axle counting without any intrusion into the road surface.

The 3D model approach offers new possibilities to precisely localise and identify each present heat source and to translate this information into a risk evaluation algorithm. With the clear positioning of the hotspots on the vehicle geometry, the system can automatically identify the type of the heat source (e.g. wheel). This allows authorities to react not only to absolute temperature violations of single hotspots with different thresholds but also to initialise an alarm when relative temperature differences, for example between two wheels of the same vehicle (e.g. due to load shift), are detected. Furthermore, the vehicle's temperature distribution can be visualized on the 3D model providing tunnel operators with an increased awareness of risk bearing vehicles enabling an efficient and safe tunnel operation.

Figure 6: Vehicle hotspot detection at the Gotthard tunnel in Switzerland

Practical results have been obtained on the A1 motorway in Switzerland at the Gotthard tunnel in January/February 2009 (see **Figure 6**). Before the entrance to this single tube road tunnel with a length of 17km, risk bearing vehicles were identified and monitored at normal speed (80km/h). The results have shown maximum wheel temperatures over 90°C and tyre temperatures of about 40°C (ambient temperature: -5°C). The overall maximum temperature measured on the exhaust pipe of a vehicle was above 350°C.

5. CONCLUSION

Combining the overhead 3D vehicle classification system with conventional digital and infrared cameras allows the automatic collection of highly accurate and reliable data on risk bearing vehicles such as dangerous goods transporters and potentially overheated vehicles.

The system can be fully integrated into the tunnel management headquarters. It supports emergency services and tunnel authorities in preventing possible incidents and in providing an immediate and appropriate reaction in case of an event.

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A RISK ANALYSIS METHODOLOGY FOR TUNNEL FIRE SAFETY

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ABSTRACT

This paper outlines a fire safety risk analysis methodology developed and applied to a major road tunnel project in Australia. The project name is withheld for confidentiality reasons. The process described is designed to provide appropriate tunnel fire safety design decisions that can be demonstrated as being robust and capable of withstanding third party scrutiny.

The methodology is based on the principles contained in the International Fire Engineering Guidelines[1] (IFEG), the guiding document for performance based fire design in Australia, however, modified for tunnel projects by the authors.

Keywords: risk methodology, tunnel fire safety.

1. INTRODUCTION

The basis of the tunnel fire safety methodology outlined in this paper ensures that the project objectives, fire hazards, proposed trial designs, analysis methods and acceptance criteria are agreed in principle before detailed analysis is undertaken. This paper provides some detail of the rigour that has been applied to a tunnel fire safety design.

2. FIRE ENGINEERING PROCESS

The fire engineering process adopted is similar to the process defined in the IFEG[1]. The IFEG[1] is the accepted guideline for the analysis of performance based fire engineering design that has been adopted by Australia, New Zealand, and Canada. The IFEG[1] process is broadly captured in the following steps, and modified for road tunnels:

i. Define the Scope of the Project
ii. Determine the Relevant Stakeholders
iii. Outline the Tunnel Characteristics
iv. Identify the Dominant User Characteristics i.e. the vehicle Driver.
v. Determine the Hazards, and Preventative and Protective Measures
vi. Outline a Trial Design for Assessment
vii. Determine Design Approaches and Methods of Analysis
viii. Determine Acceptance Criteria and Factors of Safety for the Analysis
ix. Determine Fire Scenarios and Parameters for Design Fires
x. Determine the Design Parameters for Design Occupant Groups
xi. Determine the Standards of Construction and Commissioning
xii. Determine Management, Operation, and Maintenance
xiii. Document the above steps in the FEB
xiv. Detailed Analysis
xv. Document the results in the Fire Engineering Design Report(s)

The Fire Engineering Brief (FEB) (refer Step 13 above) is developed in consultation with the stakeholders that agrees the fire safety parameters and trial design solutions. Following agreement of the FEB, the trial design is analysed to access its performance under the agreed fire scenarios. Results are compared to the agreed acceptance criteria and documented in the relevant Fire and Life Safety reports. If analysis identifies a need to vary from the agreed

FEB, the FEB consultation process was revisited and updated to reflect a new trial design, or the Design Fire Scenarios and Acceptance Criteria used within the analysis were re-evaluated. Reasons for varying the FEB could be that the Trial Design changed, or the performance of the trial design under the Design Fire Scenarios did not meet the Acceptance Criteria. At the conclusion of this process, and the completion of the other Fire and Life Safety Reports, a Summary Fire Engineering Report was prepared.

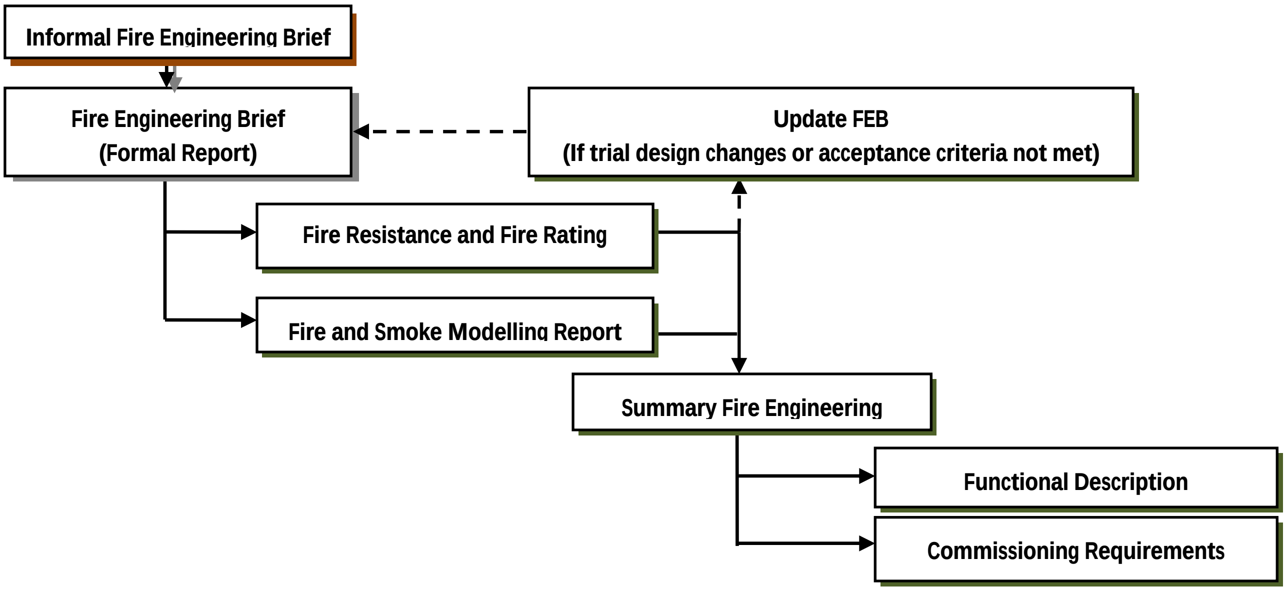


Figure 1: Flow Chart of the FEB Process

3. PRINCIPAL TUNNEL CHARACTERISTICS

Information such as the tunnel characteristics and use provide a context for design decisions. Key information gathered about the proposed tunnel includes such items as:

i. Tunnel length;
ii. Number of tubes;
iii. Number of lanes;
iv. Location of entry and exit ramps;
v. Location of breakdown bays;
vi. Tunnel geometry;
vii. Vertical and horizontal alignment;
viii. Uni- or bidirectional traffic;
ix. Tidal flows;
x. Construction method and materials;
xi. Predicted traffic volumes including peak volumes and daily characteristics;
xii. Predicted daily traffic speeds;
xiii. Predicted traffic mix;
xiv. Likelihood of congestion;
xv. Ventilation system for normal operation (air quality);
xvi. Ventilation system for incidents (smoke management);
xvii. Location, type and number of ventilation outlets;
xviii. Portal emission strategy;
xix. Non-fire incident management strategy;
xx. Emergency Services access;
xxi. Tunnel lighting;
xxii. Tunnel signage;
xxiii. Dangerous goods policy including defining which are prohibited;
xxiv. Communication systems;
xxv. Evacuation systems;
xxvi. Egress mechanisms.

4. DOMINANT OCCUPANT CHARACTERISTICS

The dominant occupant characteristics are those traits which may influence the behaviour of occupants and users of the tunnel. It includes the age distribution of the population and assumptions on the mental state of vehicle occupants. For the tunnel studied, most vehicles will likely have a single occupant who is alert and able to respond to fire cues and instructions provided. Occupants who may not be alert at the time of the incident would be likely to be assisted by fellow occupants. Consideration was given to occupants who may be reluctant to abandon their vehicles or to leave behind their possessions. Occupants in general are not likely to require assistance to move away from an incident or will be travelling with a fellow occupant who is able to provide assistance. Occupants are likely to be strongly affiliated with the driver of their vehicle and take their lead. Vehicle occupants are also likely to be affiliated with other people in their vehicle (e.g. family groups or bus tours). Consideration has been given to the number of disabled users as part of the total number of people using special equipment for mobility impairments. Design considerations need to be cognisant of vehicle occupants not being familiar with the tunnel's emergency layout or its fire safety systems.

Operators and maintenance staff are assumed to be highly trained and familiar with the fire and life safety features. They are able to provide instructions to allow vehicle occupants to self evacuate.

5. RISK ANALYSIS

Having determined the principal tunnel characteristics, dominant occupant characteristics and the project objectives, the next stage is a risk based assessment of potential fire scenarios. A systematic review of potential fire hazards was undertaken based on the range of vehicles that will use the Tunnel, anticipated vehicle numbers, and relevant fire statistics.

Table 1 shows vehicle fire statistics for the tunnel under study. The fire frequencies estimated have been used in an event tree analysis to establish credible design fire scenarios for assessment. Based on the fire statistics, severe truck fires have been estimated to occur at a rate of 0.001 fires per year. This is equivalent to an approximate return period of a severe truck fire occurring once every 1,000 years or, for a tunnel design life of 100 years, there would be a 10% chance that a severe truck fire would occur during the life of the tunnel.

Due to the lack of relevant data in Australia, the fire statistics used to estimate the fire frequency were based on European tunnel data generally without the benefit of deluge systems[4]. To adjust for the benefit of deluge systems retarding fire growth and reducing the frequency of severe fires, an event tree analysis was used.

It is also noted that a significant proportion of tunnels in Europe allow bi-directional traffic, and that in an Alpine environment, tunnels have long, steep grades where motor operation is laboured, or brakes can over-heat, tends to bias the data and over-estimate the frequency of fires compared to the flat landscape and uni-directional tunnels as occurs in Australian. This has the effect of over-estimating the fire frequency and provides an amount of conservatism.

Table 1: Vehicle Fire Statistics for the Tunnel under Study

Fire Frequency	Value	Notes / Units
Total North Traffic	80,500	Vehicles / day
Percentage of cars	95.2%	% cars
Percentage of trucks	4.8%	% trucks
Car kilometres travelled	12.73	Million km travelled
Truck kilometres travelled	0.64	Million km travelled
Car fire = 2 / 100.000,000 km	0.2545	Fires / year
All truck fires = 8 / 100,000,000 km	0.513	Fires / year
All truck fires (including damaging and severe)	0.0436	Fires / year
Damaging truck fires = 1 / 100,000,000 km	0.006	Fires / year
Severe truck fires = 0.2 / 100,000,000 km	0.001	Fires / year
Total Fires	0.306	Fires / year

To better understand the types of vehicles that will use the tunnel, the percentages of vehicles for each vehicle type are identified. It is also important to understand the effect of the transport of dangerous goods, if any, through the tunnel. Based on the hazards identified, a Hazard Register should be compiled. The intent of the Hazard Register is to form a foundation for further risk analysis leading to the selection of credible Design Fire Scenarios by agreement with the stakeholders. The Hazard Register also allowed consideration of any additional hazards to be identified. This permits an informed decision by the stakeholders regarding which hazards are considered to be unacceptable and therefore not considered in the design of the Fire Safety Measures. The hazard register also provides information for the Incident Management Plan (IMP) to be prepared by the operator. The Hazard Register should capture:

i. Type of vehicle on fire;
ii. If the vehicle on fire is moving or stationary;
iii. If traffic within the tunnel is flowing, congested or stopped;
iv. The severity of the fire. For the tunnel under study, dangerous goods were prohibited. Therefore, it was important to understand whether diesel spillage was involved;
v. Additional design features provided as a mitigation measure to address these issues.

A fire occurring within a congested tunnel has the potential to expose more tunnel users to fire risks compared to a non-congested tunnel. The following traffic modes were defined and adopted as a means of considering the consequence of congestion in tunnels and its impact:

i. Non-congested traffic: Where traffic is flowing at a speed greater than 20km/hr (5.56m/s) i.e. greater than critical velocity. At this speed, the traffic is generally ahead of the smoke front, and traffic downstream of the incident should continue to drive out of the tunnel and be unaffected by both the incident and smoke;
ii. Congested traffic: Where traffic is flowing at speeds between 5km/hr (1.39m/s) and 20km/hr (5.56m/s). If traffic is moving at a speed which is greater than walking speed, occupants are unlikely to leave their vehicles and evacuate on foot. However, there is potential for occupants to be subjected to some smoke exposure.
iii. Stopped traffic: Where traffic is flowing at a speed less than 5km/hr (or 1.39m/s). This is less than walking speed and it is considered that occupants will be more likely to leave their vehicles and evacuate on foot resulting.

For the tunnel under study, the percentage of time each of these traffic conditions were determined to occur were:

i. Non-congested 95%
ii. Congested 4%
iii. Stopped 1%

These percentages formed the basis of the inputs into the event tree analysis to determine the credible fire scenarios. The smoke control strategy also considered these different traffic conditions to mitigate the risk of smoke exposure to occupants.

6. RISK ASSESSMENT METHODOLOGY

A risk based methodology based on the that documented in Australian Standards[3] and the IFEG[1] was adopted as the framework for assessing the fire and life safety design.

Event tree input considerations were set out within the FEB and agreed with the stakeholders prior to the event tree analysis being undertaken. Event tree construction was undertaken in line with the expected sequence of events occurring during an incident as agreed with the stakeholders. Event tree considerations should include the following:

i. Fire frequency
ii. Operator responses (appropriate or delayed).
iii. Traffic conditions (Flowing, congested or stopped traffic situations).
iv. Fire growth rates (Ultra-fast growth rate or higher).
v. Deluge Impact (Failure of deluge system to control the fire).

vi. System Reliabilities (Failure or part failure of other fire safety systems).
vii. Credible combinations of such events.

The choice of design fire scenarios is one of the most important parameters for the Fire and Life Safety analysis. The traditional process of adopting a single value for the peak heat release rate (HRR) (e.g. 50MW) was considered inappropriate as it can lead to underestimation of conditions in some situations. Similarly, the adoption of a single large value may be excessive and provide expensive and conservative design. Therefore, a method of categorising the design fire scenarios based on the Hazard Analysis was adopted to provide a boundary to the scenarios to be quantified so that the design remains within economic and practical limits; and to facilitate a rational combination of very severe (but low probability) fire events with realistic egress parameters.

The Fire Design Categories are described below:

<u>Base case fire scenarios</u> represent fire scenarios which were expected to occur during the design life of the tunnel (100 years).

<u>High challenge fire scenarios</u> represent rarer but more severe fire scenarios used to test the limits of the design. High challenge fire scenarios were expected to occur at a return period between 100 and 10,000 years. These scenarios included selected system failure scenarios.

<u>Extreme events</u> were defined as fire scenarios that were expected to occur less frequently than a 10,000 year return period and therefore not considered to be credible design cases.

Extreme events have been considered and used to identify operational response procedures and preventative measures to mitigate the associated risks, but have not been evaluated as design fire scenarios.

Extreme events included scenarios which were agreed with the stakeholders to lie outside the practical or economic limits of the design, such as explosion, or BLEVE's. Subject to the estimation of return periods in the Event Tree Analysis, extreme events could include events such as a deluge failure leading to a severe HGV vehicle fire combined with stopped traffic. Similarly, multiple failures of fire safety systems occurring simultaneously could be an extreme event.

The following process was adopted for the selection of design fire scenarios:

i. Identify the potential fire scenarios based on the Hazard Analysis;
ii. Evaluate the expected return period using an event tree analysis based;
iii. Divide the fire scenarios into the various Fire Design Categories;
iv. Assess potential fire scenarios using the Risk Evaluation Matrix;
v. Review the findings against the Performance Requirements and add any additional Fire Scenarios;
vi. Select the credible Design Fire Scenarios for analysis based on grouping similar scenarios from the more severe Base Cases and High Challenge scenarios;
vii. Review the Hazard Analysis and Design Fire Scenarios with the stakeholders and agree the final list of Design Fire Scenarios.

To assist the evaluation of the Trial Design with the Design Fire Scenarios, a semi-quantitative risk based approach was adopted. The components of the risk assessment approach were:

i. Risk categories (refer Table 2);
ii. Consequence categories (refer Table 3);
iii. Likelihood categories (refer Table 4);
iv. Risk evaluation matrix, modified for the risk categories (refer Table 5);
v. Risk treatment criteria (refer Table 6).

Table 2: Risk Categories

Category	Description
1	Provision of a level of safety for tunnel occupants and users including O&M staff
2	Provision of a level of safety and access for emergency service personnel during an incident
3	Limit the impact on assets, including adjacent infrastructure and surrounding road networks

Table 3: Consequence Categories relative to Exposure Severity

Severity Level	Category 1	Category 2	Category 3
	Safety of occupants	Safety for Emergency Services	Asset and operational continuity
V	Fatality / multiple fatalities, or severe irreversible disability (>30%) to one or more persons	Unpredictable collapse of tunnel structures within 2 hours of fire incident occurring, or life threatening exposure to radiant heat or fatality remote from area of the fire	Major damage to equipment and / or localised collapse impacting infrastructure above. Tunnel cannot be operated for a significant period (>3 months). Fire that has exceeded 200MW and / or a 2 hr RWS fire curve.
IV	Incapacitation, or moderate irreversible disability or impairment (<30%) to one or more persons.	Predictable local collapse of tunnel structures in area of fire within 2 hours of fire incident occurring, or life threatening exposure or fatality in area of the fire	Extensive equipment damage and / or localised structural damage. Tunnel cannot be operated for a significant period (>1 but < 3 months). Fire ranging between 70-200MW and / or reached a 2 hr RWS fire curve.
III	Partial incapacitation Objective but reversible disability requiring hospitalisation	Exposure to heat exceeding limits of equipment, or Predictable collapse of secondary steelwork within 2 hours of a fire incident.	Significant localised damage of equipment and structure requires repair and / or the tunnel cannot be operated for a short period (1 month) Fire up to 70MW and / or a 1 hr RWS fire curve
II	Discomfort or low visibility Objective but reversible disability which may require hospitalisation	Exposure to heat but within limits of equipment	Significant localised damage of equipment not requiring major repair and / or the tunnel operates at reduced capacity for a short period Fire up to 30MW and / or a 40 min RWS curve.
I	Minor Injury, first aid may be required	First aid (minor injury)	Limited localised damage not requiring repair or minor effect on operations Fire up to 20MW and / or a 30 min RWS curve.

Table 4: Likelihood Categories relative to Risk Categories

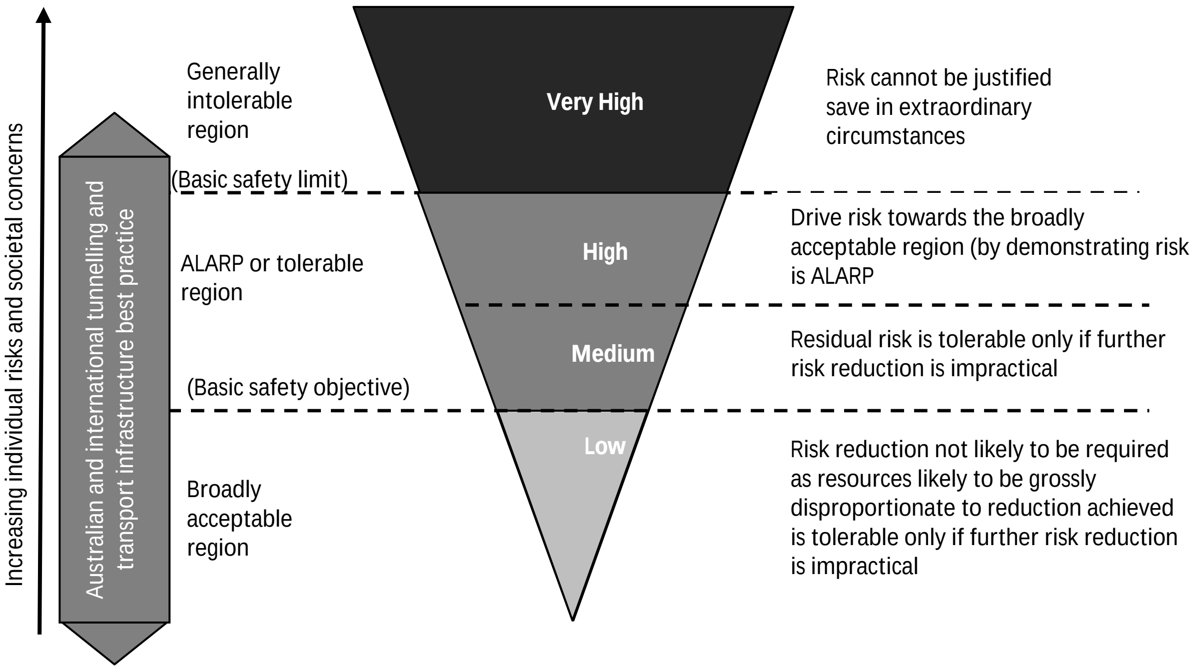
Risk Category	Level	Descriptor	Frequency
Base Case Scenarios	A	Frequent	More frequently than a year
	B	Likely	More frequently than every 3 years
	C	Possible	More frequently than every 10 years
	D	Unlikely	More frequently than every 30 years
	E	Rare	More frequently than every 100 years
High Challenge Scenarios	F	Very Rare	More frequently than once in 1,000 years
	G	Almost incredible	More frequently than once in 10,000 years
Extreme Event	Extreme Event		Less frequently than once in 10,000 years

Table 5: Risk Evaluation Matrix

Likelihood	Consequence				
	I	II	III	IV	V
A	Med	High	High	V High	V High
B	Med	Med	High	V High	V High
C	Low	Med	High	High	V High
D	Low	Low	Med	High	High
E	Low	Low	Med	Med	High
F	Low	Low	Low	Med	Med
G	Low	Low	Low	Low	Med

Table 6: Risk Treatment Criteria

Level of Risk	Recommended Risk Treatment
Very High	Risk cannot be justified except in extraordinary circumstances
High	Drive risks toward the broadly Acceptable Region or demonstrate that the risk is ALARP
Medium	Residual risk is tolerable only if further risk reduction is impracticable
Low (and Extreme Events)	Further risk reduction is not likely to be required or would be impractical as resources demanded would be disproportionate to the risk reduction achieved



Definitions:

i. ALARP – As Low As Reasonably Possible (relating to a risk event)
ii. ASET – Available Safe Egress Time (the time provided by the design to allow safe egress in tenable conditions)
iii. Basic Safety Limit – Australian and International tunnelling and transport infrastructure best practice
iv. Basic Safety Objective – ASET greater than RSET
v. RSET – Required Safe Egress Time (the time required by the occupant study for occupants to reach safe egress)

Figure 2: Treatment Strategy

7. ACCEPTANCE CRITERIA

Compliance with the acceptance criteria was considered to demonstrate achievement of a safe outcome for the tunnel. Non-compliance required further fire engineering analysis and could require modification of the fire and life safety tunnel design.

The following limitation or conditions were assumed within the assessment;

Fire Zone: In the area close to the fire, there may be untenable conditions due to heat radiated directly from the fire. The Fire Zone was defined as the area in which radiation from a fire is at or exceeds 2.5kW/m². It will be proportionate to the fire size and may be up to be 30m in length either side of the fire. This is consistent with guidance in NFPA 502[2].

Survivability in the fire zone is dependent on occupants escaping to a tenable area. For the tunnel under consideration, the time available for escape was extended as far as practical by activation of the deluge system and the tunnel ventilation (smoke management) system.

Deluge Zone: The Deluge Zone is the area over which the deluge system is activated. For the tunnel under study, it consists of a number of zones activated simultaneously to provide coverage over a length of tunnel of 60m regardless of tunnel width. Within this zone, visibility may be compromised due to the application of the deluge.

Table 7: Acceptance Criteria

Egress Acceptance Levels		
Objectives	**Egress Acceptance Level**	**Technical Criteria**
Life Safety of Tunnel Occupants	Level I If ASET > RSET preliminary acceptance is achieved.	**Step 1, Qualitative Assessment** Qualitative assessment of design fire scenario (ASET versus RSET based on reasoning, i.e. moving versus stopped traffic, and fire size). **Step 2, Quantitative Assessment** Quantitative assessment of design fire scenario (ASET versus RSET based on calculations). If ASET>RSET preliminary acceptance is achieved. Go to Step 3 to confirm an acceptable risk level for the scenario.
Life Safety of Tunnel Occupants	Level II Broadly acceptable Region	**Step 3, Risk Quantification** Calculate the risk level of the trial design for the design fire scenario. Use the results of Step 1 and Step 2 to inform consequence calculations. If the trial design's residual risk level is **LOW**, it is considered to be acceptable. Otherwise go to Step 4.
Life Safety of Tunnel Occupants	Level III ALARP or tolerable region	**Step 4, Risk Acceptance / Tolerance** The trial design's residual risk level has been determined to be a **Medium** risk. For the trial design to be considered to be acceptable, the following step is required. As the trial design is a **performance-based** design, specific demonstration that further reduction is impractical must be provided for the risk to be considered tolerable. Otherwise go to Step 5.
Life Safety of Tunnel Occupants	Level IV ALARP or tolerable region	**Step 5, ALARP Analysis** If the trail design is a **High** risk, then demonstrate that the level of risk for the trial design is ALARP. Demonstration of ALARP may require input from several stakeholders. The method to demonstrate an ALARP design will be decided on a case-by-case basis. If the residual risk associated with the trial design is ALARP it is considered acceptable. Otherwise go to Step 6.
Life Safety of Tunnel Occupants	Level V Generally intolerable	**Step 6, Non-acceptance** If risk is shown to be within the very high or generally intolerable region, design is **not acceptable** and an alternative design is required

8. CONCLUSION

A fire safety risk analysis methodology has been applied to a major road tunnel project which facilitates a rational combination of fire events, and provides a boundary to the scenarios to be quantified so that the design remains within economic and practical limits. The methodology documented provides a framework that may be adopted for all tunnel projects to ensure that design decisions are appropriate and commensurate with the fire and life safety risks.

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ODEM: A ONE-DIMENSIONAL EGRESS MODEL FOR RISK ASSESSMENT

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ABSTRACT

National and international regulations require quantitative risk assessment for various purposes, such as comparison of different tunnel options, safety measures, or admission of dangerous goods through a road tunnel. Risk is defined by the probability of an event and the expected damage. Depending on the level of detail, the event tree may require an estimate of the damage for thousands of different scenarios.

Some regulations require the analysis of smoke and heat propagation using 3-d computational fluid dynamics CFD. The special distributions and development of smoke concentration, CO levels and temperature are then used with complex egress models. The interaction of the two models and the required computation time represent critical limits to the number of scenarios that may be analysed to any detail.

One-dimensional models allow a quick calculation of the dynamics smoke propagation due to tunnel fires. For the analysis of a multitude of scenarios, the 1-d model for smoke propagation in road tunnels SPRINT has been extended in order to include the egress of tunnel users. Typically, the model requires a computation time of only a few seconds per scenario.

This paper describes the sub-models applied in the egress simulation and gives an example application of the model.

Keywords: risk analysis, numerical simulation, tunnel, fire, smoke, ventilation, egress, safety

1. BACKGROUND

New national regulations such as the German RABT-2006 specifically ask for a quantitative risk analysis QRA for tunnels with specific characteristics. In QRA, risk is defined by the probability of an event and the expected damage, expressed either as financial loss or as number of fatalities. The event tree may require an estimate of the damage for thousands of scenarios. Although many QRA-models are based on the 3-d analysis of smoke propagation, the number of scenarios requires simplifications, such as application of similar smoke regimes to a certain number of scenarios or application of one-dimensional models which require much less computational time.

In tunnel ventilation design, the operation and control mechanism of the tunnel ventilation or smoke-control system has to be demonstrated. Simulations of the smoke propagation in road tunnels generally are carried out by means of one-dimensional models (e.g. Riess & Bettelini 1999). These models allow a refined analysis of ventilation systems without using extensive economic resources.

The model SPRINT (Riess et al. 2000) has been validated and in use for more than ten years. The effects taken into account are the piston and drag effect of the vehicles, jet fan thrust, tunnel wall friction, and inlet/outlet pressure losses at the portals, the meteorological pressure differences and the influence of transverse ventilation on the momentum of the tunnel air. The temperature distribution in the tunnel is computed, which allows taking into account the stack effect. Additionally, gravity driven smoke propagation due to the strong thermal stratification in the tunnel is accounted for by using an empirical model.

Some details of the model have been updated for the specific needs of individual tunnel projects, but the core still remains unchanged. New features include an algorithm that allows PI-control of the jet fans, assuming variable speed drives, in order to achieve a pre-defined air flow velocity in the tunnel.

The obvious solution appears to be the combination of the existing one-dimensional model for smoke propagation SPRINT with a one-dimensional egress model ODEM.

2. EGRESS MODEL

The egress behaviour of individuals in a tunnel can be divided in several phased. Therefore, the egress model consists of several sub-models. The characteristics of these models are available from literature, such as (PIARC 1999) or (vfdb 2009). Each of the sub-models implemented in ODEM is described to some detail in this paper.

2.1. Population

The number of people involved in a road tunnel accident or fire is generally very low (egress model, 5 to 50 individuals) when compared to an egress scenario in a public place, such as public buildings, theatres or sports stadiums (crowd models, 200 to 20000 individuals). From the vehicles towards the emergency exit, the emergency walkways on both sides can be used with the full width of the traffic lane as extra space for overtaking. Accordingly, queuing or blocking of fleeing persons in the tunnel is not observed. It can be assumed that people reaching the emergency exit enter a safe area. Therefore, as a first assumption, people moving in the tunnel may be modelled as individuals without interaction. The appropriate egress model for this application is behavioural without micro-scale person-to-person interaction. Due to the coupling of smoke propagation and egress, the individuals face decisions that are based on the information available to them.

The individuals do not necessarily require individual characteristics such as driving and walking speed. In crowd models with interaction of people, the initial population represents a random sample of individuals with different characteristics. For the analysis of a particular fire scenario, a series of calculations has to be performed in order to obtain relevant results. Without interaction between individual people, this variation is not necessary. The elimination of random numbers gives an entirely deterministic behaviour of the model. For the practical application of the model in a risk analysis, this allows an easier documentation and reproducibility of each scenario.

2.2. Decisions: pre-movement time

People in the tunnel have to face several decisions before they reach the emergency exit. In the beginning of the scenario (before the fire occurs), people move within their vehicles. The frequency of people entering the tunnel is determined by the traffic volume and by the vehicle occupation, given as persons per vehicle.

When the vehicle is stopped either by reaching the end of a traffic queue, by reduced visibility in smoke or by traffic lights within the tunnel, people tend to remain stationary in their vehicle. The time the person remains in the car before moving towards the egress doors is called the pre-movement time. It depends on the time until occupants become aware that there is a fire via the evacuation message (PA system, variable message signs, radio re-broadcasting) or visual cues. Therefore, no general figure for the pre-movement time can be given. It is tunnel-specific and it is one of the parameters that may define the number of fatalities in a scenario.

In the model, the pre-movement time has to be set in the scenario definition. However, it is assumed that people always move from the vehicle towards the emergency exit when they observe smoke (defined by minimum distance between the vehicle and the approaching smoke front) or when the local temperature reaches a minimum threshold.

2.3. Decisions: egress direction

In the model, it is assumed that signs are installed along the tunnel, showing the distance to the nearest egress door or tunnel portal. Therefore, people generally move in that direction. However, when the smoke front is visible, they change their egress direction and flee away from the smoke, although the distance to that emergency exit may be greater.

As soon as an individual reaches the location of the emergency exit or the tunnel portal, it is marked as saved.

2.4. Egress speed and visibility

Egress speed depends on visibility or smoke concentration. (PIARC 1999) gives a relation depicting the correlation for toxic or non-toxic smoke. In the model, the correlation for toxic smoke has been simplified as a linear function. The parameters for maximum speed and minimum speed (i.e. crawling) are given in the definition file for a particular scenario. An example for the correlation is shown in Figure 1.

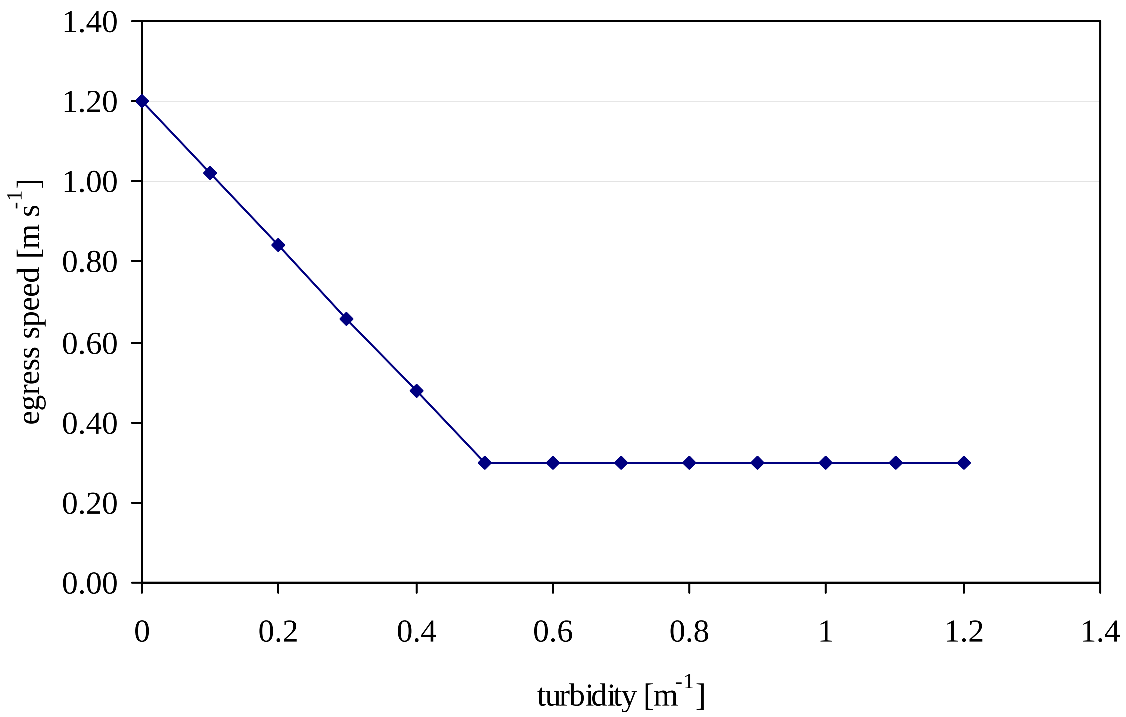

Figure 1: Egress speed as a function of turbidity (irritating smoke)

Due to changes of the main flow direction in the tunnel or due to operation of the smoke control system, a person being exposed to smoke may reach a tunnel section with clear air. In this case, the walking speed would be increased according to the same correlation.

According to previous experience with three-dimensional models for smoke propagation, a detailed model of smoke concentration is not required. If the smoke front reaches a fleeing person in the tunnel, visibility is reduced close to zero. Detailed modelling of the mixing process between turbidity 0 and 0.5 m^{-1} is not relevant to the egress process. The exception is the question if a stable smoke layer is established and people remain in clear air underneath this layer. Most one-dimensional models assume mixing of smoke over the full tunnel cross-section. SPRINT assumes complete mixing of smoke over the tunnel cross-section, but significant temperature stratification close to the fire.

2.5. Escape or fatality

The toxicity of smoke is determined by a small number of compounds, such as carbon monoxide, hydrogen cyanide and carbon dioxide which may or may not act additively. The ‘Fractional Effective Dose’-model (FED) is based on the assumption that toxic effects accumulate during exposure to these gases (vfdb 2009). When the critical dose FED = 1 is reached, the person loses consciousness or its ability to continue the escape. At an increased exposure FED between 2 and 3, the person dies of intoxication.

The fuel and therefore the composition of the smoke are not known. In the one-dimensional model, only the CO distribution is calculated as the toxic component of the smoke. A working or quickly walking person shows significant effect at an exposure of 1000 ppm for 30 min (Ackeret et al.). In order to account for other toxic gases within the model, the critical CO-dose is reduced. This dose is defined as a parameter in the input file for a particular scenario, which allows a variation of smoke toxicity.

While the fire is modelled as a heat source, the chemical kinetics are unknown. Therefore, the model has to include assumptions on CO production. ODEM is based on a CO production of 0.04 kg kg^{-1}, i.e. 0.04 kilogram CO per kilogram burned fuel, which is applicable for well-ventilated fires (Drysdale 2004). From an average energy content of the fuel of approx. 15 MJ kg^{-1}, a CO production rate of 3 g s^{-1} MW^{-1} is derived.

Besides toxic effects, fatality can be caused by high temperature. According to (PIARC 1999), a temperature of 80°C can be tolerated for about 15 min. The egress model takes elevated temperatures into account by defining a maximum temperature which is tolerated.

3. MODEL OUTPUT

3.1. Description

With ODEM, the calculation time of a standard egress scenario beginning at the fire ignition and simulating 30 min evacuation time, is a few seconds on a standard laptop computer.

The output includes the typical output of the smoke propagation simulation and the tunnel geometry including the elevation as well as locations of jet fans, air-flow monitors, and position of egress doors. Furthermore it gives a summary of the individuals involved in the fire scenario including position at the end of the simulation, status (dead, travelling or safe), speed and accumulated CO dose. From this summary, several individuals may be selected. In a second simulation, the path of these individuals through the tunnel is stored for graphical output.

Figure 2 shows a representation of a typical scenario. In the left graph, the mean air velocity at the measurement location is shown on a vertical time axis. In the above right, the position of the smoke front is shown on the same time scale. Furthermore, this graph shows the path of selected individuals in the tunnel. The graph below depicts the relevant installations in the tunnel.

3.2. Example scenario

In this scenario, a 760 m long tunnel is considered with bi-directional traffic and longitudinal ventilation by jet fans. The special characteristic of the tunnel is the 5.3% gradient falling from left to right. The tunnel is equipped with eight jet fans driven by variable speed drives. The goal of the smoke control system is to provide optimum conditions for self-rescue. If possible, a smoke stratification in the traffic space should be maintained. For this purpose, a moderate flow velocity of 1 to 1.5 m/s is established without changes in flow direction. Jet fans in the smoke are switched off.

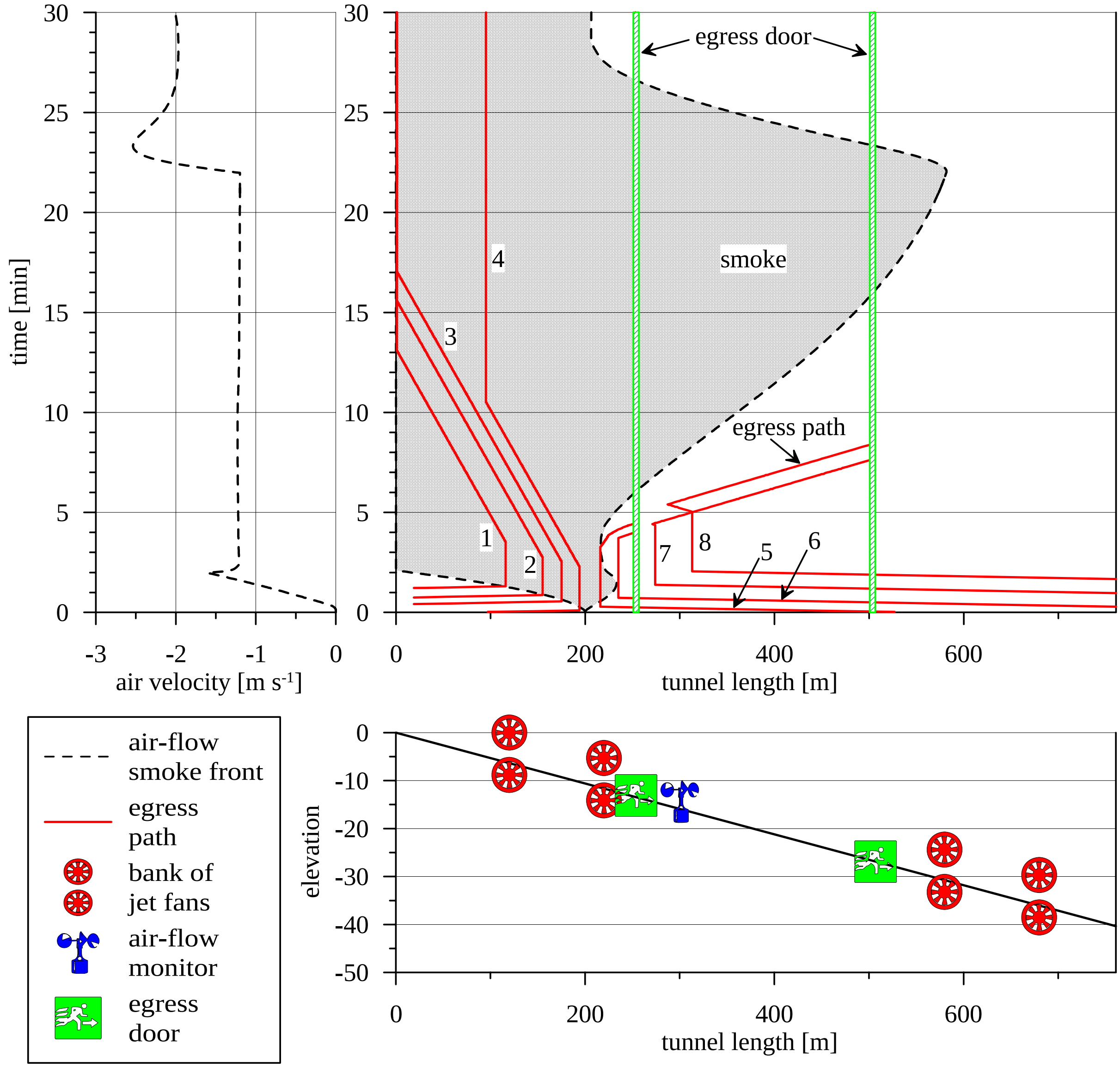

Figure 2: Graphic output air flow velocity (left) and smoke propagation and egress paths (right) versus time.

A fire starts at t = 0. The heat release rate is increased up to 30 MW within 10 min. Two minutes after ignition, the fire is detected and the smoke control system is started. Jet fans located in between the smoke fronts are automatically switched off and locked in that state. They are no longer available for air-flow control. The longitudinal air flow is controlled to 1.2 m s^{-1} by the remaining jet fans.

This air flow velocity is not sufficient to avoid back-layering of smoke, but the front’s propagation downhill is very slow. At about 22 min after ignition, the smoke front reaches the jet fan group at 580 m. The group is switched off and no longer available. Then, the thrust of the remaining jet fans is not sufficient to limit the air flow against the stack effect. The air is accelerated to 2.5 m s^{-1} and the smoke front is driven back towards the fire.

For interpretation of the egress behaviour, the individuals are numbered #1 to #8 from left to right. In the first few minutes, the tunnel users are travelling in their vehicles. They are stopped at the end of the queue or in the smoke. The pre-movement time is defined as 3 min. However, only #5 to #8 remain in their vehicles. #1 to #4 leave the vehicles earlier due to high temperature at their position.

The tunnel users choose the direction towards the nearest emergency exit with the exception of #1 to #4, which escape away from the fire, driven by higher temperature. People in the smoke have reduced walking speed when compared to people moving in a smoke-free environment. About 5 min after ignition, some individuals (#7 and #8) become aware or the smoke front. They change the direction of escape and start moving towards the emergency exit located at 510 m. In the graph, all people that are safe at the emergency exits remain stationary at the door. In this scenario, only #4 is not successful reaching a safe place.

4. APPLICATION

The smoke propagation model SPRINT has been validated both against experimental data (Riess et al. 2000) as well as other one-dimensional models (e.g. Riess et al. 2001). The different sub-models of ODEM are selected carefully and compared to data from commercial egress codes. At each stage of development, the model behaviour has been thoroughly checked for plausibility.

However, the validation of the complete egress model has been found very difficult. Experimental data is scarce and usually not applicable to a road tunnel environment. Tests in road tunnels are valid only for one particular tunnel if they do not include a variation of design features, such as tunnel cross-sections, light, signs for egress doors etc. In (Boer 2002), it was concluded that some tunnel users would not use the egress doors in an emergency. The study comes to the conclusion that the signs for the egress doors should be improved. Figure 3 shows a comparison of the egress door used in the study and a door from the recently built Giswil tunnel (Switzerland, 2004).

Development of egress models concentrates on effects such as variation of individual characteristics and queuing, overtaking, behaviour of large crowds etc. All these effects are not relevant in a road tunnel environment. Much less research seems to have been done on user behaviour in road tunnels – influenced by irritating smoke, toxic gases and lost orientation due to low visibility. Even the behaviour of a tunnel ventilation engineer could be erratic when immersed in black smoke in a tunnel test fire.

(Rogsch 2005) presents a comparative validation of four commercial egress models. This comparison shows that even for the simplest systems the evacuation times and foot traffic flows vary considerably with different simulation programs and deviate from experimental results. It appears that a successful validation of a new egress model for road tunnels against a commercial model just requires a careful selection of the appropriate software.

Figure 3: Two egress doors – same behavior in an emergency?

As the model validation is sketchy, the model should be applied with utmost care. At the moment, it is not yet capable to give absolute measures of risk. However, it is useful for a comparison of different safety measures in a particular tunnel, such as reduced distance between egress passages versus additional ventilation equipment. When applied in a quantitative risk analysis, the model consisting of SPRINT and ODEM has to be validated against the three-dimensional calculation in reference scenarios.

5. CONCLUSIONS

The following conclusions can be drawn:

i. The one-dimensional egress model ODEM has been developed to complement an existing one-dimensional model for smoke propagation.

ii. ODEM is based on deterministic behaviour of individuals. It includes decisions triggered by visual impression of the smoke front or high temperature.

iii. The model includes the influence of reduced visibility, toxic gases, and temperature.

iv. Validation of egress models for tunnel application is difficult. Experimental data is scarce and existing commercial models show a wide range of results.

v. More research has to be done in the field of people's behaviour in road tunnels, especially when confronted with reduced visibility.

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VENTILATION DESIGN TOOLS AND VALIDATION

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ABSTRACT

The ventilation system of a tunnel has to fulfil two requirements. It has to ensure that the in-tunnel air quality is good enough to allow safe passage through the tunnel. In addition it has to improve the self rescue conditions in case of a fire. To achieve these objectives specific design tools have to be used. These tools might be simple or complex, but they must be appropriate and accurate enough to ensure sound design of the system. Very often simple tools are employed for complex problems and complex tools are used for simple installations. This paper looks at different tool applications and checks validity against measured data.

Keywords: ventilation design, design tools, measurements

1. INTRODUCTION

The design of tunnel ventilation has to focus on two objectives. The ventilation system has to be capable of providing sufficient fresh air for the tunnel and must be able to control the air flow in the case of a fire.

For the first purpose it is necessary to know the amount of pollutants emitted by the vehicles. For this emission factors have to be used to describe the emission behaviour of a vehicle during its tunnel passage. Such factors are defined in national and international guidelines. However, as these factors try to describe the average emission behaviour under certain tunnel specific situations and the “average” vehicle in a tunnel is subject to permanent change in its emission behaviour, the factors must be verified on an almost regularly basis. Ventilation fans must provide enough power to deliver the air volumes needed to dilute pollution and ensure that concentration and visibility values remain within acceptable levels.

The second purpose is to control the air flow within the tunnel according to a predefined ventilation scenario. Hence the ventilation power has to be big enough to overcome all the pressure losses which occur within a tunnel and its ventilation system. There are many ways to calculate head losses. Depending on the complexity of the system the methods and tools used for calculating the pressure losses might range from a simple summing up of individual head losses to complex 3D CFD tools. Common to all of these tools is that they need assumptions, boundary conditions, simplified geometry etc. Hence, validation against measured data is required in order to establish tool performance.

2. VENTILATION DESIGN TOOLS

In Austria, ventilation design is based on the guidelines RVS 09.02.31 and 09.02.32. These guidelines state the requirements for normal and incident ventilation. Normal ventilation control can be based either on in-tunnel air quality (visibility or CO concentration) or on the number of vehicles passing through the tunnel. Correct incident ventilation involves the provision of a predefined air flow with a defined velocity of the smoke/air mass at the incident location. Hence tools are needed in order to estimate the fresh air amount for normal operation as well as to match ventilation according to the needs of operation in an incident case. Within this paper the focus is put on ventilation design in general and incident ventilation in particular.

2.1. Calculation tools for ventilation power

As soon as the fresh air demand is fixed the ventilation can be designed for normal operation. For the fire case the specifications concerning air/smoke volumes and air velocities inside the tunnel are defined in the various regulations. In Austria this is done in the RVS 09.02.31, on the international level PIARC 2008 gives a good overview of the worldwide situation. The given volume flow multiplied by the pressure loss (and an efficiency coefficient) results in the ventilation power.

2.1.1. Simple approach (sum of pressure losses)

The objective is to calculate the pressure difference on the basis of a summation of pressure losses due to resistances within the tunnel (and ducts in the case of a transverse ventilation system), atmospheric pressure differences between the portals, the influence of moving/stopped vehicles, and thermic influences. Various literatures describe specific methodology (e.g. Freibauer 1978), and resistance coefficients and friction numbers can be found in Idelchik and Fried 1989. The approach allows for a quick and simple calculation of fan power needed to move the air through the tunnel or the respective ventilation ducts. However, this method depends strongly on (well tested) empirical factors and as in general tunnel geometry often deviates from standard configurations a certain element of uncertainty remains. Thus, the usage of such factors – especially for transverse ventilated tunnels – needs some experience.

A drawback of the above method is that only stationary situations can be considered with a sufficient degree of accuracy.

2.1.2. One dimensional calculation scheme

The main interest in aerodynamic flows concerns the flow in the direction of the tunnel. Hence, normally only flow information along the longitudinal axis of the tunnel is of interest. The calculation is based on solving the conservation equations for mass (for air as well as water), energy, momentum and a passive scalar in one dimension. To do this the tunnel is split into a number of cells in which the respective equations are solved. In order to allocate the pressure correctly in the momentum equation a staggered grid is used. An explicit scheme is used for solving the time dependency in the case of a transient application.

Heat transfer between the hot air/smoke mass and the surface by forced convection followed by heat conduction into the walls is calculated on the basis of the energy conservation equation

The discretisation of the equations is based on a finite volume scheme, the numerical solution on a TDMA solver.

The model used at our lab allows the implementation of individual fans in longitudinally ventilated tunnels, various splits of the flow due to on/off ramps and a combination of tunnel geometry and ventilation ducts. The calculations are performed for moist air. This allows for the consideration of water vapour e.g. due to water mist systems.

2.1.3. Three dimensional calculation scheme

The basis of 3 D models is more or less the same as for the 1D approach described above. The relevant conservation equations are solved in three dimensional space. The partial differential equations for momentum, energy and scalar are transformed into a system of linear equations and solved in an iterative process. The closure of the Reynolds Averaged Navier Stokes equations (RANS) is done using a turbulence model. The models applied for the calculations shown below are mainly FLUENT or CFX from the ANSIS group (www.ansys.com). The advantage of 3D models is the possibility to have a very good geometrical representation of the part of the tunnel under consideration. But as they need a lot of memory and calculation time only small parts of a tunnel can be calculated within reasonable calculation times. It needs to be noted, however, that in most parts of the tunnel 3 D information is not of interest. Only a segment with complex flow situations due to complex geometry of other purposes (fire, air injection or extraction, etc.) needs to be handled with a 3 D model. Nevertheless, a sound description of the boundary conditions as well as a proper selection of models and model parameters is required in order to end up with reliable results.

3. TRANSVERSE VENTILATION – AIR INJECTION

Air injection by Saccardo type nozzles are nowadays frequently used in order to avoid installation of jet fans inside the tunnel or in order to use the capabilities of existing air supply in transverse ventilated tunnels for smoke control in an incident case.

3.1. Measurements in the Katschberg tunnel

In the Katschberg tunnel Saccardo type fresh air injection nozzles are employed for controlling the airflow and confining the smoke in case of a fire. As in such cases air is injected into the tunnel room at a high velocity, a complex 3 dimensional behaviour of air flow can be expected. **Figure 1** shows a sketch of the tunnel section with the injection nozzle and the measurement arrangement. Volume flows in the duct, as well as those on both sides of the nozzle inside the traffic room were measured. Furthermore, the pressure difference between the undisturbed flow inside the duct and the two measurement cross sections for volume flow inside the traffic room were recorded. Volume flows were monitored employing ultrasonic devices whereas the pressure differences were recorded with differential pressure capsules.

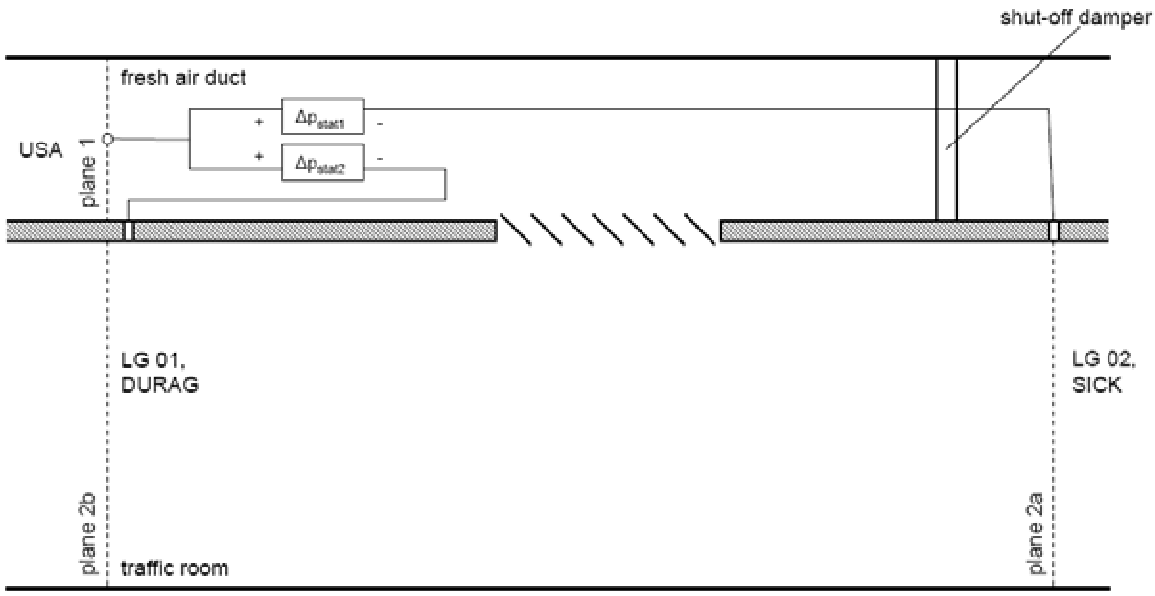

Figure 1: Sketch of the air injection nozzle and the location of the performed measurements

The velocity measurement inside the air supply duct was performed with a 3 D point monitor (plane 1 in **Figure 1**). In order to get the appropriate flow field a correction according to Pokorny et al (1981) was performed. The velocity measurements at the cross sections 2a and 2b were based on path averaged velocity information. No corrections had to be applied. The pressure difference measurements were installed such as to give the static pressure. Total pressure was calculated as sum of static and dynamic pressure.

The geometry of the injection damper is known. Knowledge of the opening angle of the damper (90° represents fully open) allows for calculation of the open damper cross section and hence the injection velocity. Based on the total pressure loss and the velocity in the nozzle it was possible to derive resistance coefficients for the injection nozzle. For opening positions 0° - 90° the pressure loss between pos. 1 and 2a was calculated, for angles > 90° the difference was taken between 1 and 2b (always in direction of the main flow). The axial fan was used at two different operating points, n1 with 370 rpm and n2 with 742 rpm.

Table 1: Results of the measurements of the air injection nozzle

		Air flow	Diff. pressure		cross-section*	u_S	$\zeta_{measured}$ **
rpm	position	total	Δp stat	Δp tot	(damper)		
[min^{-1}]	*[degree]*	*[m³/s]*	*[Pa]*	*[Pa]*	*[m²]*	*[m/s]*	*[-]*
n_2	138	179.98	1283.11	1375.12	5,55	32.44	2.22
n_2	138	185.51	1270.07	1368.60	5.55	33.44	2,07
n_2	50	211.53	934.86	1082.21	6,35	33.31	1,54
n_2	35	176.73	1178.77	1269.87	4.75	37.17	1.56
n_2	18	108.11	1498.41	1517.25	2.56	42.20	1.53
n_1	138	105.96	337.69	364.46	5.55	19.10	1.69
n_1	125	116.88	355.02	398.27	6.79	17.21	2.18
n_1	50	124.26	332.38	382.60	6.35	19.57	1.58
n_1	35	106.48	333.93	361.18	4.75	22.39	1.21
n_1	18	77.13	372.37	378.89	2.56	30.11	0.75

* flow-through area of the damper, completely opened (90°) 8.29 m²
** Mean air density over measuring period 1.0973 kg/m³

3.2. Model validation

3.2.1. Simple approach

The simple approach is based on the calculation of the resistances and the consequent pressure losses (see section 2.1.1). In order to model the air injection geometry has to be simplified somewhat. The whole path from the air supply duct to the traffic room is split into 4 sections. Section 1 covers the 90° bending of the air when being diverted from the air supply duct into the damper. Section 2 covers the entrance into the damper, while section 3 represents the damper itself. Section 4 stands for the merging of two flows, that from the damper and the existing one in the traffic room. Figure 2 depicts the simplified model for this specific section between the air supply duct and the traffic room. The resistance coefficients were taken according to Idelchick and Fried (1989), adapted to the geometry of this section.

Table 2: Resistance coefficients, comparison between selected and measured values

rev.	n1	n1	n1	n1	n1	n2	n2	n2	n2	n2
Angle [°]	138	125	50	35	18	138	138	50	35	18
ζ_{total}	2.03	2.13	1.75	1.66	1.60	2.06	2.06	1.78	1.66	1.60
$\zeta_{measured}$	1.69	2.18	1.58	1.21	0.75	2.22	2.07	1.54	1.56	1.53

Except for one test at n1 and an 18° opening angle, the differences between simulation and observation are within 10% to 15%, with simulation values always being higher than measurement values.

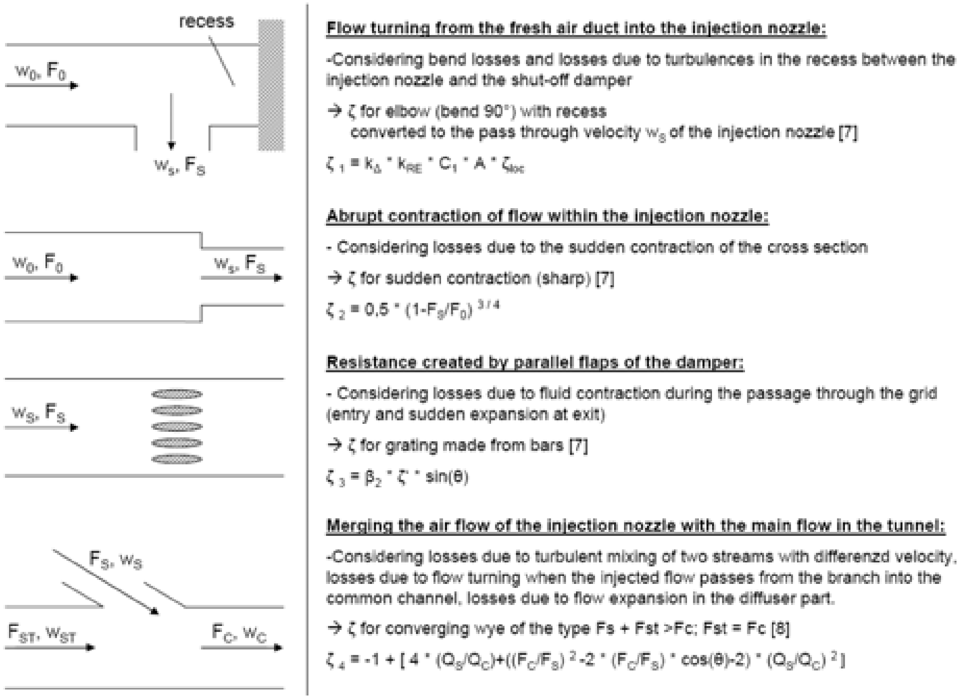

Figure 2: Simplified model of the section air supply duct – damper – traffic room, resistance coefficients according to Idelchik and Fried 1989

3.2.2. CFD Calculations

The CFD model represents a tunnel section with a length of 350 m and a tunnel cross section of 48 m² and an air duct area of 9 m², and is similar to that described in section 2.1.3. An additional cubic zone at the tunnel portal was introduced to impose atmospheric pressure outlet conditions. The damper was placed in the middle of the tunnel geometry and had a free flow cross section of 8.3 m² (at a damper flaps angle of 90°). The calculation was performed by using a hybrid mesh with approximately two million elements. This mesh consists of tetrahedral elements in the area with the damper and of wedge elements in the remaining domain. Figure 3 shows the CFD geometry used for this calculation.

The boundary condition for the air duct was a constant mass flow inlet based on an air density of 1.08 kg/m³. For the tunnel outlet conditions, a relatively static pressure of 0 Pa was set on the vertical plane of the added cubic zone. Additionally a wall roughness for the tunnel wall and for the damper was included. The turbulence was simulated with the standard k-ε model, and a logarithmic wall function was applied.

Figure 4 depicts the flow pattern in the symmetrical plane. It can clearly be seen, that the supply air – coming through the duct– is reversed by the damper and results in a highly unsteady flow phenomena downstream of the damper. The exit velocity from the damper is some 38 m/s, the maximum speed at ground level reaches some 20 m/s.

Table 3 shows the comparison between measurement and simulation for three different cases. Notice that there is a small difference in the angles of the damper flaps between simulation and measurement. This arose because the simulations were performed during the design phase, while the measurements were performed at the point of best operation. In most cases the volume flow was higher in the tests than in the simulation. However, the pressure losses showed a comparable result.

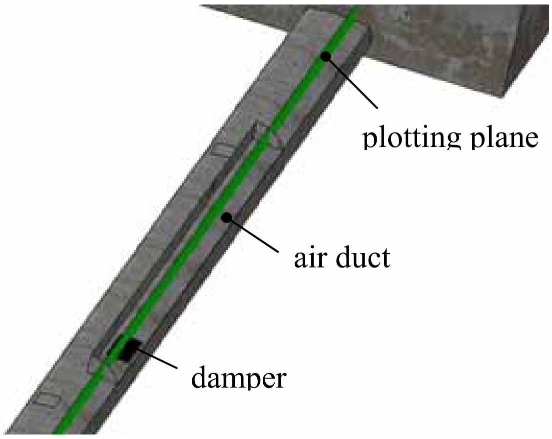

Figure 3: CFD geometry of a part of the calculation domain

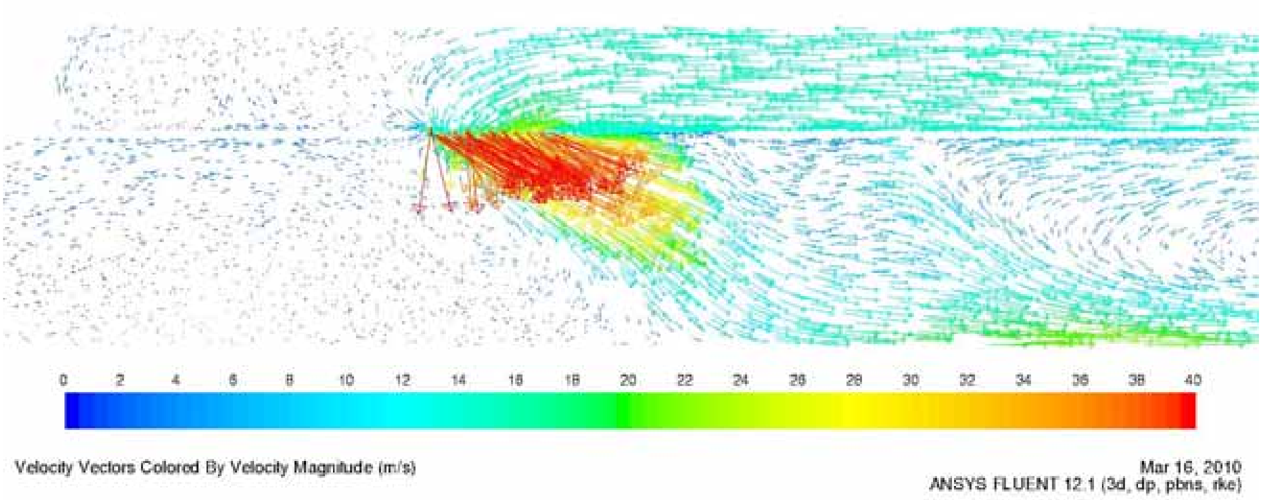

Figure 4: velocity contours in the symmetry plane for calculation case 2 (see **Table 3**)

Table 3: Comparison between measurements and CDF calculation

		Case 1		**Case 2**		**Case 3**	
		Simulation	**Measurem.**	**Simulation**	**Measurem.**	**Simulation**	**Measurem.**
Angle (flaps))	[°]	150	138	30	35	135	125
Volume flow	[m³/s]	130	180	150	177	113	117
Dp-stat.	[Pa]	1280	1283	920	1179	366	355
Dp- tot.	[Pa]	1361	1408	1034	1289	444	412

4. AIR FLOW IN COMPLEX STRUCTURES

Wherever the presence of physical constraints increases ventilation duct complexity simple calculation schemes may no longer be appropriate. The reason is that the flows upstream as well as downstream of the elements under consideration are not at all uniform (over the cross section). Hence the assumptions on which the simple resistance coefficients are based are not valid. The following example is based on a ventilation section of the cavern section of the Tauern tunnel (Sturm 2009).

As part of the upgrading of the ventilation of the Tauern tunnel the number of the fresh air supply fans was reduced from two to one per ventilation section. Thus it was possible to remove the exhaust air fan from an elevated location and place it on the same platform as the fresh air supply fans. This was necessary in order to avoid free hanging stainless steel exhaust ducts which would have had to be insulated to protect against excess radiation heat in the case of fire.

Figure 5 shows the CAD model for the two exhaust air fans and ducts supplying the two central ventilation sections. As can be seen, multiple 90° elbows are lined up within a short distance. This results in a non uniform flow pattern upstream of each of the elbows (with guiding blades) and hence in high head losses. In addition, the regions with very low velocities, or even backflow in the corners, are quite big (Figure 7). Taking the whole section between the exit of the axial fans and the entrance into the vertical shaft into account the total pressure drop accounted on average over the cross sections to 335 Pa, based on the CFD calculations (Figure 7). For the same region a simple calculation based on resistance coefficients (Idelchik 1989) was performed. Using the same volume flows the pressure losses summed to 250 Pa.

As technical problems arose, the measurements needed for validation of calculated results are still pending.

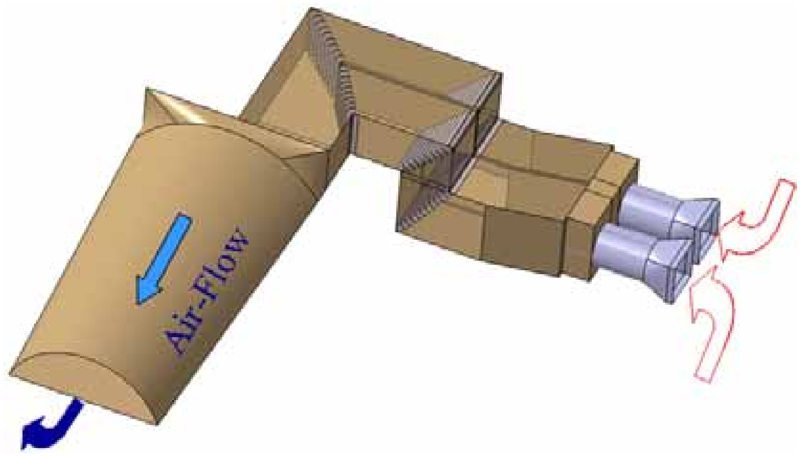

Figure 5: CAD drawing of the cavern section

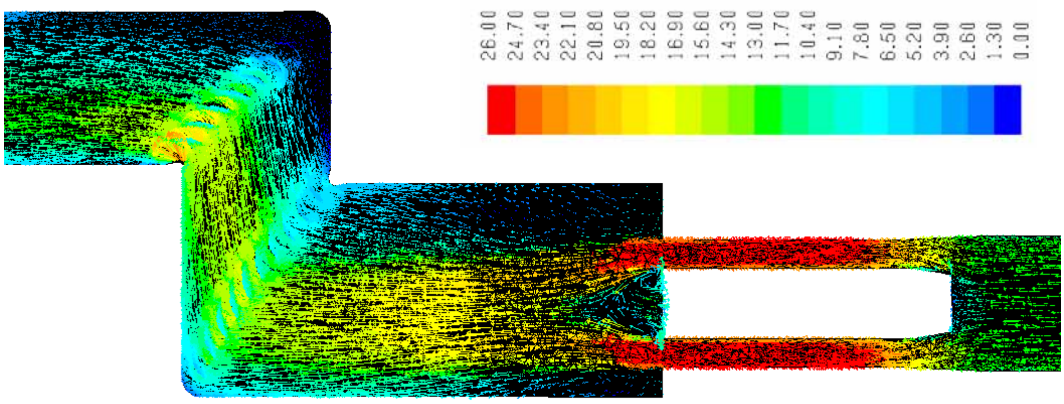

Figure 6: Flow field

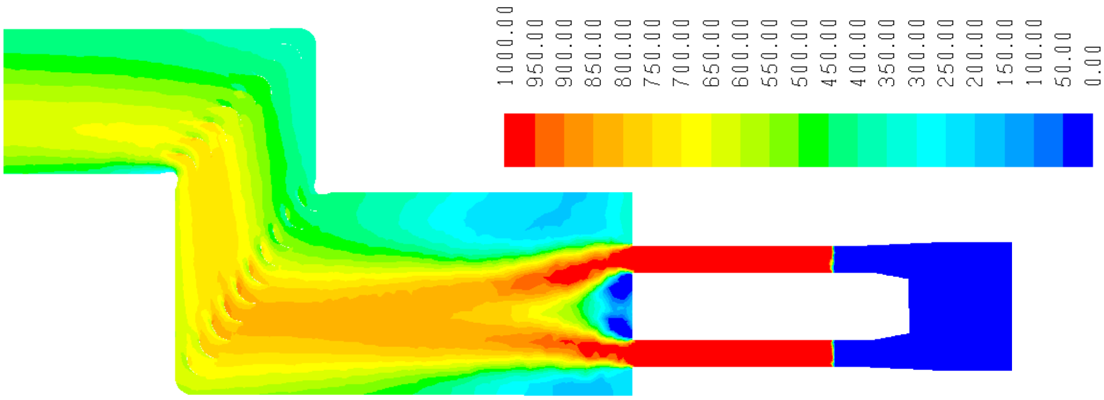

Figure 7: Pressure loss in a section of the calculation domain

5. CONCLUSION

The design of a ventilation system is based on all available information as well as on the usage of certain design tools. However, uncertainties still have to be taken into account. The final construction of the ventilation ducts, or installations such as guiding blades, are never as they appear in the CAD drawings. This is due to construction and installation tolerances and to unforeseen changes needed during construction.. Such situations can only be handled by applying additional safety margins in the calculation.

The use of calculation tools entails a different approach. A tunnel and its ducts can in most cases be considered as a one dimensional system. The main flow is along the longitudinal axes, secondary flows in the cross section play a minor role. Hence a quite simple approach of assuming resistance coefficients for the single parts of the tunnel-duct system and summing up the head losses of all these sections is in many situations sufficient. However, there are certain situations where the main assumptions for the usage of simple tools are not valid as the behaviour of the flow in such stretches is multidimensional. For such situations more complex tools such as CFD need to be used. However, the usage of CFD tools requires detailed knowledge of the principles of numerical flow calculations (usage of turbulence models, grid independency etc.). Otherwise the results gained by CFD might be more incorrect than those gained by the usage of simpler tools.

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RESPONSE OF VENTILATION IN CASE OF 40MW AND 80MW TUNNEL-FIRE – THE CFD INVESTIGATION

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ABSTRACT

The fact, that every other underground facility, as large-scale space, differs from each other in it´s geometric characteristics, sets always new tasks for researchers who are investigating the fluid phenomena. In this manner, we performed computationally aided investigation of new covered traffic road-communication that undergoes a part of Slovenian Capital of Ljubljana. Although still not finished – we were capable with the employed both (steady-state) RANS and (transient) LES turbulence treatment, to give a CFD-forecast for effectiveness of ventilation in events of both 40MW- and 80MW-fires.

1. INTRODUCTION

Due to the increasing accidental fires in enclosures, especially in that area of modern society where our freedom is mostly expressed – traffic and tourism – there is an on-growing need to undertake the scientific research, aiming at better understanding of these reactive flow phenomena[1, 2]. Therefore in our research we performed the exploration of the Slovenian "Sentvid"-tunnel that is undergoing the city of Ljubljana and is having a change in it´s cross-section surface (from three-lane down to two-lane road) and is having at about half of it´s length of 1470m the bifurcation zone, where one-lane road (tunnel-part) is climbing up to the local road.

2. TREATMENT OF THE TURBULENCE - APPLIED MATHEMATICAL MODEL IN THIS STUDY

2.1. k-ε

The flow phenomena of interest are computed by the Reynolds Averaged Navier-Stokes (RANS) equations, with the turbulence *k-ε* model, representing the major characteristic of the applied CFD-investigation-tool with the FLUENT. Since the Mach Number never was within the order of $0.012 < Ma < 0.036$, such a flow can be assumed as incompressible[3]. So, assumed as incompressible, the fluid while crossing the reaction front, doesn´t undergo thermal-caused expansion and the reaction makes no impact onto flow-velocity[4]. Further assumption, to have a planar propagation front of combustion in a motionless fluid, leads to the application of the Boussinesq approximation[5, 6] without external forces[7]. Here, the flow velocity obeys the incompressible Navier-Stokes equation[8] with a temperature-dependent force term[7]. So, the change of temperature is described by an advection-reaction-diffusion equation. For this incompressible gaseous reactive flow at low velocity, the governing equations of the combustion-induced flow read:

$$\frac{\partial \bar{v}_j}{\partial x_j} = 0 \quad (1)$$

$$\frac{\partial \bar{v}_i}{\partial t} + \frac{\partial \left(\overline{v_i v_j} \right)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \frac{1}{\rho}\frac{\partial \bar{\tau}_{ij}}{\partial x_j} - g_i \alpha \Delta \bar{T} \quad (2)$$

$$\frac{\partial \overline{T}}{\partial t}+\frac{\partial\left(\overline{T}\overline{v}_j\right)}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\frac{\lambda}{\rho c_p}\frac{\partial \overline{T}}{\partial x_j}\right)+\frac{1}{z}R\left(T\right) \qquad (3)$$

Here $\overline{v}_i$ denotes the average velocity component, $\overline{T}$ the mean local temperature, $\overline{p}$ the pressure, ρ the density, t the time and x_i the space coordinates. The *R(T) = ¼ T (1 – T)* stands for reaction rate[7] where the reciprocal value of reaction time-scale is represented by *z*, is the thermal conductivity, c_p is the heat capacity at the constant pressure. Temperature T will be used as expression for reaction-progress-variable as well, whose purpose is to distinguished burned, unburned and partially burned state, providing an easy interpretation of flame propagation. The term $-g_i\alpha\Delta\overline{T}$ denotes buoyancy, treated according to the Boussinesq approximation, where $\Delta\overline{T}$ is showing the difference between local and reference temperature. The symbol *g* denotes the gravity and is the coefficient of thermal expansion. The model for the stress tensor[9], $\overline{\tau}_{ij}$ is related to the local strain rate:

$$\tau_{ij}=(\tau_{ij})_N+(\tau_{ij})_T \qquad (4)$$

where we distinguish between the Newtonian stress $(\tau_{ij})_N=2\mu\overline{S}_{ij}$ featuring molecular viscosity; and the turbulent Reynolds stress $(\tau_{ij})_T=2\mu_T\overline{S}_{ij}$, since the stress rate tensor $\overline{S}_{ij}$ is defined as:

$$\overline{S}ij\equiv\frac{1}{2}\left(\frac{\partial v_i}{\partial x_j}+\frac{\partial v_j}{\partial x_i}\right) \qquad (5)$$

and the turbulent viscosity:

$$\mu_T=C_\mu\frac{k^2}{\varepsilon} \qquad (6)$$

with *k* the turbulent kinetic energy and the dissipation rate of turbulent energy.

The applied *k-ε* model[10] is a two-equation eddy viscosity model[11, 12] that uses transport equations for these two variables[13]. One of these equations governs the distribution through the field of *k*, the local kinetic energy of the fluctuating motion. The other one yealds the energy dissipation rate ε[14].

$$\frac{\partial k}{\partial t}-\nabla\cdot\left(C_\mu\frac{k^2}{\varepsilon}\nabla k\right)=C_\mu\frac{k^2}{\varepsilon}P_d-\varepsilon-G_b \qquad (7)$$

$$\frac{\partial \varepsilon}{\partial t}-\nabla\cdot\left(C_\varepsilon\frac{k^2}{\varepsilon}\nabla\varepsilon\right)=C_1kP_d-\frac{\varepsilon}{k}\left(C_3\lambda_v N^2+C_2\varepsilon\right) \qquad (8)$$

The energy term $G_b=\alpha g_i\frac{\mu_t}{Pr_t}\nabla\overline{T}$ is modelling the buoyancy effects, where Pr_t denotes turbulent Prandtl Number (which is of the order of unity). The constants are given: C_1=0.126, C_2=1.92, C_μ=0.09, C_ε=0.07.

The combustion – the chemistry development is explained by fast chemistry assumption including the prePDF[15] and in the ideal stoichiometric conditions the reaction runs as follows:

$$C_7H_{16}+11\left(O_2+3,76N_2\right)\xrightarrow{ignition-energy}7CO_2+8H_2O+41,36N_2+\Delta H \qquad (9)$$

2.2 LES

In Large Eddy Simulation, the turbulent motion is decomposed as large- and small-scale motions by filtering. The large-scale flow structures are calculated by solving the differential equations numerically. The effect of small-scale motions will be represented by stress terms similar to Reynolds stresses called subgrid-scale Reynolds stresses to be modelled[5]. The first step of LES is filtering which decomposes a variable $\Gamma(\vec{x},t)$ into a large-scale component $\overline{\Gamma}(\vec{x},t)$ and a small-scale component (subgrid-scale component) $\Gamma'(\vec{x},t)$, i.e.,

$$\Gamma(\vec{x},t)=\overline{\Gamma}(\vec{x},t)+\Gamma'(\vec{x},t) \qquad (10)$$

The large-scale component, $\overline{\Gamma}(\vec{x},t)$ is obtained by taking a function $F(\vec{x}-\vec{x}',\Delta)$ as the filter kernel[5]

$$\overline{\Gamma}(\vec{x},t)=\int_{\Omega}F(\vec{x}-\vec{x}',\Delta)\Gamma'(\vec{x},t)d\vec{x}' \qquad (11)$$

where Ω is the domain of interest; Δ is the filter width, given by $\Delta=V^{1/3}$; and V is the volume of a computational cell, $V=\prod_{i=1}^{3}\Delta x_i=\Delta x\Delta y\Delta z$, where Δx_i is the grid interval along the x_i direction. The filter function is

$$F(\vec{x}-\vec{x}',\Delta)=1/V \;\; ; \;\; (\vec{x}'\in V) \;\; \wedge \;\; F(\vec{x}-\vec{x}',\Delta)=0 \;\; ; \;\; (x\notin V) \qquad (12)$$

Filtering each term in governing equations gives us:

$$\frac{\partial\overline{v}_j}{\partial x_j}=0 \qquad (13)$$

$$\frac{\partial\overline{v}_i}{\partial t}+\frac{\partial\left(\overline{v}_i\overline{v}_j\right)}{\partial x_j}=-\frac{1}{\rho}\frac{\partial\overline{p}}{\partial x_i}+\frac{1}{\rho}\left(\frac{\partial\overline{\tau}_{ij}}{\partial x_j}+\frac{\partial\overline{\tau}_{ij,S}}{\partial x_j}\right)-g_i\alpha\Delta\overline{T} \qquad (14)$$

$$\frac{\partial\overline{T}}{\partial t}+\frac{\partial\left(\overline{T}\overline{v}_j\right)}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\frac{\lambda}{\rho c_p}\frac{\partial\overline{T}}{\partial x_j}\right)+\frac{\partial R_j}{\partial x_j}+\frac{\dot{q}}{c_p} \qquad (15)$$

where the overbar denotes the filtered variable. The subgrid-scale (SGS) motions are represented by an eddy viscosity with the length scale related to the grid size in the computing domain. The time scale is determined by the local resolvable dissipation. The SGS motion is calculated by the Smagorinsky–Lilly model where the unknown SGS Reynolds stresses, $\overline{\tau}_{ij,S}$ are related to the local large-scale rate of strain, $\overline{S}_{ij}$, by

$$\overline{\tau}_{ij,S}-\frac{1}{3}\overline{\tau}_{kk,S}\delta_{ij}=2\mu_{\tau}\overline{S}_{ij} \qquad (16)$$

$\overline{\tau}_{ij,S}$ and $\overline{S}_{ij}$ are defined, respectively, as

$$-\frac{1}{\rho}\overline{\tau}_{ij,S}\equiv\overline{v_iv_j}-\overline{v}_i\overline{v}_j \qquad (17)$$

$$\overline{S}_{ij}\equiv\frac{1}{2}\left(\frac{\partial v_i}{\partial x_j}+\frac{\partial v_j}{\partial x_i}\right) \qquad (18)$$

The subgrid-scale turbulent viscosity μ_t is used to provide the role of modelling the dissipative behavior of the unresolved small scales. The eddy viscosity is modeled by

$$\mu_t=\rho L_S^2\left|\overline{S}_{ij}\right| \qquad (19)$$

and where

$$\left|\overline{S}_{ij}\right|=\sqrt{2\overline{S}_{ij}\overline{S}_{ij}} \qquad (20)$$

$$L_S=\min\left(\kappa\cdot d\cdot C_S\cdot\sqrt[3]{V}\right) \qquad (21)$$

where κ=0.42; d is the distance to the closest wall; C_s is the Smagorinsky constant, lying between 0.1 and 0.23, taken as 0.1[5].

3. BOUNDARY CONDITIONS AND MESHING IN COMPUTATIONAL DOMAIN – NUMERICAL APPROACH

For transient simulations (a CFD-mode that was applied in this study) the governing equations must be discretised in both space and time[12, 16]. In choosing the numerical method we rely on the standard of the finite volumes [3, 16, 17]. The spatial discretisation of time-dependent equations employed a segregated solution method. The linearised equations result in a system of linear equations for each cell in the computational domain, containing the unknown variable at the cell centre as well as the unknown values in surrounding neighbour cells.

Since in our CFD-approach, the longitudinal artifficial ventilation was employed immediately, the tunnel-entrance and exits (both towards the main tunnel-line and towards the local road) characterised as open (pressure) boundaries with pressure increase due to the ventilation-caused velocity (of 4m/s). The fuel "pool" – the simulated fire-place, has been determined by the constant max flux rate of heptane of the order 0,4545kg/m²s[18] for simulating the fire thermal power of 40MW over the surface of 2m²; and for the 80MW-fire[19] the double mentioned value for the mass flux. Heptane was taken as inflammable good, as one of the most common used fuels in experiments and fire-tests.

Tunnel-entrance as open (pressure) boundary was used for initializing computational values for the velocity and pressure in the domain since the global temperature was set to the 293K.

The tunnel housing, tunnel road and tunnel walls as well, were presumed to be heat transparent. This decision was based on previous research experience[20, 21]., where the reality-oriented investigation on modern tunnel-construction knows for the thermal conductivity of a rock where through a tunnel was built[22]. Particularly for the Sentvid tunnel, that was built in the carst-area, the specific thermal conductivity of such limestone ($\lambda = 2,3 W/mK$)[22, 23] was integrated in the boundary conditions.

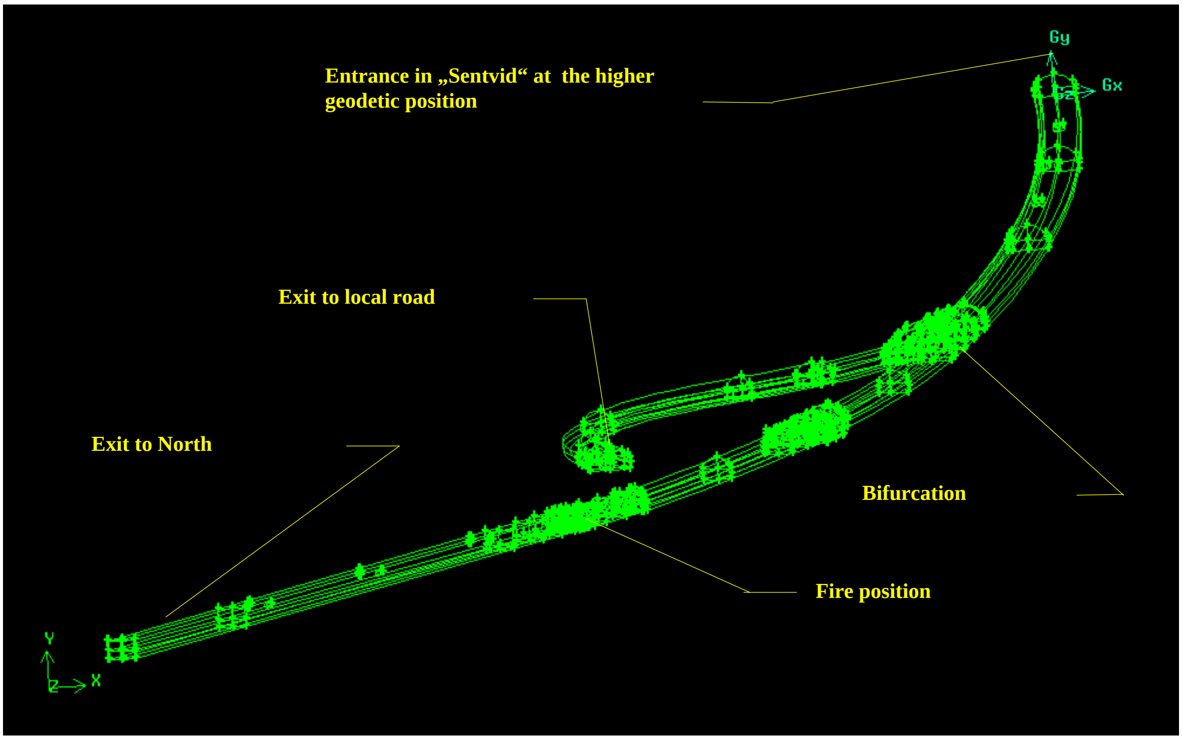

Figure 3-1: Left tube of "Sentvid" as computational domain: the 1470m long left tube of the "Sentvid" with (to-be-constructed) exit to the Celovska-street that runs above the tunnel. Upper side is entrance from Ljubljana (from the south)

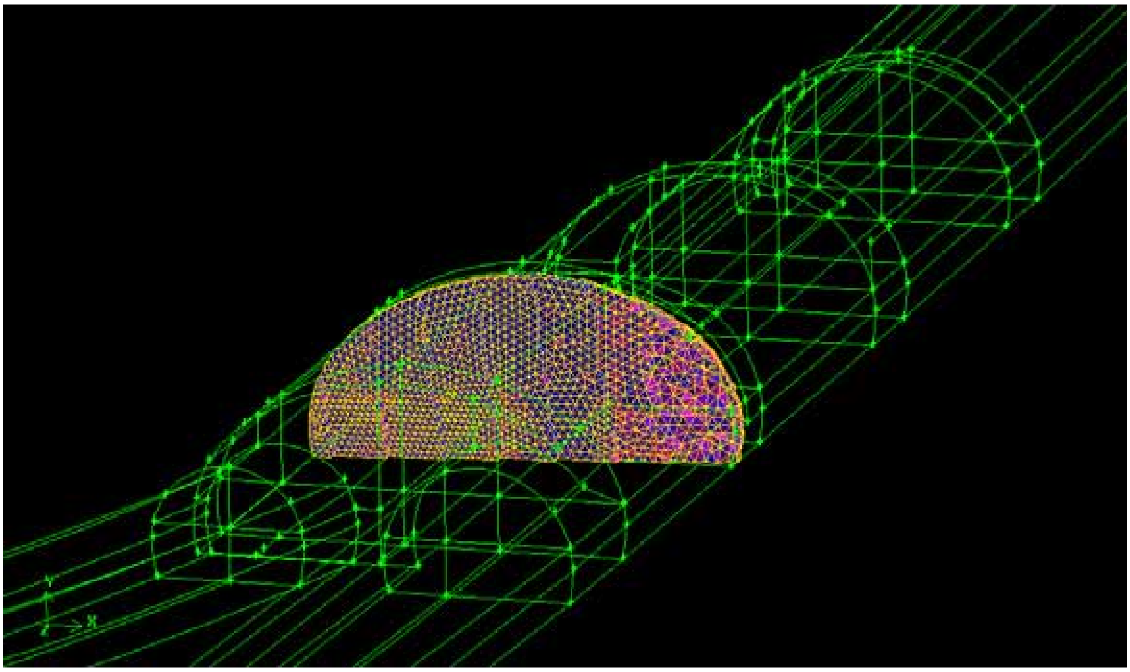

Figure 3-2: Road-junction within the tunnel with the continuing tunnel-direction(right) and the begin of the exit line towards Celovska-street (left). Different characteristics of the single-cells were applied in order to achieve mesh-independency and save computing-time in one stroke

4. FIRST STEP IN INVESTIGATION – THE SIMULATION OF 40MW-FIRE WITH NATURAL VENTILATION

After the explained computational approach was once validated[24], we firstly performed a CFD-investigation of the 40MW-fire accident, having in tunnel natural air-movement only. This numerical experiment ran for 120s as long as the real-case physical experiments[24]. Findings of this investigative step presented us that, after accidental fire is established (7th second) – we witness the strong expressed propagation (113th second) of the hot gaseous combustion products towards actual traffic-entrance (higher geodetic position).

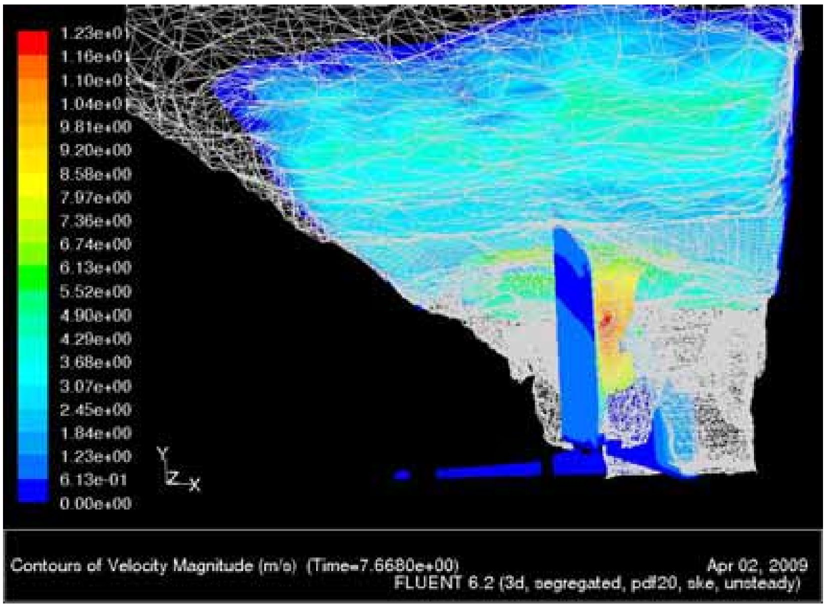

Figure 4-1: The 7th second of the 40MW fire - velocity fields point at not established propagation of the gases. Deep in this sketch is main line of “Sentvid” and finally the entrance in the left tube

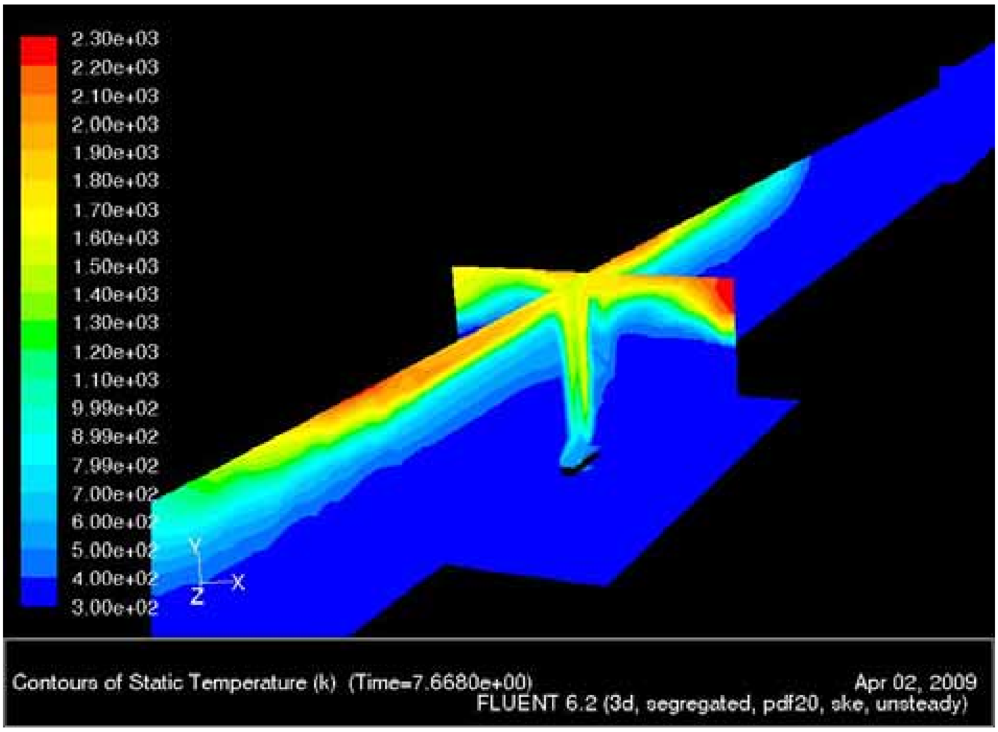

Figure 4-2: The view to the fire-place in the part with rectangular cross-section in 7th second

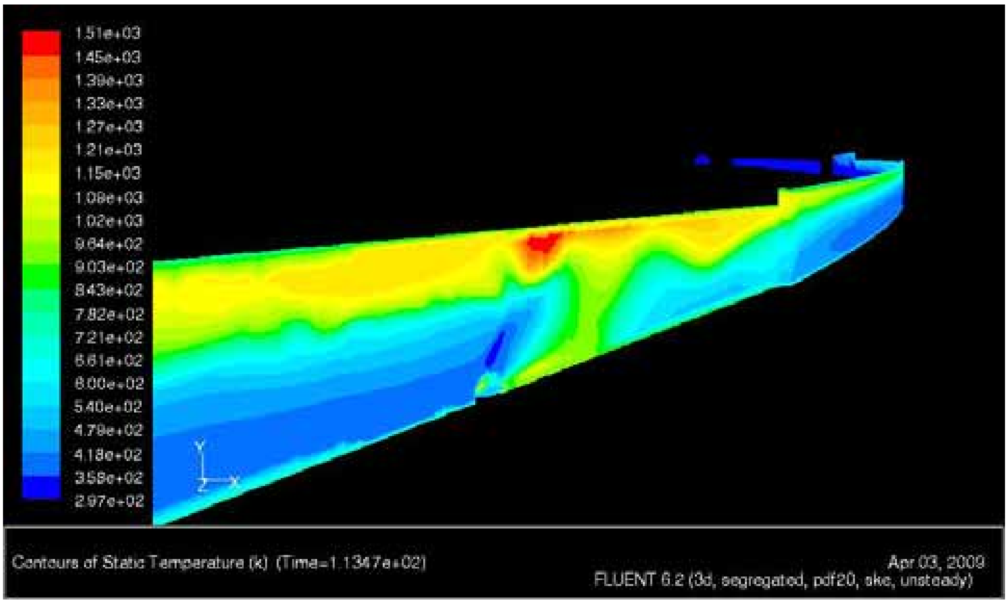

Figure 4-3: In 113th second fire is "leaving" the actual source and temperature is pointing to the inflaming of the road-asphalt. Concrete spalling is inevitable. The smoke is moving towards entrance.

5. SIMULATION OF 40MW-FIRE AND 80MW-FIRE WITH ARTIFFICIAL LONGITUDINAL VENTILATION

We started this numerical experiment with an assumption that the accidental fire (both of 40MW and of 80MW) was already established and the longitudinal ventilation in the left-tube of the "Sentvid" (composed out of 7 ventilator-pairs) was set to meat the criteria of the "critical velocity" – the velocity in the ventilating process of an tunnel-fire-event that is just enough to stop the propagation of the smoke in unwanted direction.

We estimated that for this covered road facility the value of the critical velocity is 4m/s. Indeed, in the area of the fire-accident, the over-all velocity gains on it´s value due to the constructive interference of buoyant forces in fluid (caused by combustion process) and the longitudinal air movement (caused by forced ventilation).
However the applied ventilation-velocity (due to the 16Pa pressure-difference) in the 22nd second of the fire-accident shows the characteristics of "back-layering" – the smoke movement along the tunnel-ceiling against the applied ventilation. The temperature profiles are passing the concrete spalling-temperature, the occurrence which might start in about 10th minute of some the thermal load[25].

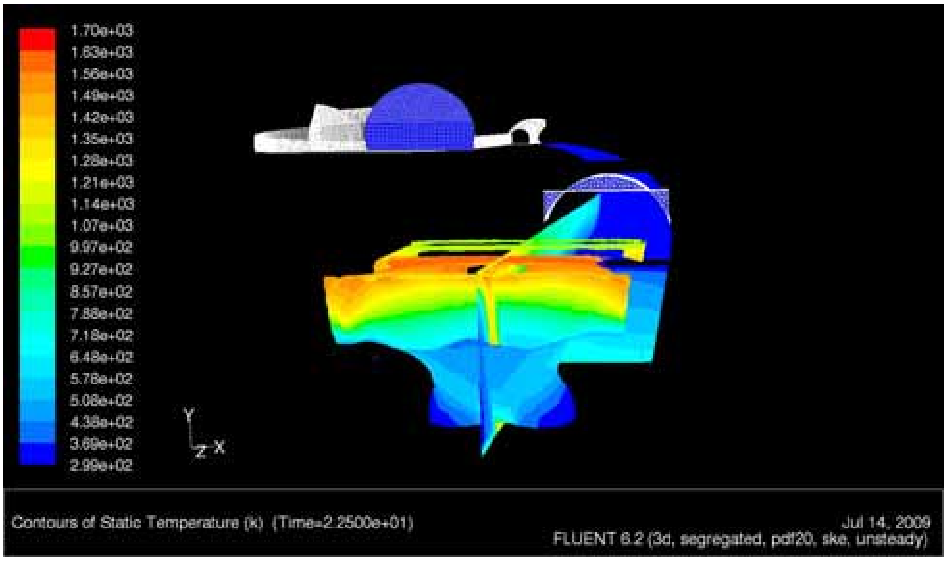

Figure 5-1: The view to the 40MW- fire-place towards the tunnel bifurcation-zone (deep in the sketch). Left upper, is the planned exit to local road. A bit further than the fire place is the connection of the two kinds of tunnel cross-section-parts (rectangular and "horse-shoe-shaped"). The temperature iso-surfaces showing destructible thermal load in the vicinity of the tunnel-ceiling (above the fire-place).

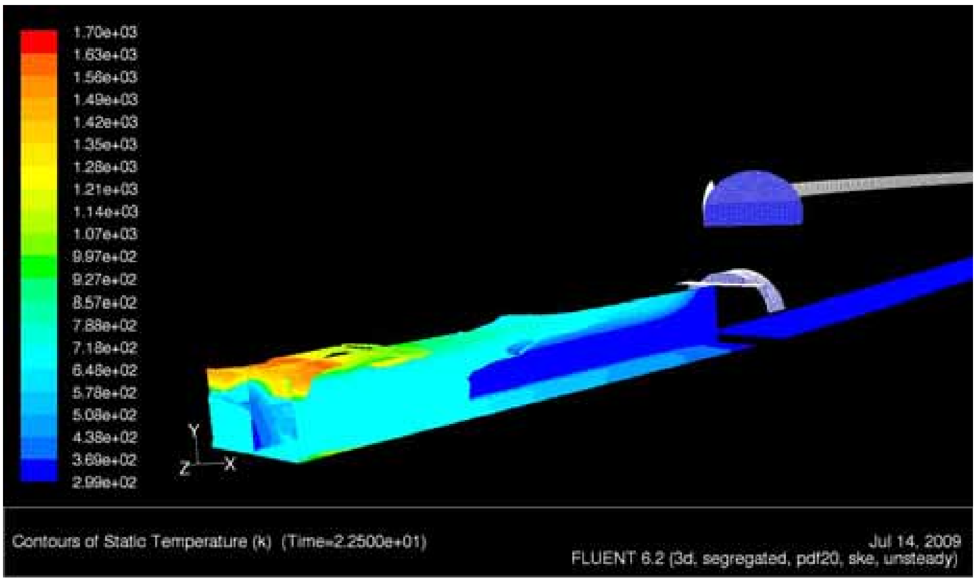

Figure 5-2: A side view of the 22nd second of the longitudinal ventilation in case of 40MW-fire event; on the iso-surfaces that represent ventilation velocity of 4m/s the temperature images are drown.

In further extraction of the results of our numerical experiment, we noticed that in the 88th second during the 40MW-fire, the longitudinal ventilation was as much as capable (in providing the lower temperatures on the tunnel cavity) as in the 120th second of the same fire-event. This implies that artifficial longitudinal ventilation adjusted for 16Pa of pressure difference can cope with the fire event up to 40MW of fire´s thermal-power – and this already after minute-and-the-half. With this engagement, the possible RC-spalling is inhibited. However the thermal impact (due to the developed temperature fields and due to the heat irradiance) is destroying the asphalt road-layer that is, in this case, a cheaper part of this underground space facility, in terms of reconstruction.

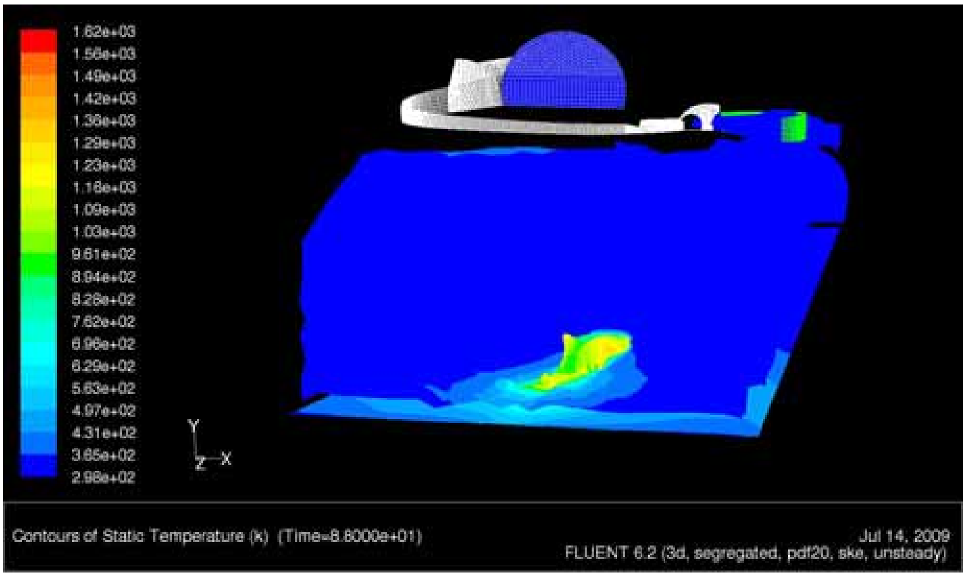

Figure 5-3

Figures 5-3, 5-4: During the CFD-investigations in "Sentvid", we recognised the flame that does not impinge on the tunnel roof[26]; here, the 4m/s ventilation-velocity in the 88th second of the 40MW-fire provides protection for the walls of the tunnel cavity. Still, there is a minor "back-layering" to be seen on the ceiling, above the fire-place only.

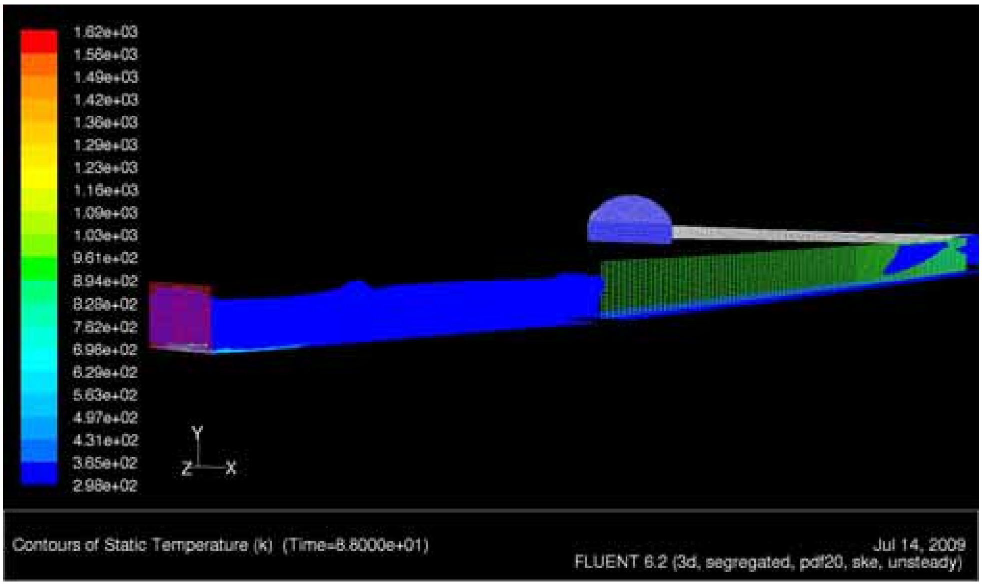

Figure 5-4

Additional size of the impact of temperature offers a view in 112s, at the tunnel-ceiling and tunnel-walls next to the 80MW-fire-place (Fig 5-5). The zones with the developed temperature of 500K (the begin of the RC-spalling) “resist” the longitudinal ventilation, that in the 40MW-fire event was able to cope the accident. These occurrences do present in this phase of the fire-development already a dangerous point for the construction of the tunnel body (Figure 5-5).

Figure 5-5

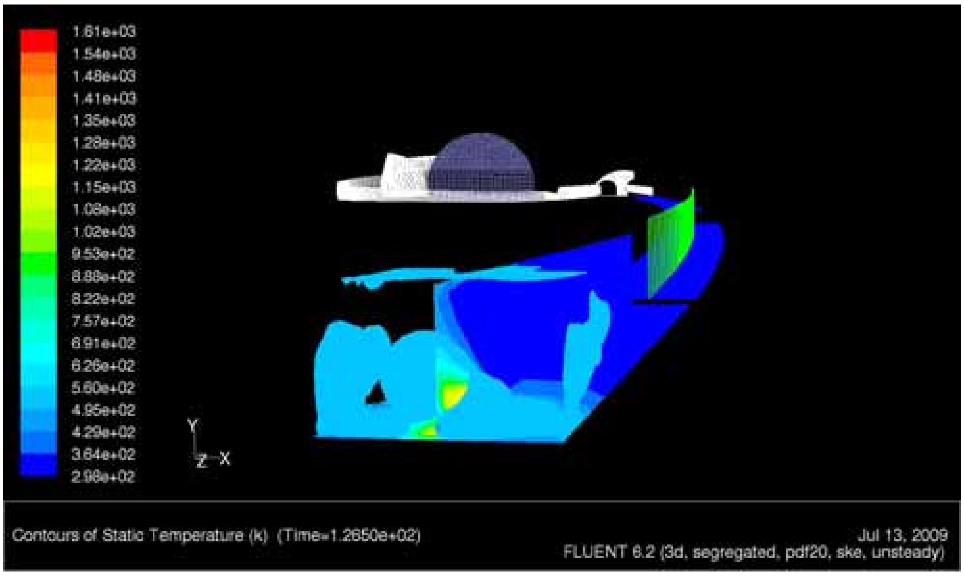

Figure 5-6: 126th second of the 80MW-fire; the central tunnel line is presented partly by the “neutral” grid and partly by the temperature´s central-plane – the concrete injuring temperature-zone is still present

This very result we gained on effectiveness of the proposed ventilation magnitude in case of 80MW-fire, invites actually to some further numerical experiment in order to estimate the optimal velocity of the ventilation (in case of 80MW-fire) that will offer appropriate thermal protection until accidental fire is fully under control. However the chosen velocity of the ventilation was able in both accidental cases to suppress propagation of the hot gaseous combustion products in unwanted direction. By performing this study on only one object of interest of the given geometric characteristics, the CFD-based investigation on the accidental fire in artifficial ventilated tunnel “Sentvid” was conducted according to the both standard and novel experimental[15, 27-29] and computer aided[30-32] research[33, 34]. Giving the small mosaic-stone to the entire urge in the community which is researching on confined large-scale

fires. With the results of this research-attempt, we intend to address also the civil-engineering sector[35, 36] and enlarge data-base for the medical health-protection[37] as well. The specific geometry of the object of interest – this traffic road-object built in Slovenia – was a "fine provocation" to conduct this research, expecting possible impact of a "reality-oriented" enclosure (computational domain) onto large-scale fire and escorting occurrences.
The "chimney effect" of the exit, up to the local road, was not "strong enough" and it´s possible influence was inhibited due to applied longitudinal ventilation that forced gaseous combustion products towards traffic-positive direction, already after the first minute-and-a-half of numerical investigations. So has the propagation of the gaseous products "followed" the tunnel line (towards lower geodetic position) and in the cases of 40MW-fire and 80MW-fire as well, the expected major influence of the tunnel-road exit was not noticed.

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DYNAMIC AND INTELLIGENT EVACUATION SYSTEM FOR TUNNELS

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ABSTRACT

A dynamic evacuation lighting system, which offers real-time, intelligent control and guiding indication using the specifically designed software has been developed to improve safety in difficult evacuation environments like tunnels. Due to the unique software and guiding light effects, the system will automatically control and guide people towards the safest escape route and away from danger, when integrated with other safety systems such as fire detection, chemical or biological detection systems.

Dynamic and intelligent evacuation systems are a more reliable, faster and safer way to control, guide and evacuate people in extreme situations than conventional evacuation systems based on static illuminated exit signs or audio signals.

Keywords: Dynamic evacuation, safety in tunnels, emergency lighting

1. INTRODUCTION

The demand for safety and emergency systems has risen steadily during the last couple of years because of recent tragedies in tunnels. These accidents have created an urgent need for intelligent safety systems to provide critical rescue information and emergency lighting. Current passive emergency systems, cannot adapt to changes in real-time conditions and do not provide enough control, guidance, or information to people in danger.

Modern evacuation models, theories and simulators provide the designers and engineers with tools for improving evacuation plans, making them more robust and appropriate given the different emergency scenarios faced. However, until now the practical tools to actually implement these scenarios have been severely limited. The traditional exit signs and photo luminescent stripes can only point to fixed exits which, depending on the situation, may not be the safest ones. In the worst case scenario, for a threat located within the planned evacuation path, some static signage might guide people in the totally wrong direction.

A modern tunnel today is equipped with several different sensor and advanced camera control systems but the information from all these systems is mainly used for manual control and human guidance during an emergency situation. An intelligent system is integrated to the tunnel management and information systems and can utilize this information for real time guidance and adapt to real time changes based on the received information from these third-party systems.

2. SYSTEM OVERVIEW

The main components of the system are the illuminating guiding stripes and controllable guidance signs which, together with the control software, can guide people effectively in extreme emergency conditions in any direction or location.

The stripe can display static, flashing and moving patterns of light that come in different colors and intensities. As the human visual perception is highly sensitive to motion, the moving light patterns efficiently notify and guide people towards the right direction (Nilsson, D., Frantzich, H. and Saunders 2005). This is an important factor to overcome typical human behavior patterns under emergency situations (pre-movement behavior and travel behavior) and therefore by improving the emergency detection, shortening people’s reaction time and increasing the movement speed we can shorten the evacuation time.

The running guiding-light effect in the LED-stripes is generated by bright, long-lasting micro-LEDs that offer speed variations and active guiding indication, or a continuous highly visible illuminating effect (see **Figure 1.**). A special stripe design with longer LED-sections has been developed for tunnels where the stripe is usually seen in lower watching angles and from longer distances.

Figure 1: Guiding stripe with green LED-lights

The stripes can be mounted at a low level on the tunnel wall or in a handrail (**see Figure 2.**).

Figures 2: Different installation methods in tunnels. A LED-stripe and symbol panel installed into an aluminum profile on the tunnel wall and into a handrail in a metro tunnel

The LED-stripes can also be used to improve the visibility of exit doors by mounting stripes directly in the exit door frame or on the wall in the exit door area by using a tailor-made profile which shows the stripe in a 30 ° angle down the tunnel edge ensuring better visibility when people are approaching the exit door along the tunnel. The stripe can also be installed in the road surface in a special profile or inside the road in a vertical position (**see Figure 3**.)

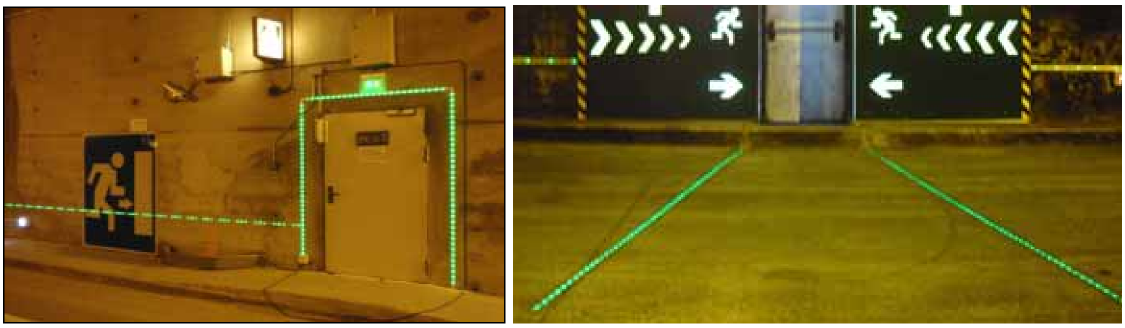

Figure 3: Different exit door awareness lighting applications. Dynamic green LED-stripes installed on the wall, in the road and in the exit door frame

3. SYSTEM COMPONENTS AND ARCHITECTURE

The system components are:

- **The LED-stripe** is a durable, extremely thin, continuous flexible circuit board with surface-mounted Light Emitting Diodes (LEDs), which is extruded by a specific coating material. The stripe is IP68-rated and made of flame-retardant, non-toxic materials.
- **The symbol and light panels** are thin, robust and bright controlling and guiding panels. The panels are based on a globally patented Diffractive Optic (DO) design, and there are many different standardized symbols available. The symbol and light panels are also IP68-rated meeting same requirements than the LED-stripe.
- **The stripe and panel driver** allocates unique addresses through the group driver, to each LED-stripe and panel thus enabling the monitoring and controlling of each individual stripe and panel. The data transfer between components takes place through the proprietary protocol.
- **The integrated group driver** controls and monitors the state of the stripe, panels and power supply units, and signals an alarm to the system control unit (the controlling tool software) if the preset limits are exceeded.
- **The power supply unit** is connected to the main supply AC voltage, in order to provide low voltage DC for the subsystem. In the event of a mains power failure, an on-board, sealed lead-acid battery supplies power to the system, for at least one hour.
- **The system control unit** is an industrial PC running the controlling tool and monitoring tool software. The system control unit is used by the authorised administrator of the system for controlling the operation of the system, when people must be directed to correct emergency exit routes. The system control unit is connected to the group drivers by the proprietary protocol.

The architecture of a basic system is illustrated in **Figure 4**. The system is controlled and monitored by the System Control Unit (SCU), which is an industrial PC running the control and monitoring software. The SCU is connected to external systems like fire alarm systems that provide input to the evacuation system. Based on this input the control software chooses the right guidance scenario from a predefined list.

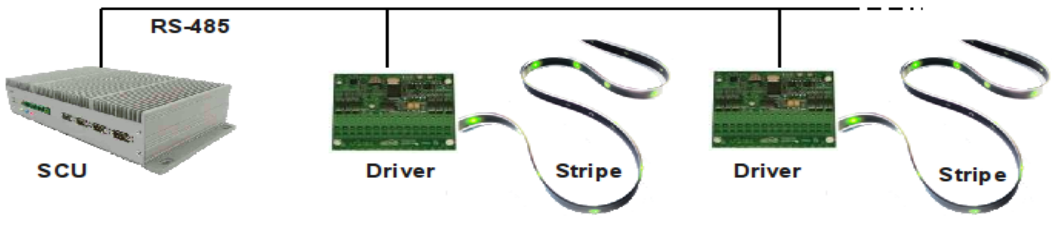

Figure 4: System architecture

The SCU controls the stripe and panel drivers over an RS-485 bus that can contain tens of drivers and span up to one kilometer in length. Depending on the model, each driver can control 1-4 LED stripes or up to 12 chains of symbol or light panels.

4. SOFTWARE AND SYSTEM FUNCTION

The system adjusts and controls, according to the situation, and guides people to safety, and it helps to provide a logical pre-designed plan of action for any human evacuation situation.

The operation of the system is designed and programmed step-by-step with the design and programming tool, starting from the programming of the subsystems, which are the basic structural "building blocks" of the system.

4.1. The Controlling Tool

4.1.1. Intelligent and Automatic Control

The system is normally used as an intelligent system, in which the system receives information from an external control system (for example a fire alarm system), and based on that information directs people to safe exits and away from potentially life-threatening situations. The evacuation is based on predesigned evacuation to avoid human errors in evacuation. The scenarios for different emergency situations are designed based on evacuation and safety know-how from authorities and tunnel safety personnel as well as information of available evacuation routes and exit doors. This is essential information to avoid unnecessary queuing and to use all the existing evacuation capacity in an optimum way.

Traditional emergency guidance systems have tended to focus on fire alone. However, modern emergency planning should also take other kinds of hazards into consideration such as chemical leakage, blackouts, terrorist threats, flooding etc... . Depending on the situation, different kinds of threats might require different kinds of actions.

4.1.2. Manual Control

The entire system can also be controlled manually by the controlling tool software which runs in the system control unit. With the system control unit's controlling tool software the responsible operator selects the main emergency exit routes manually, by activating one of the master guidance templates programmed by the system designer in the design and simulation tool.

4.1.3. Automatic or Manual Control with a Control Box

The system can also be controlled by a control box for a limited number of evacuation scenarios. Operation is automatic or manual by activating one of the predesigned evacuation scenarios.

4.2. The Monitoring Tool

The entire system and each addressed component of the system are monitored by the monitoring tool software. The monitoring tool software can be run on-site, through the Local Access Network of the site or remotely through the Internet. The monitoring tool can be installed and run either on a laptop PC or a desktop PC, as long as the system hardware requirements are met. Each group driver and stripe and panel driver is programmed with an address and component serial number, which makes it possible to plan and program detailed emergency exit routes, and to find defective components with extreme precision and accuracy.

The monitoring tool can be programmed to send a check question to each system component frequently (with an interval of only few seconds). The answer from every component gives information of the component status and guarantees that every single component of the system is ready and functioning if needed. If one component fails and doesn't confirm its status by sending back the answer message, a report will be generated for system responsible personnel for corrective actions. This means in practice that no traditional maintenance or manual system check-up is needed to check the system and component status.

5. REDUNDANCY

The system can also be equipped with a secondary (slave) system and redundancy to ensure the correct functionality in the event that the system malfunctions or is broken. Scenarios to ensure the system operation in following error situations can be created;

- Control signal (= data line) is cut
- Master Group Driver malfunctions
- Master Stripe/Panel Driver malfunctions
- The main supply voltage of the Power Supply Unit with battery backup is cut
- Master Power Supply Unit malfunctions
- Stripe short-circuits
- Stripe is cut

System redundancy can be built to several levels (see **Figure 5.**) for example between two technical rooms, between cabinets and even in the stripe chain between two drivers by connecting stripes at both ends to specific integrated drivers which are dedicated to handle power and data supply to both directions in the chain if one of the stripes in the chain is broken or cut.

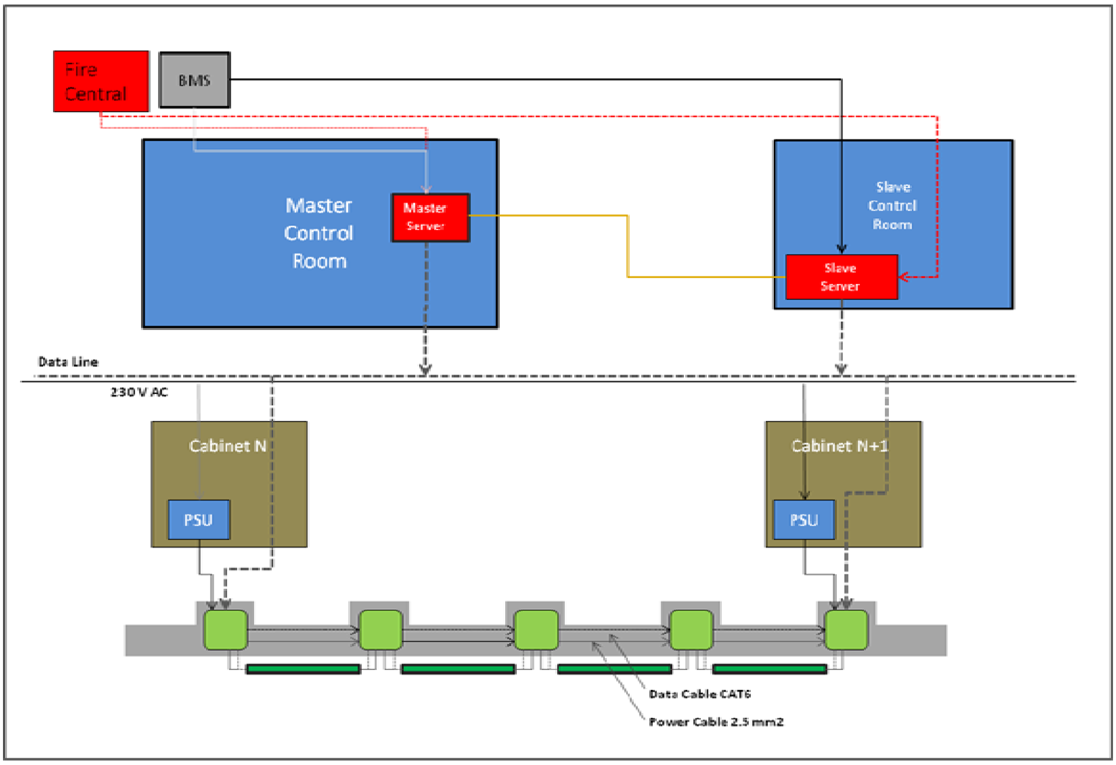

Figure 5: System redundancy

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THE FUTURE OF ROAD GUIDANCE IN TUNNELS

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1. INTRODUCTION

The risk analysis of road tunnels is currently an important topic for university faculties in this field of expertise. Quantitative risk assessments help to determine individual risk characteristics for tunnels. Determining factors are the gravity of an accident as well as the probability of its occurrence. The security risk is calculated using these two factors (Baltzer, 2009).

2. OPTICAL GUIDANCE SYSTEMS

Guidance systems based on LED technology in tunnels play a key role because they are used both as a preventative measure as well as in case of an emergency. Nevertheless, the optical guidance system has not yet been defined as a separate parameter for the risk analysis. Currently the optical guidance system only is defined as one of many parameters reducing the probability of accidents.

Figure 1: Optical guidance systems reduce the risk of accidents among older car drivers

An optical guidance system makes especially older car drivers feel more safely, when driving through a tunnel, and therefore helps to reduce the risk of accidents. Several international studies have shown that the driver much better recognizes the road edge and therefore dangerous "encounters" near the middle lane can be avoided (Bartenbach, 2004). In case of emergency or fire, the guidance system serves as a warning sign that leads the fleeing pedestrians safely and quickly to the nearest emergency exit or tunnel portal. In the Netherlands, this is reinforced by the installation of green LED modules.

Figure 2: The optical guidance system helps to find the nearest exit - Tunnel A2 Utrecht, NL

Optical guidance systems using LED modules have become a standard in the equipment of modern road tunnels. Different national policies require different designs, LED colors, and spacing of the modules (see RABT 2006 for Germany and Austria for RVS 9.282). The following technical functions are in use: on / off, different modes of operation (German RABT), brightness control in up to 8 levels and blinking.

Computer and LED technology are offering many new product ideas. Easily LED modules may become intelligent. These microprocessor-controlled modules offer many new functions! The modules are individually addressed and can be controlled separately. New features are chaser lights, group chaser lights in a certain speed according to the speed limit (km/h) and chaser lights leading to the next or the best emergency exit. New modules can collect additional information and report back to the operation room. This may be a simple status information (module works / does not work) or the signal may contain environmental data such as temperature and traffic information. Intelligent modules will be able to detect a fire, count the number of vehicles, measure the speed of passing vehicles, and more.

3. TECHNICAL DESCRIPTION OF OPTICAL GUIDANCE SYSTEMS

Different requirements for the installation technique in a tunnel have lead to two different systems that are available in the market: the multi-system with a direct cable connection, and the inductive system transferring power through an inductive system of coupler and LED module (Goldbrich, 2009).

3.1. Multi-system

The Swareflex multi-system consists of the following components:

- Multi-controller with power supply of 24 or 48V and 2.5 or 5A
- * Appropriate interface to the operation room
- * Direct connection using a cable or strands 2 x 2,5 mm2
- * Various module designs (Swaroline multi, LeveLite multi).
- * HD-connector IP68

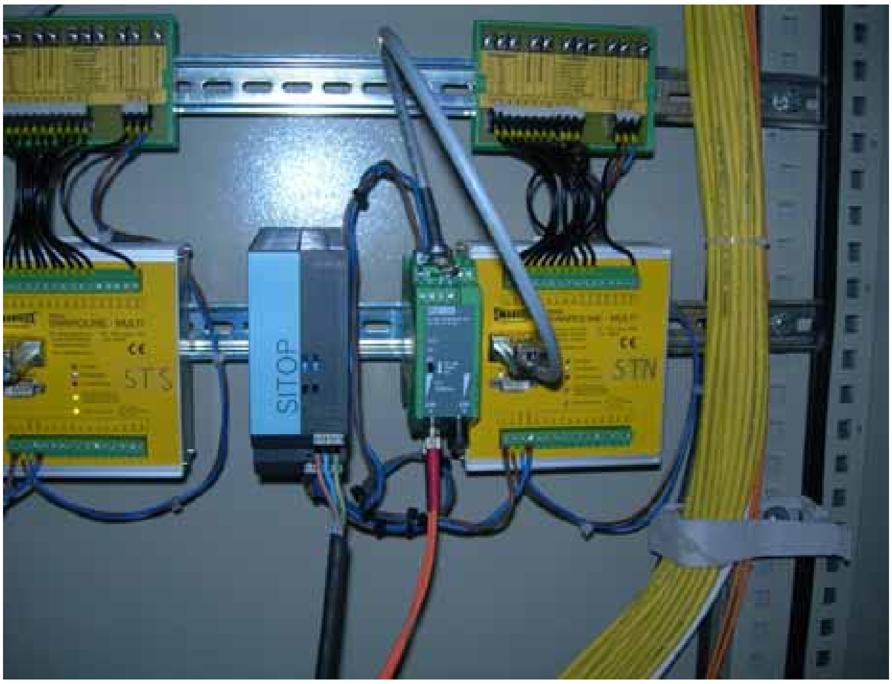

Figure 3: Tunnel Gousselerbierg, Luxermburg, Multi-system

The control unit powers the multi-modules and establishes the interface to the tunnel operation. Information is transmitted in both directions. Energy supply and control signals are sent via a simple cable or strands. The intelligent modules are microprocessor controlled and can send and receive data. Each control unit can drive up to 255 separate modules. The control signals trigger different functions such as different levels of brightness, separate control of both sides of the module, 2 different color conditions (eg: green or red), chaser light, group chaser light and blinking light. The modules can return a variety of signals including various operating conditions and other data like the temperature or the number of vehicles passing.

3.2. Inductive system

The Swareflex inductive system consists of the following components:

- IHP control unit, resonant circuit 38,5 kHz, 5A current and voltage up to 200V
- Appropriate tunnel interface
- Power supply of the modules via induction coupler
- Compensator to maintain the resonant circuit
- System cable 2x6 mm2.

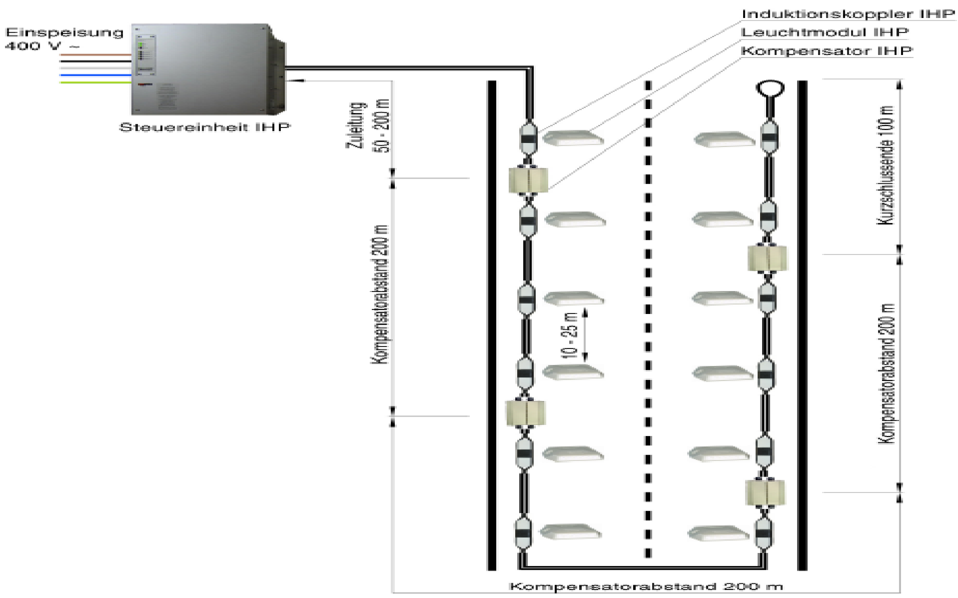

Figure 4: Basic configuration system inductive

The inductive system consists of one or more control units (depending on the length of the tunnel and the location of the power supply), which operate LED modules wirelessly via inductive energy transmission. An induction coupler generates the energy transfer. The modules are best mounted onto or near to the kerbstone. The brightness of the modules is adjustable via the control unit. Daytime and nighttime intensity are triggered by an external signal or by a brightness sensor.

4. INTERNATIONAL TEST PROJECTS

4.1. Chain of tunnels - Packsattel, Styria, Austria

The chain of tunnels is located on the A2 between Graz and Klagenfurt. The section Mooskirchen - Pack covers a length of 32 km at 338 to 1050 m above sea level. The tunnel was at a poor technical standard before the renovation. Since the renovation in 2007 the tunnel chain fulfills the highest standards. The optical guidance system (Swareflex Swaroline IHP) is an important part of the security and the traffic control

Figure 5: Tunnel chain Pack, Styria

The following features have been tested:

- indication of middle lane in conjunction with variable message signs in temporary traffic displacements
- influence average speed via group chaser lights
    - optimal speed
    - speed reduction
- escape route signalization with chaser light indicating the nearest exit

4.2. Tunnel River Elbe - Hamburg, Germany

The city of Hamburg has commissioned a study on optimizing the traffic flow in the Elbe tunnel (Study optimization of traffic flow in the Elbe Tunnel, 1998). Different traffic scenarios were simulated using a special computer program. The effects of flashing lights and chaser lights were tested on the “Companion” system. Here a brief summary:

"The combination of flashing lights and chaser lights have a significant effect on improving the traffic flow. Speed profiles and average travel times show dramatic improvements. The formation and resolution of traffic jams can be effected very positively by optical guidance systems – with the effect of a general reduction of traffic jams. Flashing lights and chaser lights help to more evenly distribute the traffic flow and support the resolution of traffic jams, resulting in a quicker end to jams. The effects of the simulation based on different hypothesis need to be proven in reality.”

"Another advantage of the system is the possibility of warning drivers. On the most sensitive road section in the Elbe tunnel early warnings can be realized over a long road distance.”

4.3. Gousselerbierg Tunnel, Luxembourg

The tunnel Gousselerbierg with 2.695 meters is the second longest tunnel in Luxembourg and is part of the A7. Both tubes are equipped with 2 lanes and a hard shoulder. The official opening of the tunnel was on 24.1.2008.

Figure 6: Tunnel Gousselerbierg, Luxembourg

The optical guidance system was realized using the system multi (Swareflex multi-system) (Osch, 2007).

The following features have been tested:

- group 4 chaser light to influence the average speed
- group 4 chaser light with basic brightness
- modules one side continuous light and flashing light on the other side

5. CONCLUSION

New technical possibilities open a wide field of additional applications for optical guidance systems. Now the same modules can be used to influence the driving speed, to indicate the escape route, to indicate traffic delineations, and other applications. At the moment the lack of guidelines and scientific studies limit the possible application of new technologies. We need to better study possible applications and establish the necessary regulations.

The socio demographics are changing and the population ages – older people driving cars is a fact. Especially for those drivers an optical guidance system can help improving traffic safety.

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FINDINGS FROM FIRE TESTS IN TUNNEL CONSTRUCTIONS WITH VENTILATION SYSTEMS AND FIXED FIRE SUPPRESSION SYSTEMS

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OVERVIEW

The IBS Institute for Technical Fire Protection and Safety Research was able to gather numerous findings during the last years which were obtained in the course of controlling fire tests in tunnel constructions.

It is the aim of the lecture to take a look at the time flow from the start of fire, detection, system activation to the point of the stable state both by the example of ventilation systems and by the example of fixed fire suppression systems (in combination with ventilation systems) and to provide evidence with exemplary measured curves (flow speed, temperature profile, turbidity, etc.). On the basis of these kind of measured curves as well as visual observations (videos) an assessments can be made under consideration of the time course how far the ventilation system and/ or the fixed fire suppression systems are significant for reaching the intended protection goals in underground traffic constructions “self-rescue phase”, “escape exit safety” in the direct fire area and outside of the fire area, “support of the fire fighting operations” and “sustainment of the carrying capacity of the tunnel construction”.

1. INTRODUCTION

Different guidelines for the operation of tunnel constructions, which have partly been declared binding in relevant laws in some countries, control the requirements concerning ventilation systems (for example RVS 09.02.31 in Austria) and partly already at fixed fire suppression systems, as far as they are considered as necessary based on an object-related risk assessment (expert observation of the potential risk depending on the traffic volume).

In the Uptun - Engineering Guidance for Water Based Fire Fighting Systems

for the Protection of Tunnels and Subsurface Facilities (Work Package 2 of the Research Project UPTUN of the European Commission (Revision 08) R251 - August 2007) there are for example very specific minimum requirements for the execution of fixed fire suppression systems.

2. FIRE TESTS

For verification the IBS took charge of the testing for different fire tests and carried out all measurements accompanying. Finally the recorded test results got evaluated and an according test report including the evaluation of the results for the specific fire test series got issued.

2.1. Ventilation systems in case of fire

The general requirements for ventilation systems in case of fire as required in Austria in the relevant RVS guidelines are as follows:

- Longitudinal ventilation with one-way traffic:
  - Set value longitudinal flow velocity : 1,5 -2 m/s
- Longitudinal ventilation with two-way traffic:
  - Set value longitudinal flow velocity: 1,0 -1,5 m/s
  - Jet fans: 250° C over 60 minutes

- Semi-transverse ventilation and transverse ventilation :
  - 120 m³/s suction capacity related to a section of 150 m
  - Max. distance between the suction ports: 110 m,
  - In case of full transverse ventilation: max. 55 m distance between the supply air insertion openings
  - Test for ventilators and flaps: 400° C over 120 minutes

Regarding the smoke removal capability as well as the smoke control of emergency exits the transverse ventilation systems have an advantage compared to the longitudinal ventilation systems. But the smoke layer behaviour even though works very well in general in case of longitudinal ventilation – as far as the specified longitudinal flow velocity is kept -. The aim is a low smoke zone of approx. 2m at ground level. A “smoke-free” layer, as often mentioned in specialized literature, is definitely not given in case of real fire in tunnels. The decisive protection goal in the direct fire area is to enable the Fire Brigade to move forward with the help of breathing apparatus to carry out the extinguishing process and if necessary and still possible rescue injured people.. Furthermore it should at least be possible to keep the smoke development in the area of the nearest emergency lay-bys at a minimum so that an escape for the purpose of the self-rescue concept– under consideration of the allowed limit values (CO, CO2, O2, smoke gas temperature) - stays possible.

2.2. Test results (Extract)

During the last two decades the IBS Institute for Technical Fire Protection and Safety Research was able to gather numerous findings in the field of functional verification of ventilation systems in case of fire. First of all it should be noted that the following mentioned measuring results are exemplary and have been chosen because they represent the typical process (trend) of the measuring results such as temperature, flow velocities in front of and behind the fire area as well as CO values in a very good way.

The following example shows the test results of a standard fire test (RVS) in an approx. 3 kilometre long two-way traffic tunnel with semi-transverse ventilation.

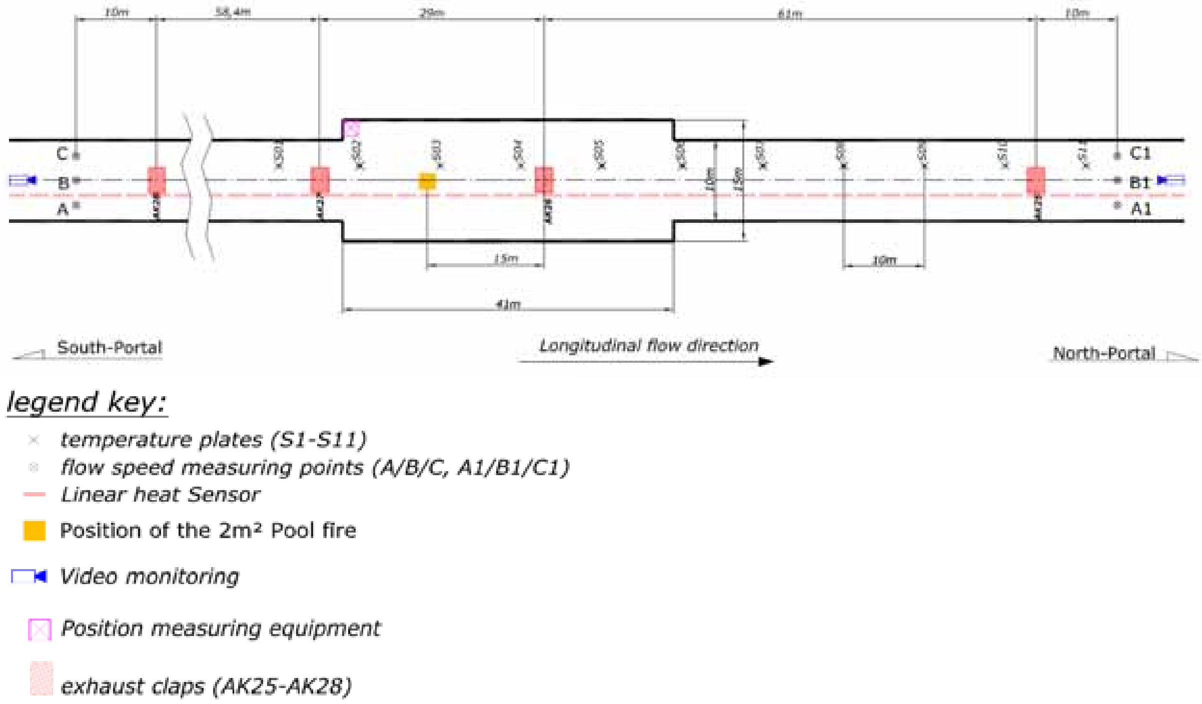

Figure 1: Overview

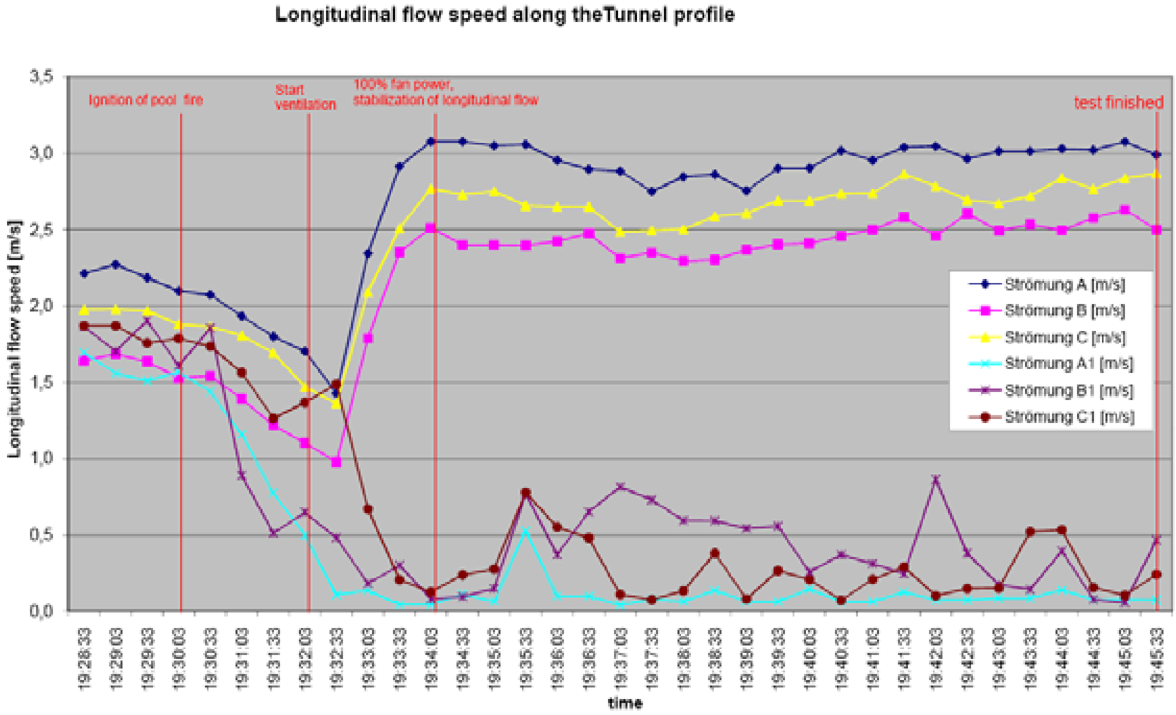

Figure 2: Flow profile

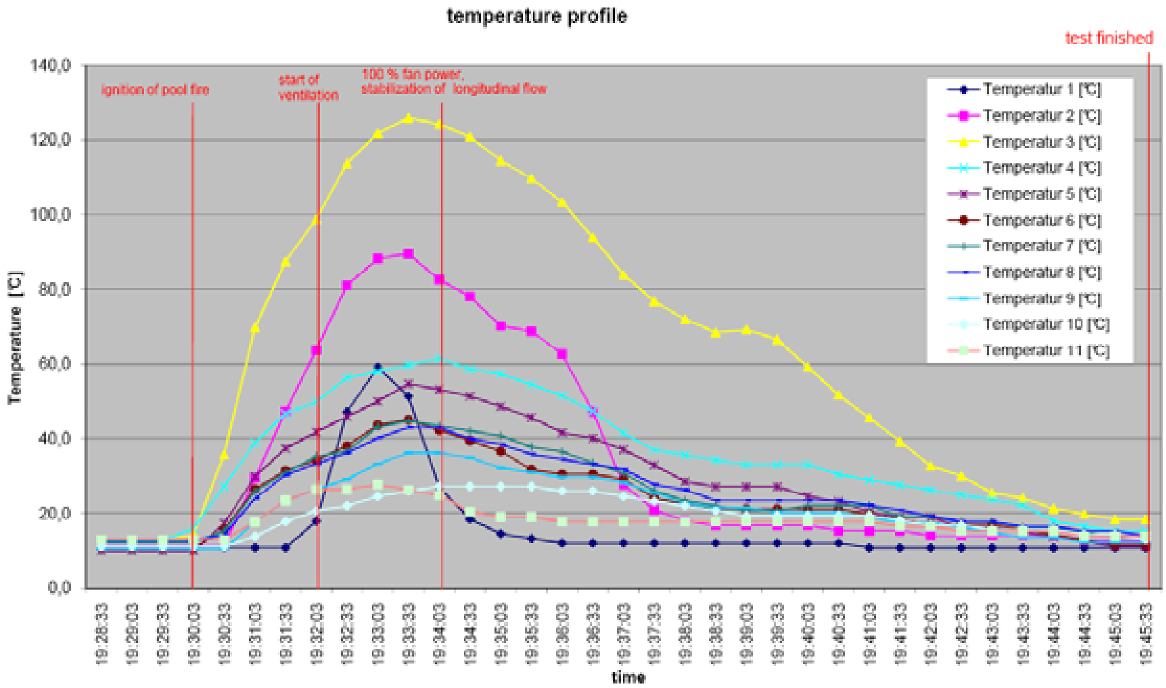

Figure 3: Temperature profile

Summary:

Because the „worst case“ situation for starting the ventilation system into the fire smoke suction operation during low traffic is given the following adjustment for ignition of the pool fires has been chosen. This adjustment has the following parameters:

- Ventilators turned off
- Partition flap (vertical flap) closed
- Flap 24-29 approx. 50 % open

The natural longitudinal flow direction in north direction was amounting to approx. 2 m/s. Approx. 1 minute and 30 seconds have been defined as pre-burning time because as known from according approval tests the alarm starts during this time in case of an open fire in all stationary linear heat detector systems in tunnel constructions. Directly after entry of the alarm signal which is normally transmitted to the tunnel control- and monitoring system redundant –on the one hand by means of the serial interface of the heat detector controller, on the other hand by means potential-free contacts- the defined fire program starts (traffic light, emergency lighting activation, etc.) - and among other things the ventilation program sequence “case of fire” starts.

In the specific case of semi-transverse ventilation the wind direction dependent ventilator north starts up 100% and the 3 suction flaps which are assigned to the fire area open up 100%. This start-up procedure (ventilators are normally started over frequency converters) takes about 2 minutes. Only at this point the ventilation system starts to activate – regardless of the previously activated operating program -. Until then – depending on the prevailing longitudinal flow velocity – an uncontrolled smoke propagation is expected.

Approx. 1 minute later the aimed start-up of the ventilation sections causes the stop of the longitudinal flow to => 0 m/s, whereby it is achieved that from this point the smoke which is produced by the source of fire can be controllably discharged over the ventilation section of approx. 130 m. Again 1 minute later the aimed smoke layer (at the top smoke layer, at the bottom low-smoke zone) is visually obvious. From this point it at least enables the Fire Brigade to move forward with appropriate protective equipment. The maximum smoke temperatures – measured along the ceiling within the suction zone – at that time already move < 60° C.

2.3. Fixed fire suppression systems

The IBS Institute for Technical Fire Protection and Safety Research was already able to gather findings at the end of the 90’s which were obtained in the course of a fire test series with real burning tests in tunnel constructions in combination with fixed fire suppression systems.

On the basis of the previously run research project EUREKA EU 499: FIRETUNE the following minimum requirements were made for these fixed fire suppression systems regarding the protection goal of these systems:

- < 350° C in a distance of 5 meters within 120 seconds
- < 250° C in a distance of 5 meters within 5 minutes
- < 50° C in a distance of 20 meters within 120 seconds
- Prevention of a flashover to neighbouring, combustible materials in a distance of 5 meters to the fire
- Protection of the tunnel construction (< 100° C , 10 mm within the concrete layer)

Many further test series during the last years confirmed the previously used system design which conceptually has stayed the same to date and which meanwhile has basically been recorded in the Uptun Engineering Guidance for all producers.

Recent test series of the Dutch Ministry of Transport (RWS Rijkswaterstaat) in collaboration with the production and installer company Aquasys and the Norwegian test institute SINTEF showed once again the efficiency of these fixed fire suppression systems both for solid and liquid fires. The diagrams and definitions are partly taken from the report with the title „Re-Scale of Aquasys Water Fire Suppression in Runehamer Test Tunnel, No.: NBL F08113, SINTEF NBL as" dated 22nd June 2008 and have been released for presentation both by the RWS Rijkswaterstaat and the Aquasys Technik GmbH.

2.3.1. Solid fires

Enclosed an extract of the measuring results from a test series with an approx. 100 MW fire, which has been reached by ignition of a stack of 180 wooden pallets.

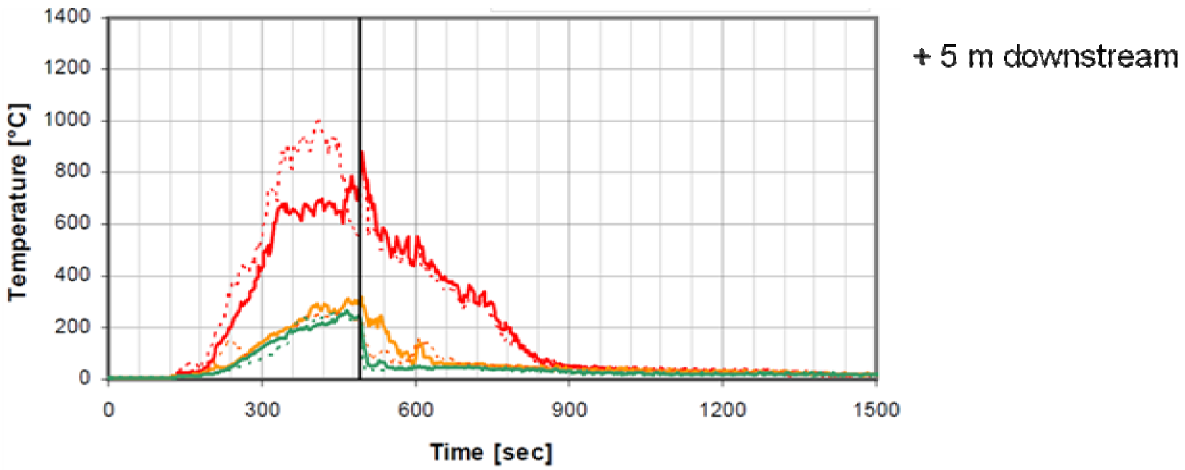

Figure 4: Temperature Profile, 180 wooden pallets

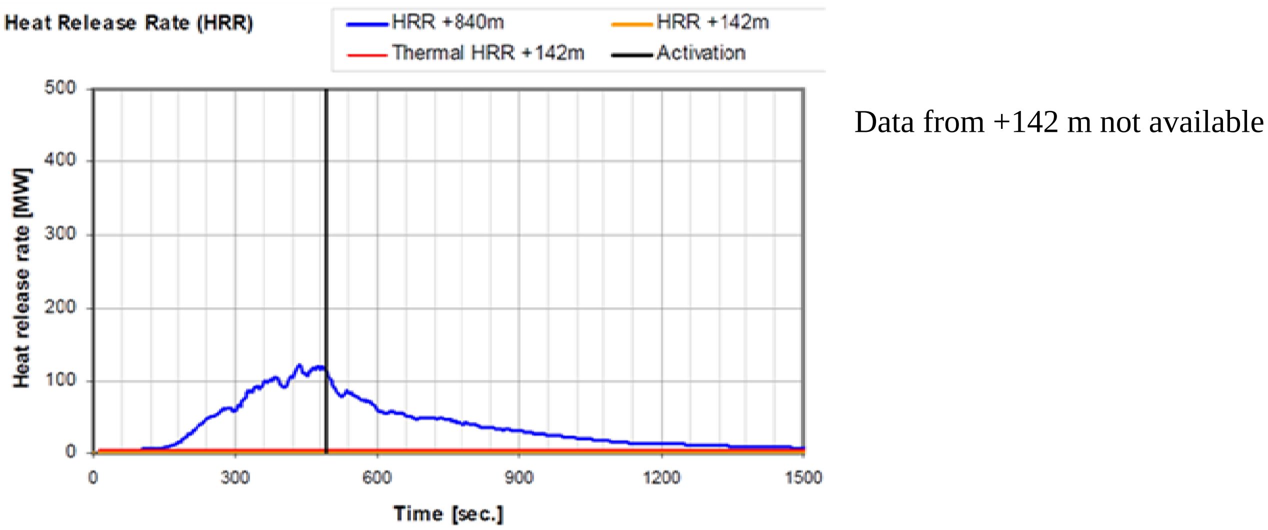

Figure 5: HRR course, 180 wooden pallets

At a pre-burning time of 8 minutes the fire develops to a total fire which causes a heat release rate of approx. 100 MW. From this point the fixed fire suppression system (high-pressure water mist) is activated. After approx. 5 minutes activity of the system the temperatures already start to move under 200° C at all measuring points in a distance of 5 meter to the fire. The heat release rate can now be reduced to 30-50 MW again.

2.3.1. Liquid fires

The above mentioned protection goal definition, which has been defined in the late 90s, has been concretized especially for liquid fires in the course of this test series 2007 in the Runehamer test tunnel and is defined as follows:

The requirements are:

- The water mist system shall control the solid design fire scenario and achieve following conditions in maximum 1 minute after activation:
  - in a distance of 30 m upstream of the fire (upstream end), the heat flux shall be not larger than 3 kW/m², at a maximum ambient temperature of 50 ºC;
  - in a distance of 20 m upstream of the fire (upstream end), the heat flux shall be not larger than 5 kW/m², at a maximum ambient temperature of 50 ºC;
  - in a distance of minimum 5 m downstream the fire (downstream end), the heat flux shall be not larger than 12.5 kW/m², at a maximum ambient temperature of 280 ºC.
- The water mist system shall control the fire for at least 49 minutes after the fire reduction of the first minute.
- The water mist system shall extinguish the liquid design fire scenario within 1 minute upon activation.

Enclosed an extract of the measuring results from a test series with an approx. 250 MW fire, which has been reached by ignition of a 100 m² diesel pool fire.

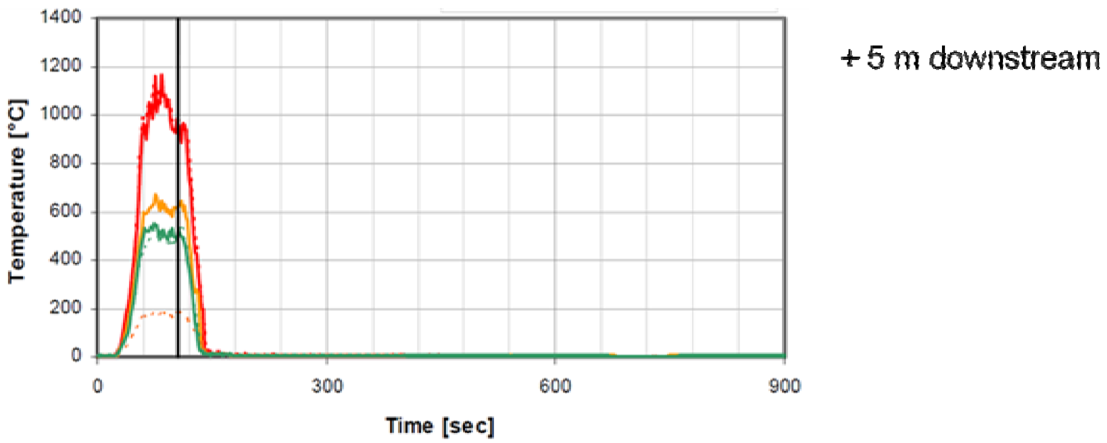

Figure 6: Temperature Profile, 100 m² diesel pool fire, +5 m downstream

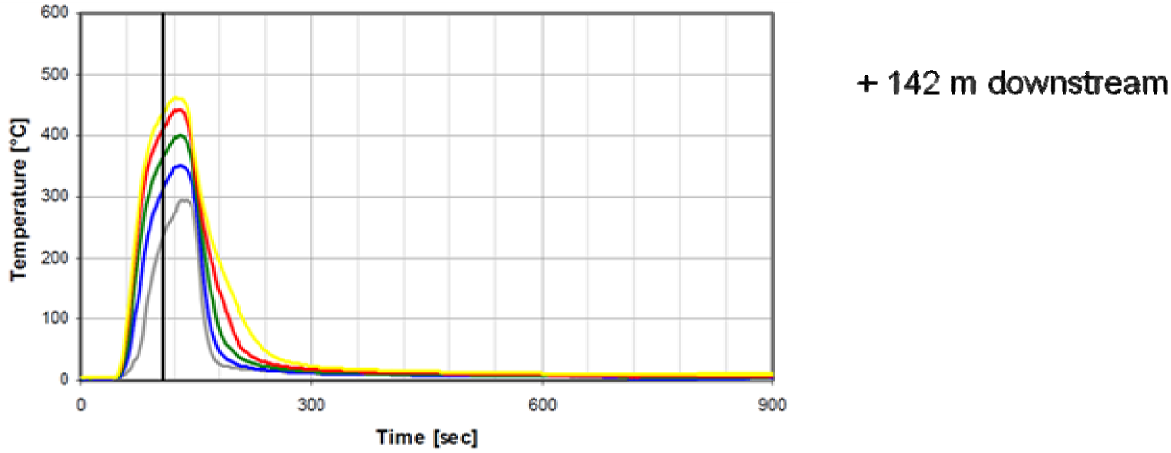

Figure 7: Temperature Profile, 100 m² diesel pool fire, +142 m downstream

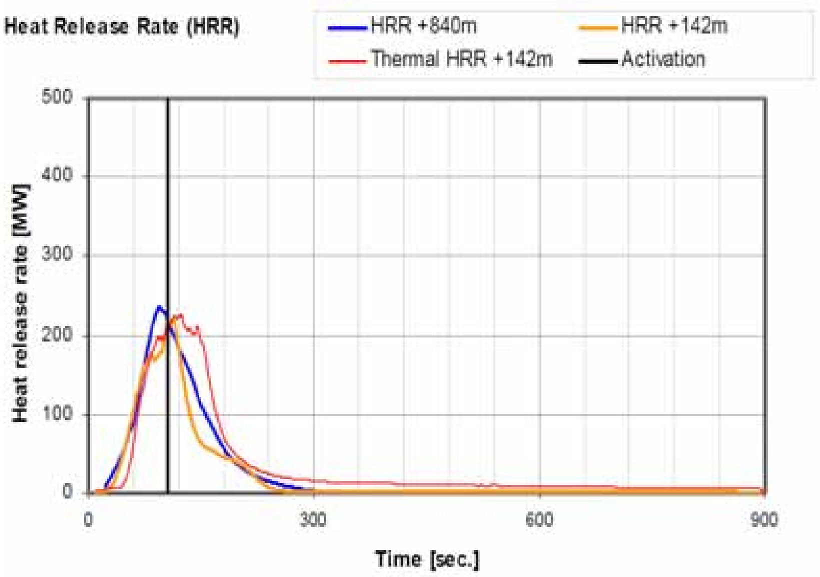

Figure 8: HRR course, 100 m² diesel pool fire

The ignition of the 100 m² diesel pool fire already caused a ceiling temperature of approx. 1200° C and a heat release rate of approx. 250 MW after approx. 2 minutes. This „worst case“ scenario can be controlled through the fixed fire suppression system within a very short time and the extinguishing success starts within 1 minute after activation of the system.

3. CONCLUSION

The following table summarized what can be derived from the test findings and which protection goals with which system types resp. their combinations can be sustained.

	Ventilation system		Fire fighting system	Ventilation + Fire fighting system
	< 30 MW	> 30 MW		
self rescue phase / escape exit safety ± 150 m distance to fire				
until minute 5 after start of fire 1)	no	no	no	no
after minute 5	yes	no	no	yes
escape exit safety outside the immediate fire area				
until minute 5 after start of fire	no	no	no	no
after minute 5	yes	no	conditionally (upstream)	yes
support of the fire brigade & fire fighting operations				
until minute 5 after start of fire	no	no	no	no
after minute 5	yes	no	conditionally (upstream)	yes
sustainment of the carrying capacity of the tunnel construction	yes	no	yes	yes

1) *The in the table mentioned 5 minutes are only orienting values. Thereby the incipient fire phase until the earliest possible effect of a technical devise under consideration of the fire detection and system run time of the single system components, until the complete system (for example the ventilation system) is 100% available, is supposed to be demonstrated. Object-specifically this can also take 7 or 10 minutes. The quoted absolute value is therefore not decisive for the assessment.*

SAFETY MANAGEMENT FOR AUSTRIAN RAILWAY TUNNELS

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ABSTRACT

The Austrian Federal Railways (ÖBB) are currently operating 293 tunnels, and the number of tunnels is expected to rise considerably, as the number of construction projects is anticipated to increase in years to come.

Including the future tunnel user (operator) into the design process, setting up uniform emergency response regulations and organizing the co-operation between the railway company and rescue services constitute key components in the safety management for railway tunnels.
With respect to regulations, a special focus is put on initial operational emergency response measures, self-rescue procedures and emergency management regulations.

Keywords: safety, railway tunnel

1. INTRODUCTION

In Austria, the Alps, which form the largest mountain range in Europe, have always played a dominant role. As early as 1884, the Arlberg tunnel, the first major railway tunnel, was opened to the public. Subsequently, additional large-scale tunnel projects followed on the Austrian rail network, including the Tauern, the Karawanken and the Bosruck tunnel.

Whilst the number of tunnels forming part of the Austrian rail network has remained more or less stable for a long time, it is now – mainly due to line improvement projects and new high-speed line projects – increasing substantially, with growth rates comparable to those of the construction boom at the end of the 19th century. In fact, the percentage of tunnels in the ÖBB's tunnel network is expected to triple up to the year 2025 (see Figure 1).

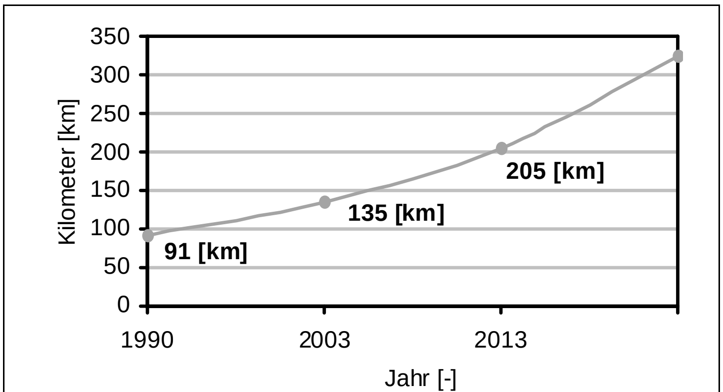


Figure 1: Development of the total length of all railway tunnels in the ÖBB network

In total the Austrian Federal Railways (ÖBB) are presently operating 293 tunnels, 29 of which are longer than 1,000 m. The longest tunnel so far, the almost 13-km-long Inntaltunnel, will not remain the only tunnel of such length. The Wienerwaldtunnel, the Lainzertunnel, the Unterinntaltunnel will be completed in 2012, the Koralmtunnel (approx. 33 km in length) is currently under construction and projects like the Brenner Basistunnel (approx. 55 km) and the Semmering Basistunnel are currently under design.

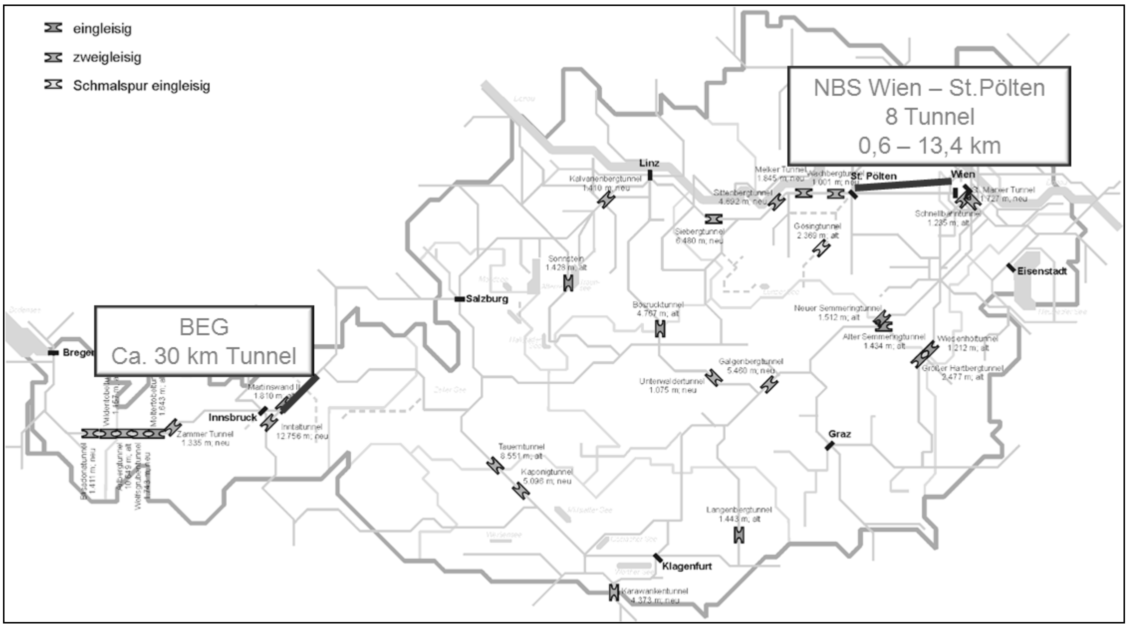


Figure 2: Existing tunnels with a length exceeding 1 km and new tunnels to be taken into operation

In order to maintain a very high safety level for all tunnels in Austria, standardised safety management documents and procedures are imperative, in both the design phase and the operating phase.

2. SAFETY PLANNING DURING THE DESIGN, COMMISSIONING AND OPERATING PHASE

The planning of the required safety measures is continuously developed in the individual phases of a tunnel project and is gradually elaborated in more detail as the design of the project progresses.

When developing safety concepts for railway tunnels in Austria, the following parties tend to be involved:

- Tunnel owner (represented by the project management)
- Engineering departments of tunnel owner
- Designers of safety concepts as well as other expert designers
- Reviewers and experts involved in the permitting procedure
- Future technical operators of railway tunnel systems
- Future user of the railway infrastructure, including railway tunnel systems. [1]

[1] This organisation is in Austria not identical with the operator of railway tunnel systems.

The concepts are continuously co-ordinated with the fire brigades and other emergency response organisations – if required.

The owner of the tunnel is responsible for designing and constructing a tunnel, the safety equipment of which will have to meet state-of-the-art standards. The operator is responsible for providing a reliable tunnel system (inspection, maintenance and repair). And the user is responsible for

- implementing the tunnel safety concepts
- preparing the necessary codes dealing with organisational and operational issues
- organising the deployment of skilled staff members
- coordinating the cooperation with rescue services
- considering experiences made during tunnel operation
- considering insights gained during incident management
- reviewing and updating existing concepts

For decisions to be made on structural safety measures and safety equipment requirements in tunnels, reference is made to the respective guidelines and regulations. Reference documents used for tunnel-specific issues include the following guidelines and regulations:

- Technical specification of interoperability (TSI) relating to ”safety in railway tunnels“
- Occupational safety and health regulations for railway personnel (EisbAV)
- Guidelines for the design of HIGH-SPEED railway systems
- Guideline ”Construction and Operation of New Railway Tunnels on Main and Branch Lines; Demands Made on Fire Protection and Emergency Management“; issued by the Austrian Fire Fighters Association

By involving the user in the design process, it is possible to incorporate both, experiences made under “normal” operating conditions as well as those made under incident management conditions. This approach also allows the future operator to secure any personnel and material resources required in due time and to make them available for operation start-up and operation.

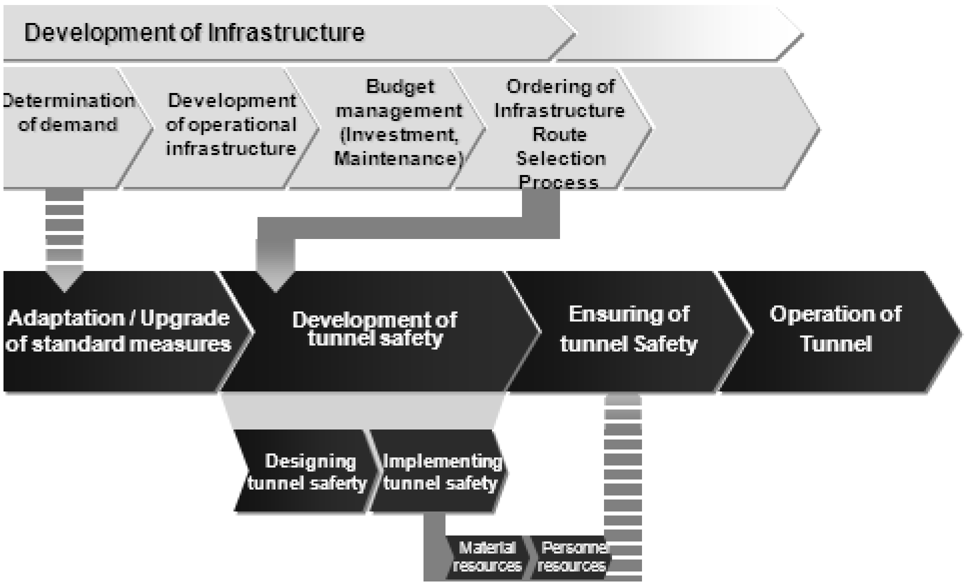


Figure 3: Involvement of tunnel user in development of safety concepts (example)

As is evident from Figure 3, the user is involved in the development of the safety concept at a very early stage of the project.

During the permit application procedure in compliance with railway law, the safety concept is reviewed and approved by the relevant authority.

During the operating phase, possible retrofitting needs in response to the development of new safety standards or the enactment of new laws are identified and implemented by the ÖBB management, considering various aspects.

In the year 2009, owner, operators and user were brought together, setting up the ÖBB-Infrastruktur AG.

3. EMERGENCY RESPONSE AND SAFETY DOCUMENTS

Essential instruments of safety management are the elaboration of emergency response regulations as well as a consistent and comprehensive documentation of the safety equipment available in the individual tunnels. Any further development of regulations is efficiently communicated and implemented by staging training sessions and information workshops for staff members.

3.1. Initial emergency response measures

If a fire is detected on a train running through a tunnel, the prime objective consists in moving all trains – and especially the emergency train – out of the tunnel.

Should there be signs indicating that a train has derailed, the initial response measure – in analogy to a train derailment on an open track section – is to bring the incident train as well as all trains approaching the incident scene to a halt as quickly as possible.

These instructions are laid down in the regulations and are to be implemented by the operating personnel. The regulations apply to all trains serving the ÖBB network.

If a fire occurs, other trains shall be prevented from entering the tunnel. All trains travelling through a tunnel at the same time as the incident train, should leave the tunnel if possible, without endangering any person leaving the incident train in a self-rescue effort.

These procedures are initiated and monitored by the train controller in the train operations centre.

Figure 4: Train controller at train operations centre

3.2. “Self Rescue” Procedure

Every safety concept developed for current tunnel projects is based on the principle that the predominant emergency response will be a self-rescue effort of passengers assisted by train personnel. In the “Self-Rescue” regulation ZSB 24 (amendments to signalling and operating regulations) of the Austrian Federal Railways (ÖBB), this principle is uniformly defined for the entire Austrian network. This regulation contains instructions for the train staff supporting passengers in a self-rescue situation.

Figure 5 presents the key principles of this regulation.

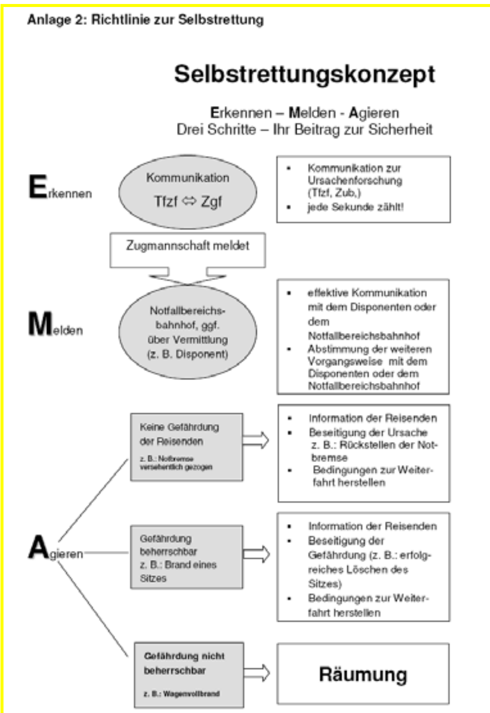


Figure 5: Self-Rescue Procedure

A crucial criterion in this process is the actual decision to conduct a self-rescue effort. This decision is either made by the train crew or by the train driver. The train operations centre, which is responsible for the respective emergency area, should be informed prior to any evacuation operations, to allow them to take the necessary protective measures (e.g. prevention of potentially dangerous train traffic).

3.3. Emergency response management by the ÖBB-Infrastruktur AG

The emergency response manual ZSB 26 provides instructions regarding such issues as areas of responsibility (e.g. incident commander), systematic implementation of measures following the occurrence of an incident (search for causes, continued professional training, technical measures) as well as frequencies and contents of emergency drills. These instructions shall be applicable to the entire railway line network including the tunnels. The manual furthermore contains check lists, layout drawings, and alarm plans, which serve as templates for emergency folders, which are adapted to the conditions prevailing at the respective railway line and tunnel structures.

Notfallbereich	INFRA.netzbetrieb	ÖBB Infrastruktur Betrieb
	Ereignis-Checkliste (ECL)	

Meldung Nr:		Datum:	Zeit:
Fdl:		Fahrt (Zugnummer):	
in (zwischen):			
Gleis:	Weiche:	Signal:	km:

Vorfall:

☐ Verletzte ☐ Tote
☐ Brand
☐ RID-Gut (Artisabfrage, Frachtbrief, Feststellung vor Ort, OK)

Gefahrnummer
UN-Nummer

1. SCHÜTZEN

- Haltstellen von Signalen ☐
- Nothalt über Zugfunk (DISPOLINIE 88) ☐
- Verständigung der angrenzenden Betriebsstelle (Rotte...) ☐
- Oberleitung NOT-AUS bzw. Gefahrenabschaltung Basa 7760 ☐
- Evakuierung bzw. Absperrung bei Feuer / Gefahrgut / Bombendrohung veranlassen (Selbstschutz!). Fahrt nicht im Tunnel anhalten! ☐

2. HELFEN, HILFE ANFORDERN

!Hinweis auf gesondert notwendige Zustimmung zum Betreten nicht allgemein benutzbarer Bahnanlagen!

Verständigung/ Zuständigkeitsbereiche	Von km Bis km	Von km Bis km	Von km Bis km	Von km Bis km	Zeit:
Rettung / Notarzt (0)144					
Feuerwehr (0)122					
Polizei (0)133					

3. BETRIEBLICHE MASSNAHMEN SETZEN

- Gleise sperren / Keine Fahrten ☐
- Freischalten der Oberleitung ☐
- Erdung sicherstellen ☐
- Selbststellbetrieb ausschalten ☐
- Hilfssperren, Zielsperren, Befahrbarkeitssperren bzw. Hinweisschilder setzen ☐

✦ *Fahrstraßenprüfung / fmdl Rückmelden / Freiprüfung (AS, DS, BS) ???*
✦ *gegebenenfalls Störleitfaden/Störcheckliste verwenden!*

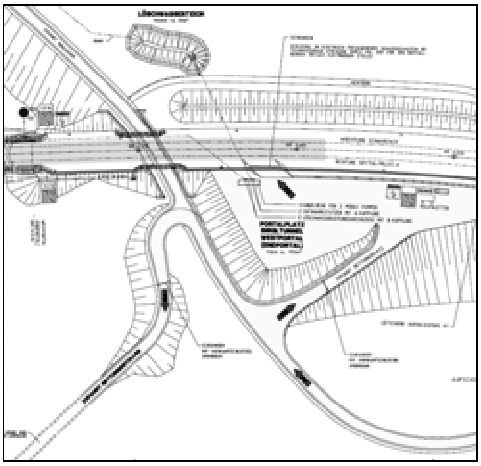
4. VERSTÄNDIGEN

	Rufnummer	Zeit
FDL-Notfallkoordinator Anforderung Hilfszug, Mungos (Absperrungen, Evakuierung), EL	7777	
Dispo/Zuglenker		
Betriebsmanager		
INFRA.service über ZSM bzw. ESDIS		
Verständigung Kriseninterventionsteam über Rotes Kreuz		

Figure 6: Incident check list and meeting point of emergency service coordinators

3.4. Tunnel safety documentation

The tunnel safety documentation concisely describes the tunnel structure and the safety equipment. It furthermore specifies operational and organisational measures, which go beyond the general ÖBB regulations. The tunnel safety documentation is available at the respective train operations centre. The corresponding drawings highlight all installations and structures which are of relevance for the safety of the tunnel.



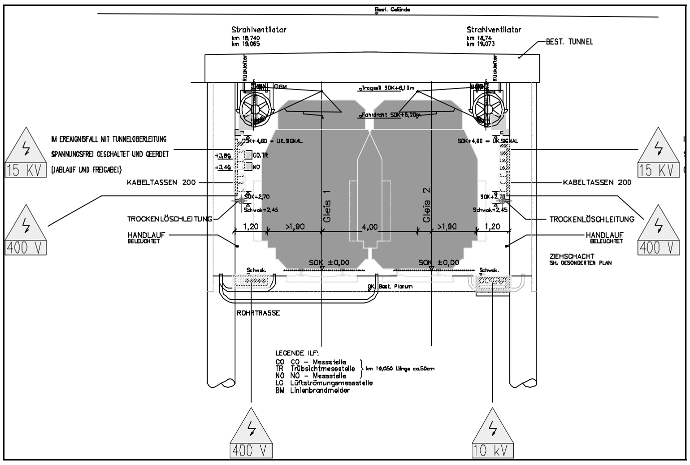


Figure 7: Drawings showing tunnel safety features

4. COORDINATION AND SUPPORTING DOCUMENTS FOR FIRE BRIGADES

In a joint effort of the Austrian Fire Fighters Association and the Austrian Federal Railways, the manual “Fire-fighting Operations in Track Areas” was developed, which combines the safety interests of the Provincial Fire Fighters Associations and the Austrian Federal Railways in one document. This document which describes the fire-fighting services in track areas from a safe operations perspective, allows these services to be regulated all over Austria. This manual not only lists possible dangers encountered during operations at railway infrastructure sites, but also offers a number of valuable tips to protect the fire-fighting teams.

In a new edition of this manual issued in 2009, the topic of “rescue services in tunnels” was added to the existing information. The complexity of tunnel structures and the interaction with technical installations and organisational procedures call for rescue operations to be performed in a highly structured way. Check lists shall support the rescue organisations as well as the ÖBB staff members, by increasing their confidence to take the right actions and ultimately by contributing to improving the safety of the rescue teams.

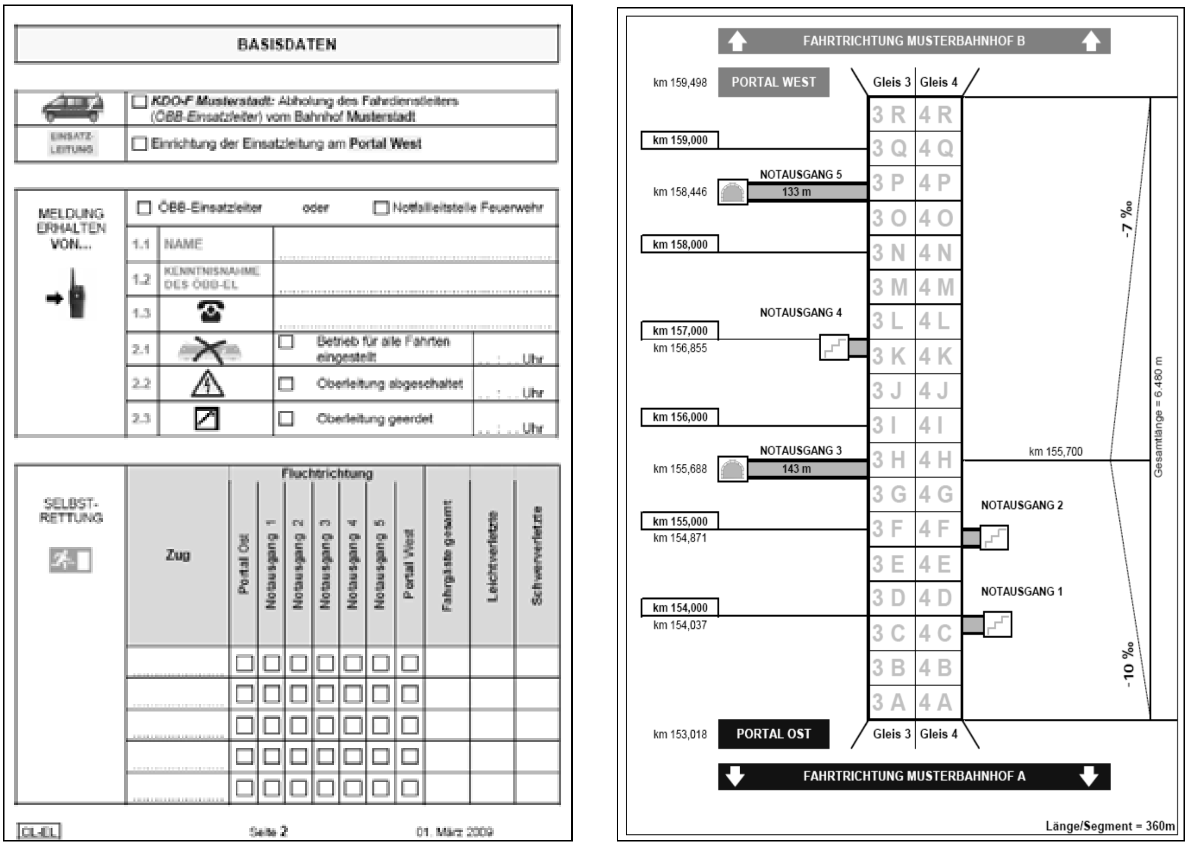


Figure 8: Check list for the fire service coordinator (excerpt)

MINIMUM FLOW VELOCITY THROUGH OPEN CROSS PASSAGES IN TWIN BORE RAIL TUNNELS

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ABSTRACT

An important basis for the design of a tunnel ventilation system in twin bore rail tunnels is the minimum flow velocity through open cross passages which prevents smoke from propagating into the safe opposite tube. 3D-CFD fire simulations were carried out to analyze the relationship between the minimum flow velocity in a cross passage and the longitudinal flow velocity in the tunnel. The results show that for a 28 MW fire longitudinal flow velocities of approximately 2.0 m/s require the highest flow velocities through open cross passages. Lower cross passage flow velocities are sufficient for low longitudinal flow velocities because of the smoke layering, and for high longitudinal flow velocities because of the greater dilution and cooling of the fire gases.

Keywords: ventilation design, critical velocity, incident ventilation

1. INTRODUCTION

In twin bore rail tunnel systems, which are connected with cross passages, the opposite tube serves as a safe area. In case of fire, smoke must be prevented from propagating through the cross passage(s) into the safe tube by the tunnel ventilation. Usually this is ensured by creating a pressure difference between the tubes in order to generate an air flow from the safe tube towards the incident tube during the passengers escape.

For the design of a tunnel ventilation system a minimum flow velocity through open cross passages has to be defined. The choice of an adequate value is not trivial. A low flow velocity increases the risk of smoke propagation into the safe opposite tube. If the chosen flow velocity is too conservative, a high amount of air and therefore a high power requirement results. In addition to this, for some ventilation systems (e.g. point extraction from the incident tube) high longitudinal flows, which can affect a possible smoke layering, can result.

In literature different values for minimum flow velocities for emergency exit doors can be found, but none take into account the special geometric conditions of cross passages with two separate doors.

On behalf of the Austrian Railway (ÖBB-Infrastruktur AG) 3D-CFD fire simulations were carried out to optimize the design of emergency ventilation systems. Various scenarios were considered for a typical cross section geometry with differing longitudinal flow velocities in the incident tunnel, two different heat release rates and with/without a train in front of the cross passage.

2. MINIMUM FLOW VELOCITY

The minimum flow velocity is defined as averaged minimum flow velocity through the emergency exit door necessary to prevent smoke penetration into the opposite tube (and not into the cross passage itself).

Different values for the minimum flow velocity through emergency exit doors were found in literature. The value 1.0 m/s is for example recommended for the ventilation design of road tunnels [ASTRA, 2008]. The value 2.0 m/s is recommended for pressure ventilation design for buildings [TRVB, 2004]. In both cases only one emergency exit door separates the location of the fire from the safe area.

For Austrian rail tunnels there is no guideline that states a minimum flow velocity through open cross passages. In other rail tunnel projects (e.g. AlpTransit or Brenner Base Tunnel) a flow velocity of 2.0 m/s is used as design criteria (for a 20 MW fire). This value is based on a theoretical one-dimensional approach that is derived from the calculation of the critical velocity that prevents backlayering in the incident tube [Tarada, 2000]. In this simplified approach it is assumed that the smoke is fully mixed (no stratification) and that the fire is situated exactly in front of the cross passage. This theoretical model predicts the highest cross passage flow velocity when there is no longitudinal flow in the incident tunnel. On increasing the longitudinal flow, the temperature in the tunnel decreases due to the greater dilution and cooling of the fire gases and so a lower flow velocity through the cross passage is required.

In all listed cases the three dimensional nature of the typical cross passage geometry (lower height of the cross passage than of the tunnel, two emergency exit doors in the cross passage) and also possible smoke stratification is not considered.

3. CFD SIMULATIONS

3.1. Model details

The simulations were carried out with a 3D-CFD simulation program [STAR, 2009]. The model includes one segment of the incident and one segment of the opposite tunnel (with a cross-section of approx. 44 m^2) as well as the connective 40 m long cross passage. The cross passage is equipped with two emergency exit doors with a free cross-sectional area of 4.4 m^2 (see **Figure 1**).

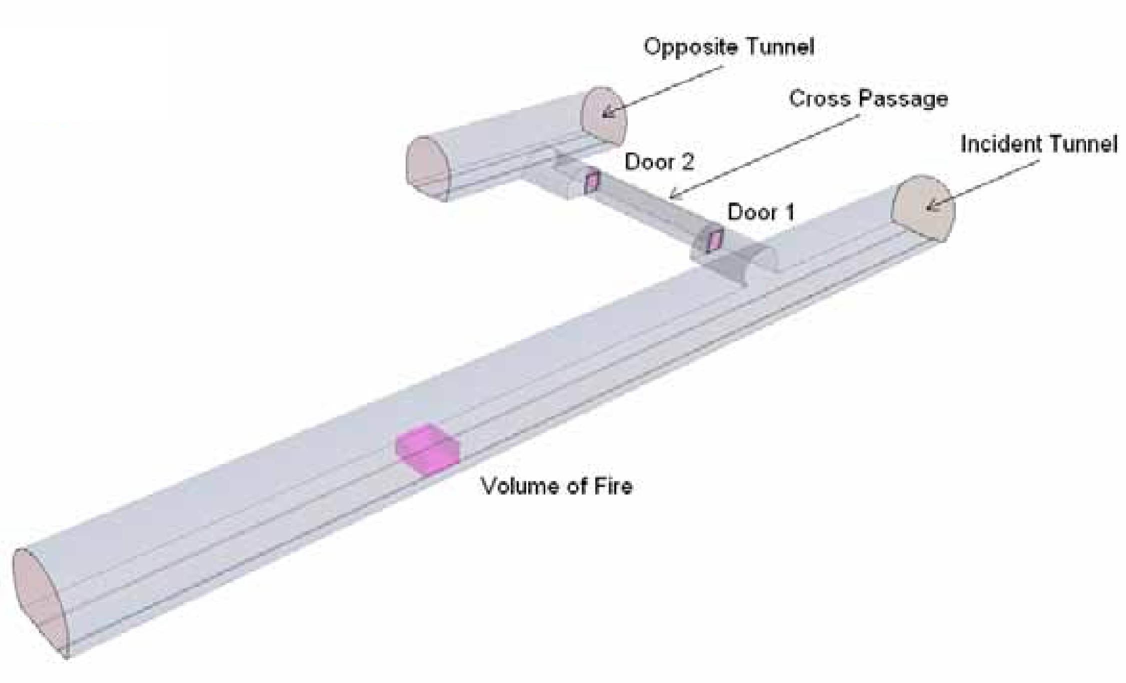

Figure 1: Simulation model

At the boundaries of the opposite tube ① and ② as well as at boundary ③ of the incident tube an inlet flow velocity is specified (**Figure 2**). The downstream boundary of the incident tube ④ is modelled as pressure outlet. The fire in the incident tube ⑤ is a volumetric energy and passive scalar source. For the heat release rate of 28 MW a volume of 32 m^3 was chosen in order to limit the maximum temperature at the fire source.

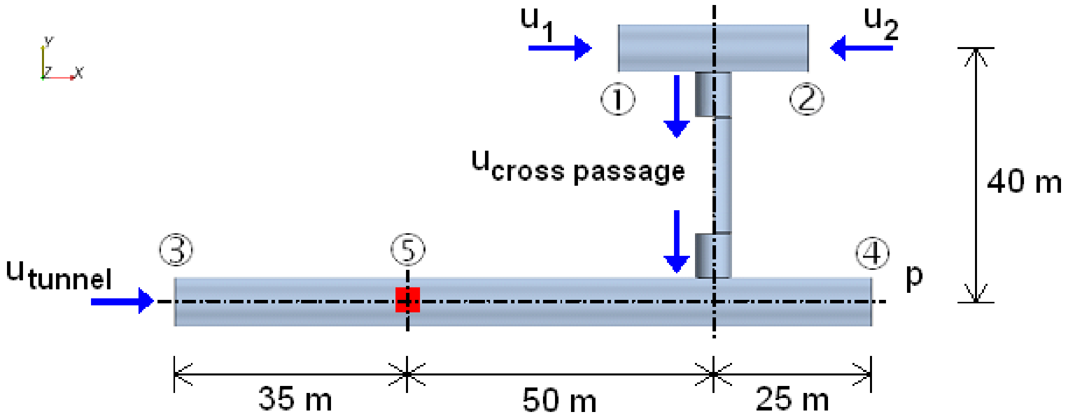

Figure 2: Boundary conditions, and position of the fire source

In the simulations different longitudinal flow velocities u_{tunnel} were combined with different flow velocities through the cross passage $u_{cross\ passage}$.

In a first phase the simulations were carried out with a heat release rate of 28 MW and without a train in front of the cross passage. In a second phase the scenarios included a standing train in front of the cross passage, and also a lower heat release rate (8 MW).

3.2. Evaluation

In all simulations the temperature and the smoke extinction coefficient distribution, as well as the flow velocities in the incident tube and in the cross passage were analyzed. The evaluation of the minimum flow velocity is based on the results of the airflows only (see Chapter 3.3.2). The temperature distributions shown in Chapter 3.3.1 allow a better understanding and give additional information. Evaluation of the simulations is shown in **Table 1**.

Table 1: Evaluation criteria for the simulations

Evaluation criteria for the simulations	**symbol**	**flow velocity through door 1**	**flow velocity through door 2**
No smoke entry into cross passage		positive	positive
Limit case of smoke entry into the cross passage		threshold	positive
Smoke entry into the cross passage but no smoky entry into the opposite tube		negative	positive
Limit case of smoke entry into the opposite tube		negative	threshold
Smoke entry into the opposite tube		negative	negative

Beside cases with a clearly positive flow velocity, or a clearly visible negative flow velocity (always in the upper part of the door), situations were observed whereby only marginal flow velocities at the upper frame of the door are visible. These small volumes of back-flow can be explained by pockets of local turbulence which don't transport smoke into the cross passage or opposite tunnel.

3.3. Results

3.3.1. Temperatures

All results in this chapter are based on simulations with a heat release rate of 28 MW and without a train in front of the cross passage. In **Figure 3** the temperatures in the incident tube and in the cross passage are shown for a flow velocity of 1.0 m/s in the cross passage and for three different longitudinal flow velocities in the incident tube.

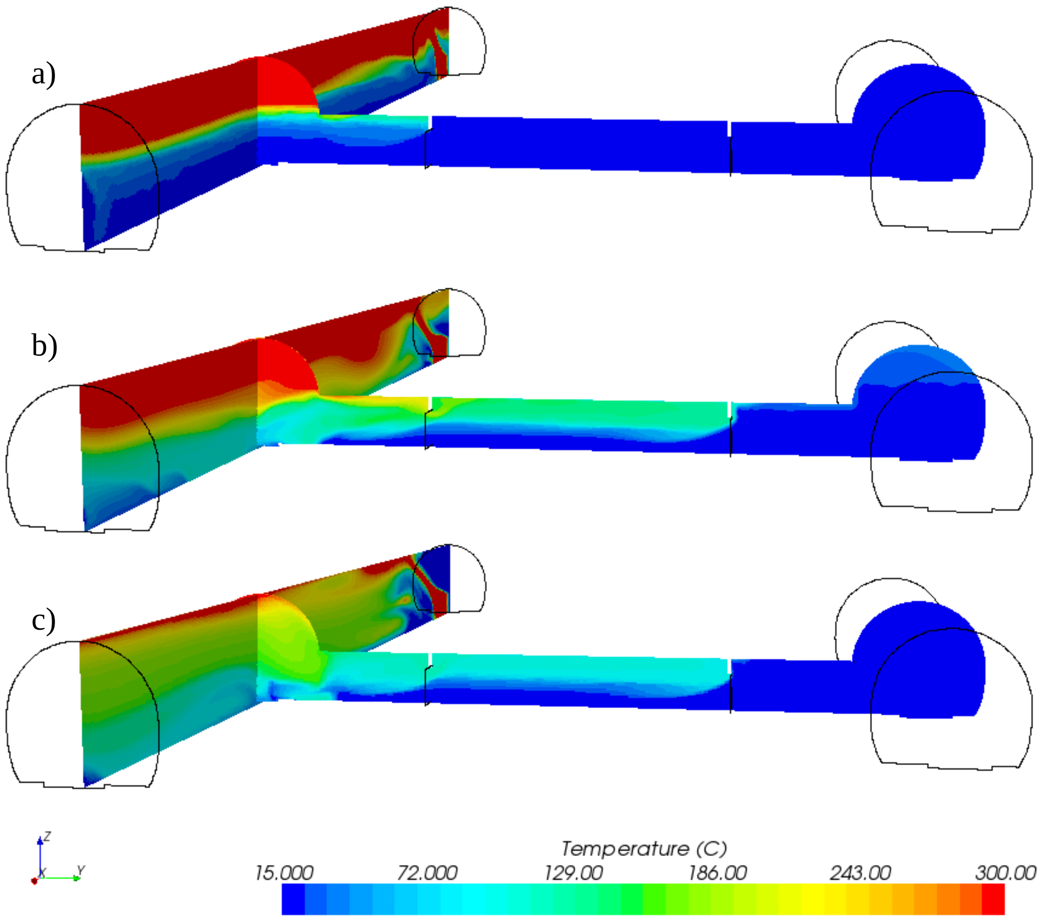

Figure 3: Temperatures in the incident tube and in the cross passage for $u_{cross\ passage}$ = 1.0 m/s and u_{tunnel} = a) 1.0 m/s, b) 2.0 m/s and c) 3.0 m/s

It can be seen that with the low longitudinal flow velocity of 1.0 m/s a thermal stratification, and thus a smoke stratification, develops in the tunnel (**Figure 3**a). Due to the low dilution of the fire gases with fresh air, high temperatures occur in the incident tunnel. These high temperatures are located in the smoke layer just under the ceiling. Because of the stratification the temperatures at the emergency exit doors are low enough that a flow velocity of 1.0 m/s is sufficient to prevent the smoke moving into the cross passage.

With a higher longitudinal flow velocity of 2.0 m/s the smoke stratification is less pronounced, i.e. hot gases are also present in lower parts of the tunnel (**Figure 3**b). The average temperature in the tunnel decreases with increasing longitudinal flow (more dilution). Due to greater mixing the temperatures at the emergency exit doors are higher when the airflow is increased from 1.0 m/s to 2.0 m/s. The flow velocity of 1.0 m/s through the cross passage is in this case not sufficient to prevent smoke penetrating into the opposite tube (see **Figure 3**b, close to the ceiling).

In the case of a longitudinal flow velocity of 3.0 m/s a considerably less pronounced stratification is observed (**Figure 3**c). However because of the greater dilution and cooling of the fire gases the temperatures at the emergency exit doors are lower than in the case with the longitudinal flow velocity of 2.0 m/s. The flow velocity of 1.0 m/s in the cross passage can prevent the smoke moving into the opposite tube but not into the cross passage.

In **Figure 3** it can be clearly seen that the constriction due to the two doors (diminution from the cross section of the cross passage to the cross section of the door) have the effect of a smoke curtain. That means that the constrictions help to avoid a smoke propagation.

3.3.2. Airflows

Figure 4 and **Figure 5** show the flow velocity through the open emergency exit doors in the cross passage for the case of a longitudinal flow of 2.0 m/s in the incident tube and a flow velocity of 1.5 m/s through the cross passage. In that case the smoke propagates through the first door (door 1) into the cross passage but not through the second door (door 2) into the opposite tube. The maximum positive velocity in door 1 reaches 2.8 m/s (i.e. in the direction of the incident tube) in the lower part of the door and a maximum negative velocity of 1.5 m/s (i.e. in the direction of the opposite tunnel tube) in the upper part of the door. In door 2 the velocity is solely positive (i.e. in the direction of the incident tube) and relatively uniform.

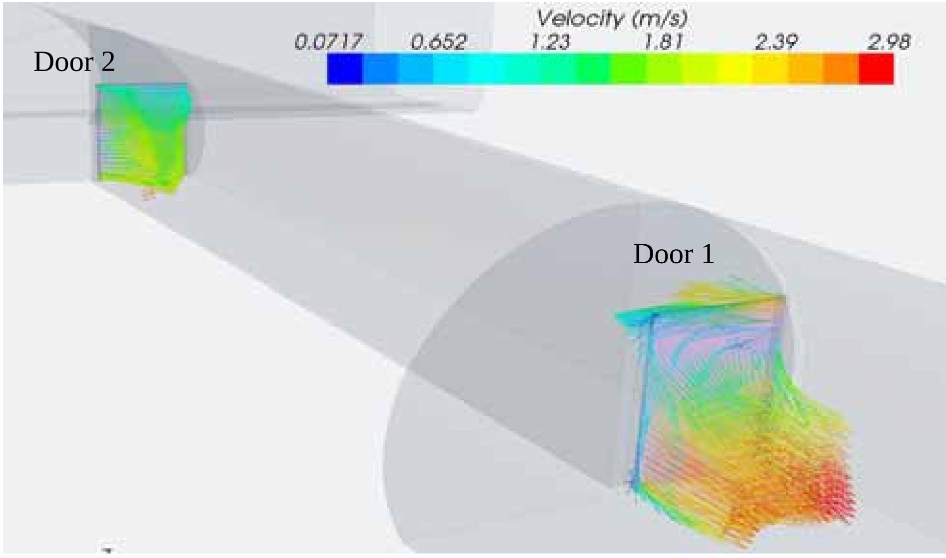

Figure 4: Velocity vectors through the emergency exit doors for the case u_{tunnel} = 2.0 m/s, $u_{cross\ passage}$ = 1.5 m/s)

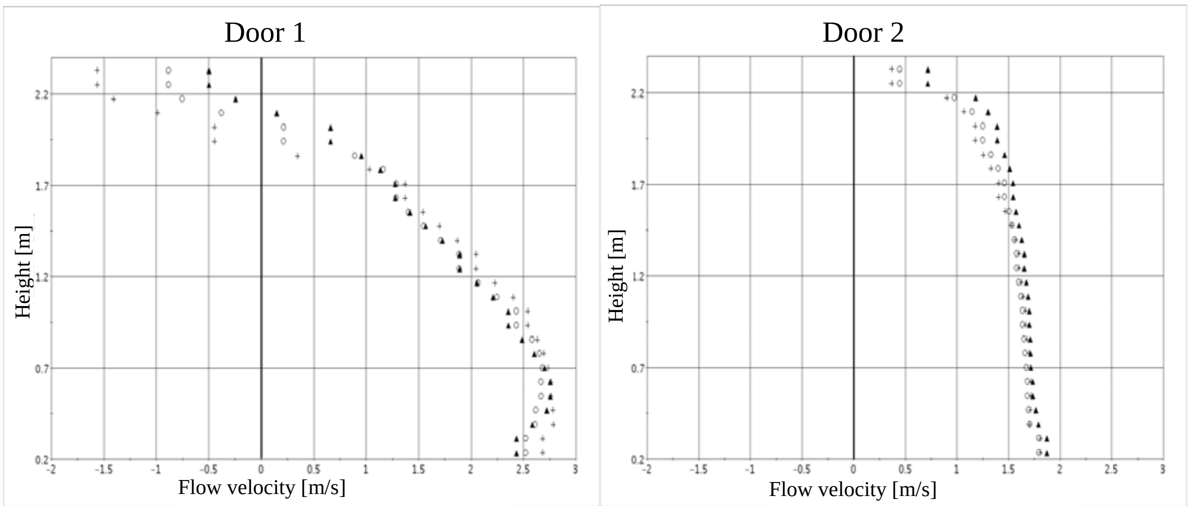

Figure 5: Flow velocity in three vertical sections in the emergency exit doors for the case utunnel = 2.0 m/s, ucross passage = 1.5 m/s)

3.4. Summary

The simulation results from the cases with the heat release rate of 28 MW and no train in front of the cross passage show that for longitudinal flow velocities of approximately 2.0 m/s the highest flow velocities through open cross passages are required. Lower cross passage flow velocities are sufficient for lower longitudinal flow velocities because the smoke layer is situated above the door and for higher longitudinal flow velocities because of the greater dilution and cooling of the fire gases.

For longitudinal flow velocities higher than 2.0 m/s the simulation results are in good agreement with the analytical 1D approach [Tarada, 2000]. In contrast to the analytical model the required flow velocity through the cross passage is smaller for longitudinal flow velocities lower than 2.0 m/s.

Figure 6 shows the summary of the simulation results for cases with a heat release rate of 28 MW. Each point represents a single simulation with a given longitudinal airflow and a given velocity through the emergency door. The symbols used in

Figure 6 correspond to those in Table 1. The diagram is divided into three parts. The upper vertically dashed area shows conditions whereby smoke movement into the opposite tube can be avoided. The lower horizontally dashed area signifies an expected movement of smoke into the safe area. An area of uncertainty lies between the two. For combinations of longitudinal flow velocities and flow velocities through the cross passage in this transition area a smoke propagation into the opposite tube cannot be excluded.

Further simulations show that a smaller heat release rate (e.g. 8 MW) requires, as expected, a smaller cross passage flow velocity. For high longitudinal flow velocities this is clear because of the lower temperatures. For longitudinal flow velocities of 1.0 m/s the smoke stratification is less pronounced for a smaller heat release rate. But in this case the temperature at the door is also smaller which requires lower flow velocities through open cross passages. To quantify the effect of smaller heat release rates on the minimum flow velocities further simulations would be required.

Several simulations were carried out with a train standing in front of a cross passage. The results show that a slightly smaller flow velocity through the cross passage is required compared to the cases without train. The results shown in

Figure 6 are thus on the "safe side".

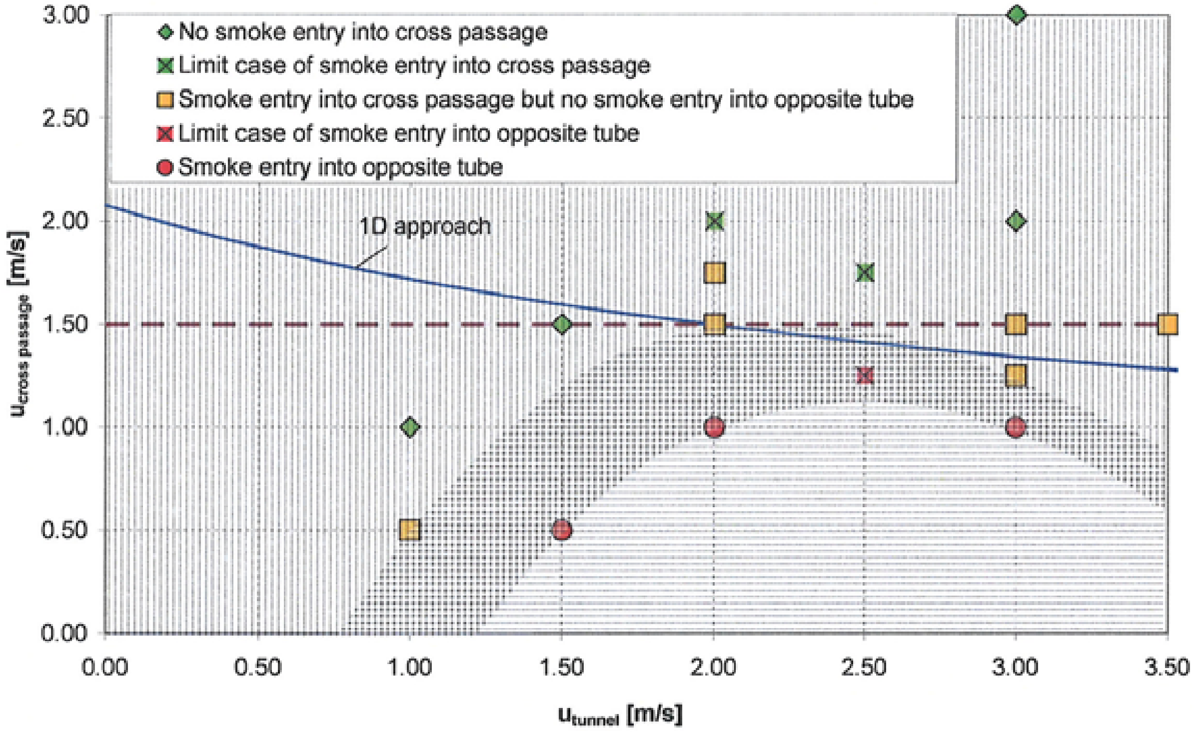

Figure 6: Summary of the simulation results (28 MW)

4. CONCLUSION

The following findings can be derived from the 3D-CFD Simulations:

- The minimum flow velocity required to prevent smoke propagation into the opposite safe tube is not only dependent on the heat release rate but also on the longitudinal flow velocity in the incident tube. Both factors have an impact on the temperature at the cross passage doors.
- The geometry of the cross passages (abrupt diminution from tunnel height to the cross passage height) as well as the geometry of the two emergency exit doors (abrupt diminution from the cross section height to the door height) helps to prevent smoke entry. If there is a smoke stratification the abrupt diminutions act like smoke curtain.
- The system configuration of the cross passage, with two doors that act like smoke barriers, plays an important role in preventing smoke penetration into the opposite tube.
- For a heat release rate of 28 MW the highest flow velocities through open cross passages are required for longitudinal flow velocities of approximately 2.0 m/s. Lower cross passage flow velocities are sufficient for lower longitudinal flow velocities because of the smoke layering, and for higher longitudinal flow velocities because of the greater dilution and cooling of the fire gases.

- For a heat release rate of 28 MW a flow velocity of 1.5 m/s (averaged over the cross section of the cross passage doors) is sufficient to prevent a smoke propagation into the opposite safe tube. A flow velocity of 2.0 m/s is required to prevent a smoke propagation into the cross passage. For heat release rates that are smaller than 28 MW smaller flow velocities are required.
- The 1D approach for a longitudinal flow of 2.0 m/s [Tarada, 2000] can be chosen as upper limit for the flow velocity through the cross passage doors.

ACKNOWLEDGEMENT

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TECHNICAL ISSUES ON VENTILATION OF UNDERGROUND RAIL TRANSIT (RT) SYSTEMS; FOCUS ON TURKEY

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ABSTRACT

Appropriate ventilation of underground rail transit (RT) systems has been a primary concern in the design of these systems. The ventilation concept of RT systems comprises two main issues, namely emergency ventilation and comfort ventilation. The emergency ventilation concept refers to the situation when one or more cars of the operational trains catch fire and the need for safe evacuation of the passengers arises. The emergency ventilation can be divided into two sub branches, which are tunnel emergency ventilation and station emergency ventilation, both of which has its own technical issues and operational measures. The comfort ventilation concept refers to the situation when the air quality within the stations is reduced due to presence of working mechanical, electrical equipments, train operation schedules and over-crowded stations. The passenger comfort can also be disturbed by excessive air movements induced by train operations, and thus the need for taking measures arises. This paper will expand the aforementioned concepts on ventilation of underground RT systems, design criteria and technical issues, amplifying their corresponding importance for safe and comfortable public transport giving specific examples from specific applications in Turkey.

Keywords: emergency ventilation, comfort ventilation, fire simulation, underground rail transit systems, piston effect

1. INTRODUCTION

Due to increase in fuel prices and traffic intensity, the need for mass transit systems increased considerably in big cities. Being among the most effective mass transit means in terms of passenger transport capacity, the underground rail transit systems are continuously built in cities whose populations are growing rapidly. From passengers' point of view, these systems should be fast, reliable, cheap and maybe above all, they should be safe and comfortable. The safety and comfort issues are closely related with ventilation strategies of these systems and these strategies play an important role in the planning and design process of the overall system. Ventilation for emergency requires selection of properly sized emergency ventilation fans and their equipment. Ventilation for comfort is important for passengers, who ought to be subjected to clean and comfortable air conditions, and it requires selection of appropriate ventilation fans and suitable ducting, as well as taking constructional measures to mitigate the adverse effects of air movements induced by train operations. These requirements must be determined and analyzed at the very first stage of planning and design phase of the overall system and the construction of the system must be started after these safety and comfort issues are warranted by technical investigations.

2. EMERGENCY VENTILATION

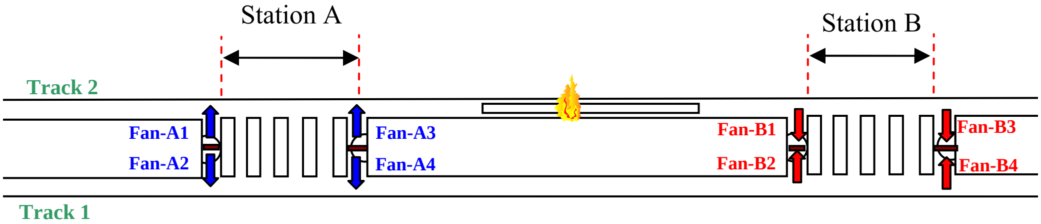
One of the most important safety measures of underground RT systems is the isolation of people from the danger zone when a part of the train catches fire. This is obtained by directing the generated smoke to a predetermined direction by ventilation equipment and evacuating the passengers in the opposite direction. The generated smoke is leaded to the predetermined direction by having sufficient amount of air velocity which is obtained by the emergency ventilation fans and equipments. In Turkey, these fans are usually located at the ends of the underground stations which have their own emergency ventilation rooms where these fans are seated. The initial design parameter of the emergency ventilation system is the determination of fan capacities which are capable of supplying sufficient amount of air into the fire location. Ventilation shafts and channels should be investigated to determine the fan total pressure rise requirements. The necessary amount of air that should be supplied into the fire zone and the features of emergency ventilation system are strongly affected by the fire load in the system. Thus, the fire load of the operational trains must be determined or gathered from technical specifications before the design and selection of the emergency ventilation fans and equipments. The underground RT systems in Turkey have different fire loads for emergency ventilation design because the trains are different for each city-specific application. The fire load of Underground Light Rail Systems in Istanbul and Bursa are specified as15 MW[1,2], where those of Ankara and İzmir are 9 MW[3] and 12 MW[4], respectively. The fire load of Istanbul Metro System is specified as18 MW[5] and that of Ankara is 15 MW[6]. Emergency ventilation can be divided into two sub branches, tunnel emergency ventilation and station emergency ventilation.

2.1. Tunnel Emergency Ventilation

The emergency situation in a tunnel initiates when a carriage of the train catches fire and train stays inoperable within the tunnel. At this situation, the passengers must be evacuated according to the requirements of a proper ventilation/evacuation scenario, which is capable of supplying fresh air above the critical air velocity over the fire zone, while evacuating the passengers to a safe zone free of smoke and excess temperatures. The critical air velocity is defined as the minimum air velocity that can drag the smoke to the downstream of the fire zone and prevent backlayering. Thus an escape route free of smoke and high temperatures for the evacuees is formed opposite to the ventilation direction. If the ventilation velocity is smaller than the critical velocity, then backlayering will occur and the escape route will be affected by the smoke and high temperatures.

In Turkey, the emergency ventilation of tunnels is usually accomplished by push-pull principle. This principle requires that the emergency ventilation fans located at one side of the fire location should work in “supply” mode while those on the other side of the fire location should work in “exhaust” mode (**Figure 1**). The number of stations whose emergency ventilation fans should be operated in an emergency case is dependent on several factors such as the location of fire, track alignment, tunnel geometry and it is determined via fire simulations.

One important aspect in the tunnel ventilation is the selection of ventilation direction in case of a fire incident. The ventilation direction must be selected such that minimum number of cars would be exposed to smoke and minimum number of passengers is affected by the smoke. Thus, according to the fire location on the train, the system operator must decide on the direction where minimum number of people is affected by smoke during the evacuation period. Because the fire location along the train is indefinite as a design parameter, the emergency ventilation systems in Turkey are designed conservatively, such that the system can satisfy critical velocity requirement at both ventilation directions.



Station	A		B	
Location:	North	South	North	South
Tunnel Ventilation Fan:	A1-A2	A3-A4	B1-B2	B3-B4
Mode	Supply	Supply	Exhaust	Exhaust

Figure 1: Push-Pull working principle of tunnel emergency ventilation fans.

In addition to satisfying critical velocity requirement as the lower limit, the ventilation velocity should not exceed the high limit of 11 m/s, as suggested by the SES Design Handbook[7] , NFPA 130[8] and the Technical Specifications in action in Turkey, in order not to impede walking of evacuating passangers.

The fire simulations must show that the ventilation velocity is higher than the critical velocity in the fire region. The fire locations used in simulations should be selected after a detailed system investigation. Special attention must be paid to regions where tunnel gradient is severe and cross sectional area of the tunnel is high. For most of the underground RT systems in Turkey, numerous fire scenarios covering all the critical locations along the tunnels are simulated on a systematic basis. After these systematic simulations, flow capacities of the emergency ventilation fans which are capable of supplying the necessary flow rates into the underground tunnels are determined. Because the portals, through which emergency ventilation fans supply air into the underground system, are usually located at the ends of the stations, the fraction of airflow that goes to the holding tunnels is affected by the system resistance at the other side of the portal. In order to increase the fraction of air flow that goes to the holding tunnels, thus having the opportunity to select lower capacity fans, various measures may be taken. One common solution to this problem in Turkey is the application of fire doors in tube stations (**Figure 2**). The fire doors obstruct the air flow so that minimum amount of air "leaks" through the stairways and connecting tunnels; so a higher fraction of air is diverted to the tunnel on fire. Also, dampers are mounted to have the chance to ventilate the intended tunnel more effectively by closing the opening to the adjacent track (**Figure 2**).

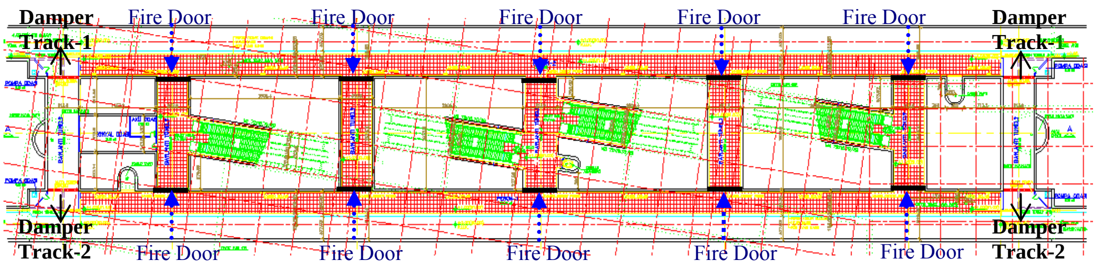


Figure 2: Typical Tube Stations with Fire Doors and Dampers

Crossover regions, where cross sectional areas of the tunnels are large, are one of the most critical locations along the tunnels in terms of emergency ventilation. The ventilation air velocity in these regions gets smaller and the possibility of backlayering increases. Additional jet fans are frequently used in these regions. Jet fans impose extra momentum into the volume and the ventilation air is supported to gain sufficient velocity in the region. However the designer should be aware of the geometry of the crossover region and should work in conjunction with the construction engineers for proper installation. Possible constructional limitations on the installation of the jet fans will affect the selection and positioning of jet fans in these regions. Common practice in Turkey is to have at least two rows of jet fans, each row having the capability of sustaining the design air velocity individually, in case one row becomes out of service during the fire incident.

Furthermore the presence of crossover regions between two neighboring stations strongly affects the ventilation capacity of the holding tunnels. The blockage effect of the train in one holding tunnel causes the airflow to follow the other low resistant route, i.e. adjacent tunnel. This situation is thoroughly examined in the simulations and necessary precautions are taken to supply the sufficient amount of air into the fire locations (**Figure 3**).

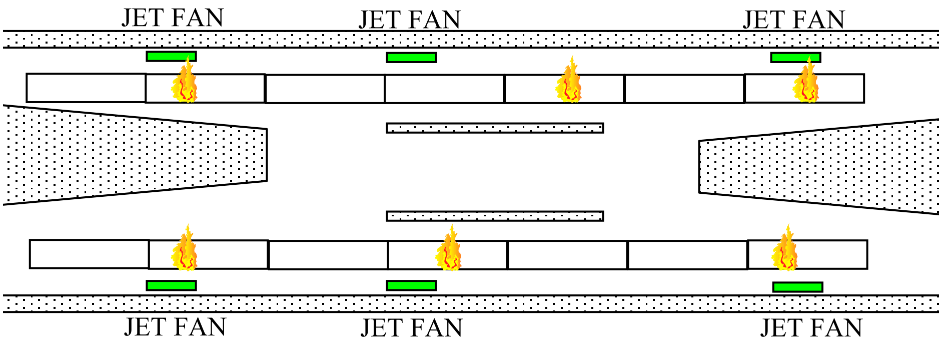


Figure 3: Typical precaution by jetfans in Crossover Regions

The temperature distribution along the evacuation route is another important design parameter. NFPA 130[8] standard suggests that the temperature along the evacuation route should not exceed 50^0C. The simulations should be checked to satisfy these criteria and the results should be presented to the authority.

How the emergency ventilation system is operated for particular fire scenarios are presented via tables. These tables must give the information on the emergency ventilation fans to be operated, their modes (supply or exhaust), jet fans and their operation directions, other operational measures like fire door openings, evacuation direction etc. according to the each critical fire location (**Table 1**). These tables are then integrated to SCADA systems which automatically select the proper ventilation scenario for a particular fire location.

Table 1: A Typical Summary of Fire Scenarios

SCENARIO	Station A Fan A1-A2	Station A Fan A3-A4	Station B Fan B1-B2	Station B Fan B3-B4	FIRE LOCATION (m)	FIRE LOCATION (TRACK)	Critical Velocity (m/s)	Ventilation Velocity (m/s)	Max. Temperature (C)	Evacuation Distance and duration (m/sn)	Evacuation Direction
1	Supply	Supply	Exhaust	Exhaust	12485	Track-1	2.67	3.14	304	217/289	Station A
2	Supply	Supply	Exhaust	Exhaust	12475	Track-2	2.69	3.19	314	217/289	Station A
3	Exhaust	Exhaust	Supply	Supply	12485	Track-1	2.67	3.46	195	255/340	Station B
4	Exhaust	Exhaust	Supply	Supply	12475	Track-2	2.69	3.47	194	169/225	Station B

2.2. Station Emergency Ventilation

The emergency situation in a station can be considered as the incident when a carriage of the train catches fire but the train is still operable and brought to the nearest station. At this situation, the passengers must be evacuated according to the requirements of proper ventilation scenario which is obtained by detailed fire simulations. For fire simulations of large and complex constructions like the stations, advanced computational fluid dynamics (CFD) tools are used. The detailed three dimensional CAD models of the stations are obtained and these models are solved with CFD tools to monitor smoke and temperature distribution in the station. The regions of high smoke density and temperature are determined and the evacuation routes are selected along with the ventilation scenario. In station fire simulations, ventilation is mainly obtained with tunnel emergency ventilation fans. However, in some applications, over track exhaust (OTE) fans that are resistant to high temperatures are complementarily used to facilitate the smoke extraction. The transient analyses which simulate the growth of heat release are performed; the smoke and temperature distributions in the stations are investigated at each instant of time. The conditions along the evacuation route at any instant of time are checked from safety point of view and it is ensured that smoke-free, low temperature conditions are satisfied. In the stations, 10 meters visibility range is set as the criteria for smoke-free conditions and 50^0C maximum temperature in the evacuation route is set as the low temperature criteria. The criteria for evacuation period are set as 6 minutes for platform level and 10 minutes for the station[8]. So the transient CFD analysis is expected to show that the evacuation route meets the aforementioned safety criteria during this evacuation period. Usually the reliability of transient analyses of each ventilation scenario is checked with steady-state analysis that simulates the conditions when full fire load is present at the initiation of fire and stays constant until the end of the evacuation period.

2.3. The Properties of Emergency Ventilation Fans

The emergency ventilation fans of underground RT systems have bi-directional (supply or exhaust) operation capability and should be selected as axial flow fans with 100% reversibility (no performance reduction when direction of rotation is reversed). Fans and all the related equipment that are subjected to smoke and high temperatures must be resistant to high temperatures. NFPA 1308 standard suggests that the emergency ventilation equipment must resist 250^oC during at least one hour. However, the temperature limit is set as 400^oC in Istanbul and Ankara RT systems, which is very conservative. A total pressure drop analysis of the ventilation system in which the fans are operating must thoroughly be done in order to select the most appropriate fan in supplying the required flow rate to the system. 15% of calculated total pressure rise is generally added as safety factor. The fans must be selected such that they will operate in regions away from their stall limit on their performance curve. Fan motors are required to achieve their full operating speeds within no more than 30 seconds[8].

3. COMFORT VENTILATION

Comfort ventilation for underground stations is essential as the continuous operation of trains and passengers cause the air quality within the station to decrease regarding cleanliness and comfortable temperature levels thus a need for supplying fresh air arises. This need is fulfilled by two mechanisms. The first mechanism is the piston effect of trains within the holding tunnels. The circulation due to piston effect feeds the station partly with outside atmospheric air via piston relief shafts and stairways and partly with the air inside the tunnels. The second mechanism is the mechanical ventilation with OTE fans. In some applications, the emergency ventilation fans are operated at reduced speeds and used for routine ventilation with the help of convenient ducting. The effectiveness of the comfort ventilation is measured by the air exchange rate criteria set by ASHRAE standards.

The transient air movement within the stations due to piston effect must be investigated by simulations. The amount of fresh air entering into the station via piston relief shafts and stairways for a certain time period is determined and checked whether the air exchange rate criterion is satisfied. Air exchange rate of the underground stations' platforms levels is defined as the ratio of total amount of fresh air entering to the platform level during one hour to the volume of the platform level. In ASHRAE standards, this criterion is specified to be within 8-12 range for closed atriums which have working electrical and mechanical equipment in it9. For underground stations, big part of the air exchange rate is covered by train piston effect. The amount of air entering to the station is calculated by simulations. The amount of air entering to the station during one hour is highly dependent on the train headway, so the headway information of the trains must be obtained from responsible authority and the simulations should take this parameter into account. Usual approach in Turkey is to simulate the critical conditions when passenger density is low and the train headway is high. A typical headway value for low passenger density hours is 600 seconds (6 trains/hour). The results of simulations are checked whether the criterion is satisfied. In situations when the criterion is not satisfied or in unusual situations like the presence of hot air currents or cease of piston effect due to train failures inside the tracks, OTE fans, Under Platform Exhaust (UPE) fans and the concourse level air conditioning systems are operated to back up the complementary part. The emergency ventilation fans running at reduced speeds with the help of frequency converters can be utilized for comfort ventilation if air treatment equipments are available.

Other concern of the piston effect is the platform air velocity limit that should be satisfied. The technical specifications require that the maximum air velocity due to train piston effect on the platforms and stairways should not exceed 5 m/s and 2.5 m/s, respectively. In order to maintain these velocity limits within the station, the piston relief shafts are designed to relieve the excessive air flow outside the underground system. The applications in Turkey have two major types of relief shafts. In the first type (Ankara RT Systems), the shaft portals are located at the side or ceiling of the tunnels and a separate shaft is directly venting the excessive air into atmosphere. In the second type (Istanbul RT Systems), unlike the direct venting of the first type, the piston air is passed through the fan rooms (around the fan unit) and then reaches the ventilation shaft (**Figure 4**). Because the design should consider that the air current should face minimum aerodynamic resistance, the first type of design is preferable.

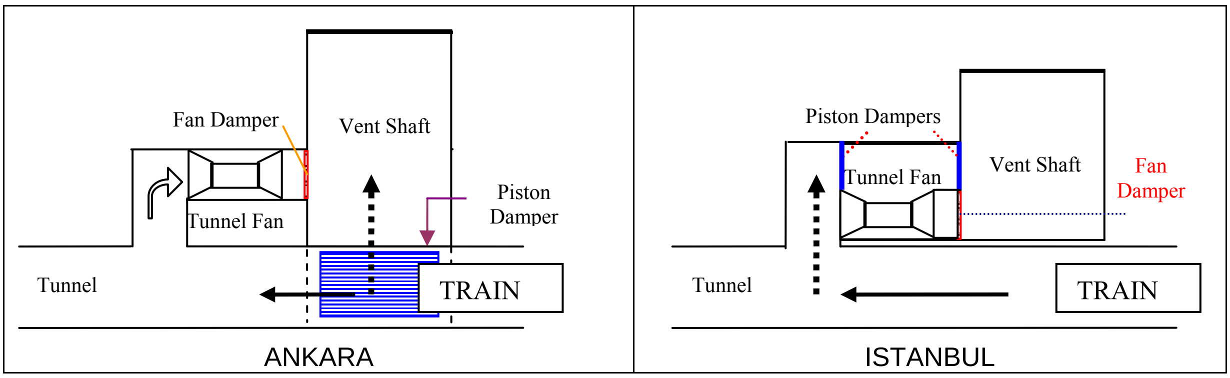


Figure 4: Schematic Representation of Vent shafts in Ankara and Istanbul RT systems

If the piston relief shafts are insufficient for piston air relief, additional precautions are taken. One major precaution is to increase the airflow resistance between the ends of the stations and relief shaft portals by building high flow resistant structures. This increased resistance causes the air current to pass through the vent shafts instead of passing through high flow resistant structure. This method is applied in most of the stations of Istanbul underground RT system (**Figure** 5). Another precaution to increase the amount of air stream passing through relief shafts is the abrupt area increase associated with a smooth directing of the stream by aerodynamic construction. This is applied in Ankara underground RT system (**Figure** 5).

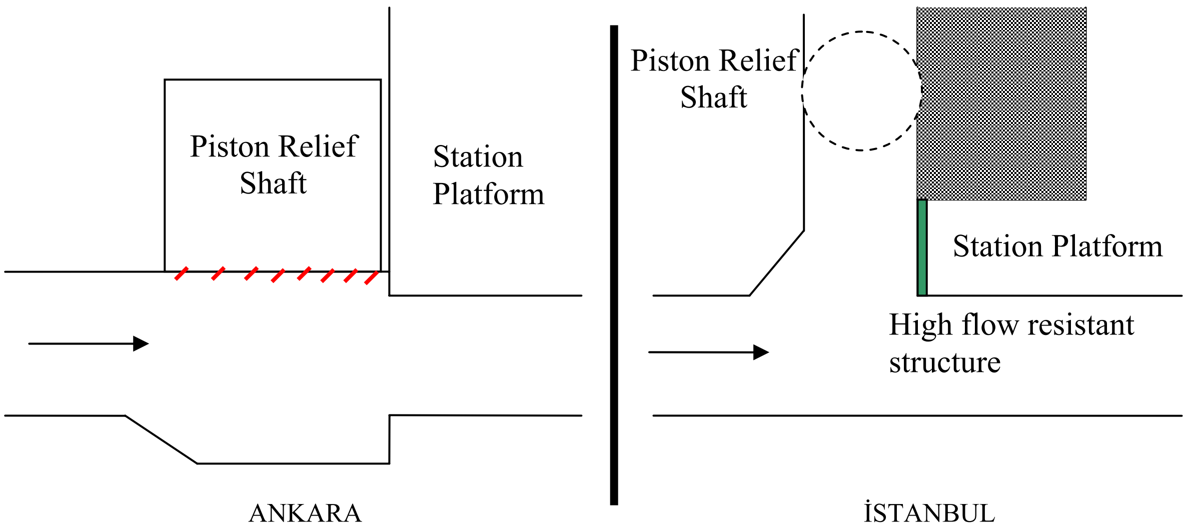


Figure 5: Measures for reducing piston effect in stations

Air velocity values should be checked by simulations. The air velocity in the stations due to piston effect is highly dependent on the train blockage ratio (train cross sectional area/tunnel area) and train speed profile within the tunnels, so this information of the trains must be obtained from responsible authority and the simulations should take these parameters into account. In Istanbul and Ankara RT systems; the train speed limits within the tunnel and station are 80 km/hour and 40 km/hour, respectively.

4. CONCLUSION

In this document, the technical issues and approaches regarding the ventilation design and simulation of underground RT systems are presented. Some variations among the applications in Turkey in terms of design approaches and criteria are adverted. In order to have safe and comfortable ventilation, the systems must be planned and designed properly prior to the construction so that structural precautions can be taken more easily and must be maintained and operated with well-defined procedures and methodologies.

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SAFETY INSTALLATIONS IN ROAD TUNNELS – ARE THEY USED IN INCIDENT CASES?

Günter Rattei
ASFiNAG Service GmbH
(Austria's motorway and expressway funding company)

ABSTRACT

ASFiNAG **plans, builds, maintains, and collects tolls** on Austrian motorways and expressways. It currently operates a network comprising approximately 2,100 km of roads. This network includes approximately 140 km of special toll roads such as the Bosruck tunnel, the Gleinalm tunnel, the Arlberg tunnel and the Tauern tunnel. A further 350 km of motorways and expressways are currently either at the planning stage or under construction.

A total of 140 tunnel facilities with a total length of approximately 324 km are currently in operation on the network. This is the same distance as a journey from Vienna to Salzburg on the A1 West motorway. Approximately 135 km of tunnel facilities are either at the planning stage or under construction. This is the same distance as a journey from Salzburg to Villach on the A10 Tauern motorway.

In view of the large number of tunnels on the network, ensuring the highest possible level of safety and economic efficiency in motorway and expressway tunnels is one of ASFiNAG's main objectives.

1. INTRODUCTION

Ever since the tragic events of 1999, people in Austria have attached great importance to the issue of tunnel safety.

With the help of both technical developments and organisational measures, tunnel safety has been significantly improved in order to ensure maximum safety for tunnel users in the event of an incident.

2. OVERVIEW OF THE CURRENT EQUIPMENT STANDARDS FOR NEW TUNNEL CONSTRUCTION AND MODERNISATION

Major constructional and electromechanical installations which significantly influence the safety level and behaviour of the road users are:

- Emergency call installations in the tunnel and tunnel entrance area
- Design of the escape and emergency services routes
- Construction and installations of the lay-by niches

Emergency call installations in the tunnel and tunnel entrance area

All emergency call installations in the tunnel are positioned in walkable and illuminated niches. The emergency niches are situated at intervals of around 125m in the tunnel on the right hand side seen from the driving direction. Opening of the doors is monitored by door contacts. The walkable emergency niche is equipped with a robust handset for making emergency calls. The functionality of the emergency installation is signalled to the emergency callers through an operation and malfunction display. The two fire extinguishers can be taken from the fire extinguisher section on the outside of the emergency cabin. Removal of the fire extinguishers is contact monitored and triggers a fire alarm upon removal. Furthermore, two hand hazard signals for SOS and fire reports are provided on the outside of the emergency cabin. Emergency installations in the entrance areas are housed in closed cabins; the equipment is similar to that of the niches in the tunnel.

Design of the escape and emergency services routes

Escape and emergency services routes are crossways in the neighbouring tunnel tubes or connections to the outside. Various types of crossways are differentiated in Austria. There are drivable crossways at every lay-by niche, furthermore, there are crossways, which are only drivable with special vehicles of the emergency services and walkable crossways.
All escape and emergency services routes are separated from tunnel traffic areas by gates and doors and lit with the same luminance as in the tunnel roadways. Escape route orientation and signs lights lead to these escape routes.

Equipment and installations in the lay-by niches

Lay-by niches are provided every 1000m in the tunnel. The lay-by areas are around 40m in length and 3m in width. The illumination level in the lay-by niches is clearly higher than that of the roadways, whereby these areas are clearly highlighted in the tunnel. Important operating and safety installations such as yaw/pitch/zoom cameras, wall hydrants, loudspeaker systems, fire fighting niches, emergency call niches etc. are fitted in the area of the lay-by niches. Distance indicators to the portals are provided on the tunnel walls in the lay-by niches.

3. TUNNEL DATABASES

In order to meet the provisions of the Road Tunnel Safety Act, several tools, including the tunnel safety database, were developed. This database has been in operation since 01.01.2006. All accidents, fires, and cases of property damage relating to tunnel operation are recorded and entered in the database in order to allow improvements to be made as quickly as possible.

In the database were collected in up to 25.02.2010 total 1541 events.

Furthermore, since 01.01.2009 ASFINAG operates a tunnel barrier database.

In the database all the tunnel barriers can be entered. The collection and allocation of data takes place in three categories, planned locks, events and incidents.

All these evaluations are based on the contents of these two databases.

Figure 1: Tunnel database

Results of the analysis from the databases

The databases were evaluated according to the type of events. Events were evaluated for fire, personal injury and property damage, in connection with the use of safety equipment in the tunnel.

Until 26.02.2010 1541 events were recorded in the database. 46 events were fires. Figure 2 shows the use of safety devices in the fire events.

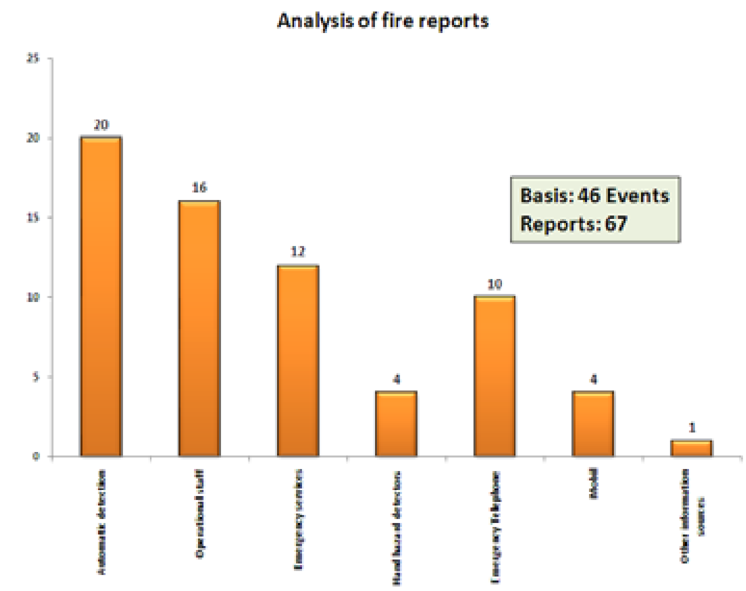

Figure 2: Analysis of fire reports

At 46 fire incidents, only 10 times (15%) the emergency telephone was used. The hand hazard detectors were only 4-times (6%) used. Much of the alarm (72%) took place automatically or by operators and police.

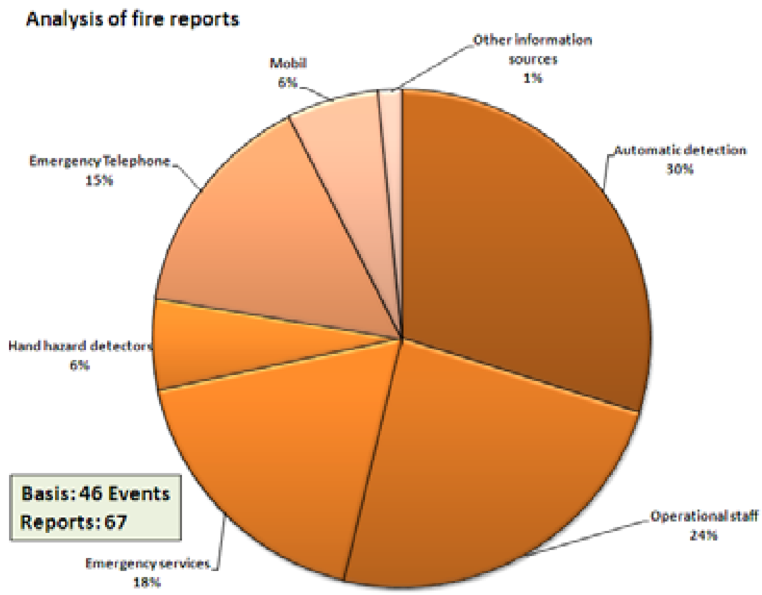

Figure 3: Analysis of fire reports

Figure 4 show that there were at 30 events no emergency calls to the operation center. In 46 fires, only 11 times the fire extinguisher was used. 19 fires could be extinguished by the road users. 27 fires are extinguished by the fire department.

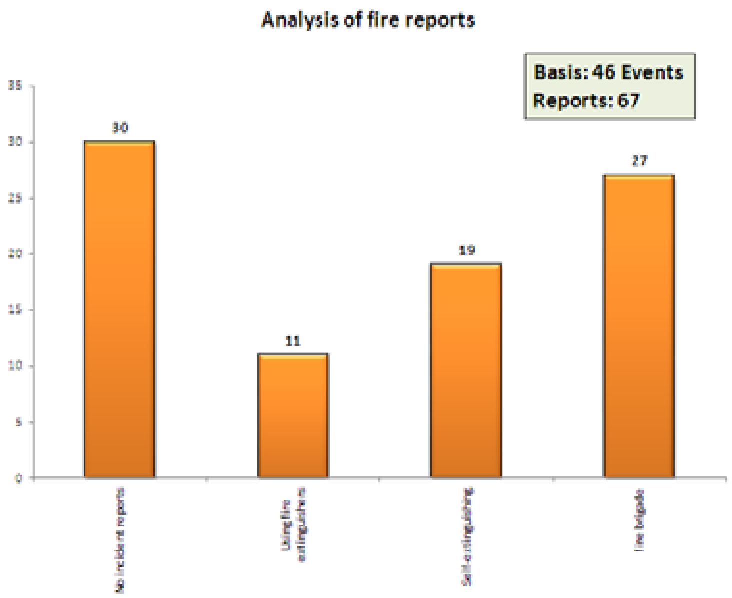

Figure 4: Analysis of fire reports

377 events were personal injuries. Figure 5 shows the use of safety devices in the events with personal injuries.

At 377 incidents, only 56 times (12%) the emergency telephone was used. The hand hazard detectors were only 6-times (1%) used. Much of the alarm (79%) took place automatically or by operators and police.

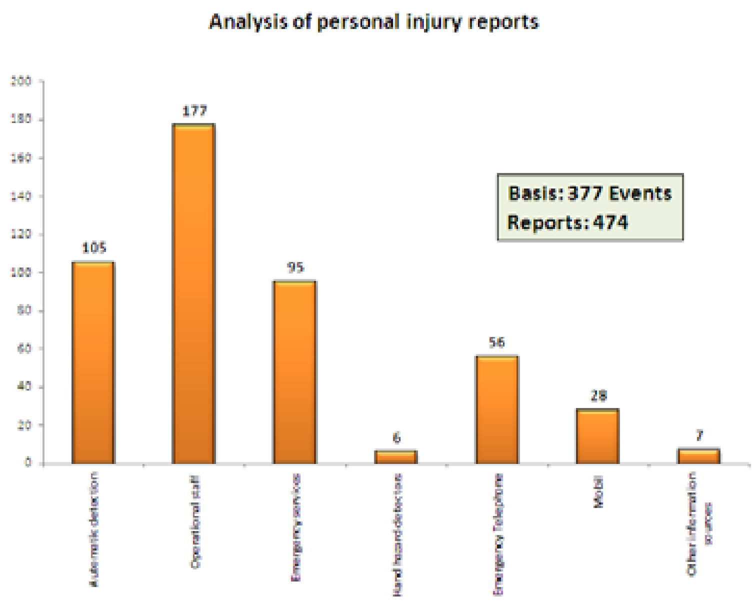

Figure 5: Analysis of personal injuries

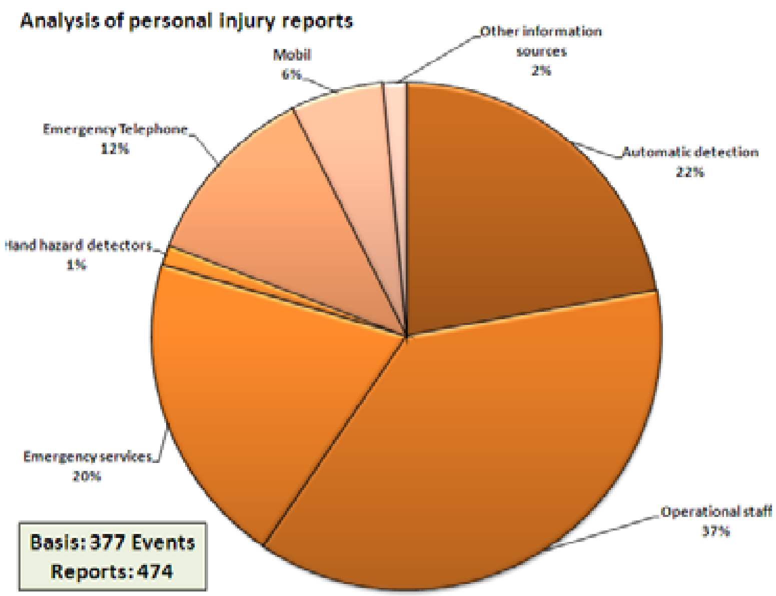

Figure 6: Analysis of personal injuries

1080 events were events with property damage. Figure 7 shows the use of safety devices in the events with property damage.

At 1080 incidents, only 135 times (10%) the emergency telephone was used. The hand hazard detectors were only 6-times (>1%) used. Much of the alarm (79%) took place automatically or by operators and police.

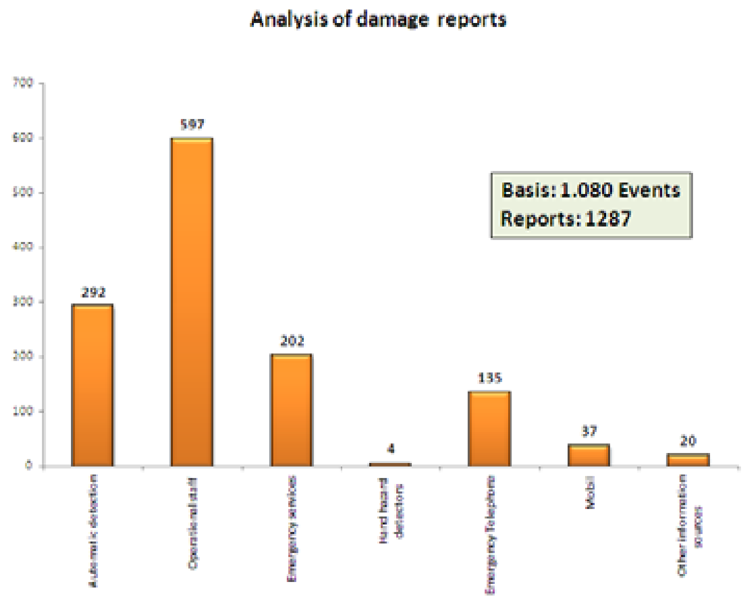

Figure 7: Analysis of property damage

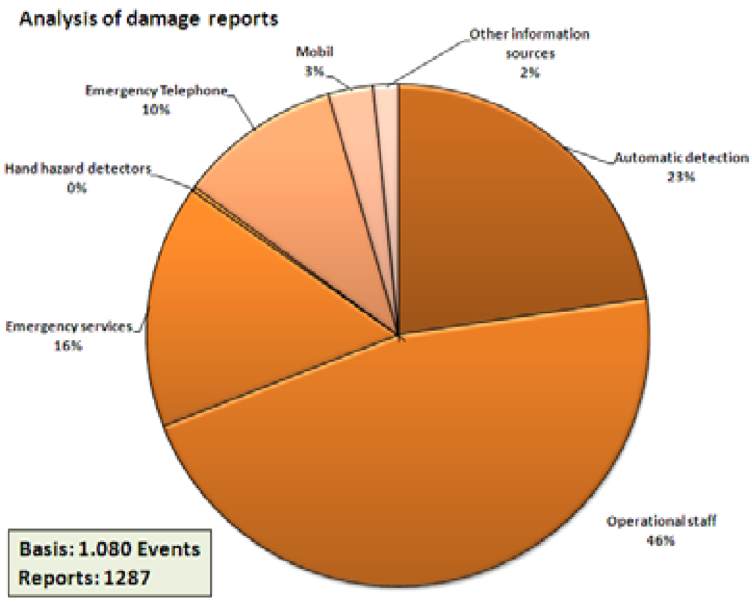

Figure 8: Analysis of property damage

Figure 9 shows the use of safety devices of all incident reports.

At 1541 incidents, only 205 times (11%) the emergency telephone was used. The hand hazard detectors were only 14-times (>1%) used. Much of the alarm (83%) took place automatically or by operators and police.

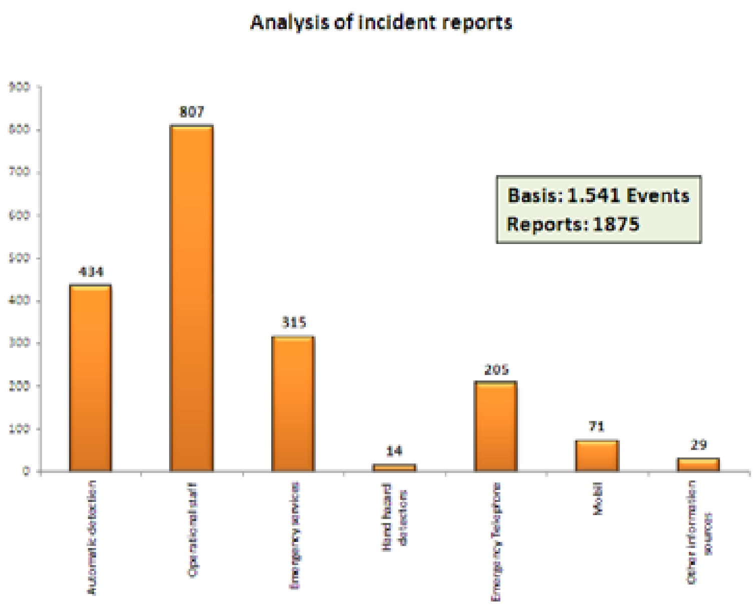

Figure 9: Analysis of all incident reports

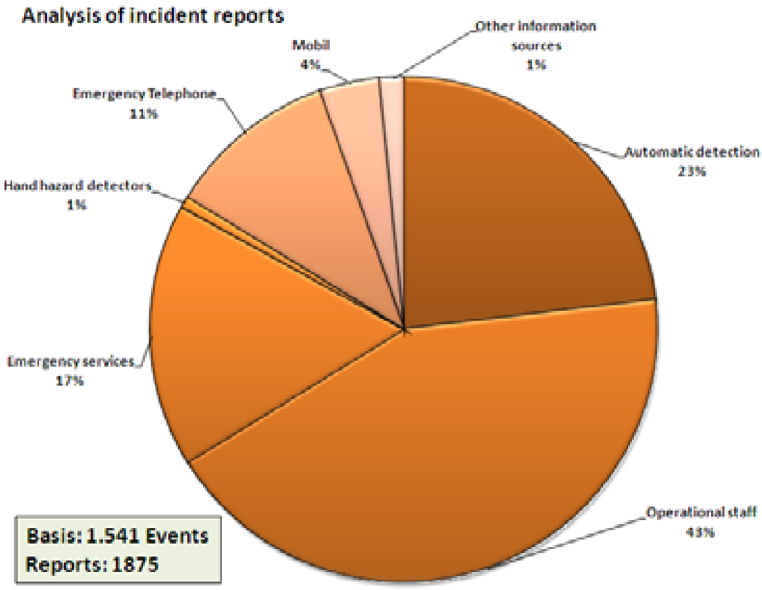

Figure 10: Analysis of all incident reports

In 80% of the events no emergency call was made, only at 20% of the events, an emergency call was made. (Figure 11)

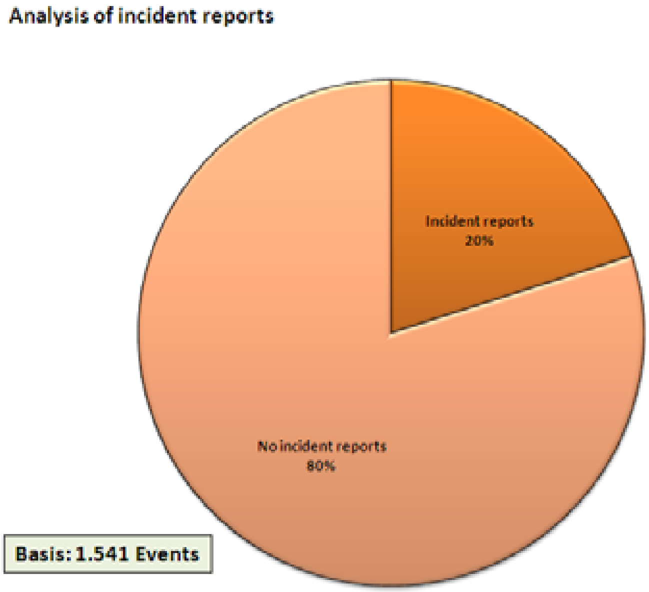

Figure 11: Analysis of all incident reports

4. SUMMARY

A review of the past few years clearly shows that as a result of the current ambitious programme of investment and the development of a streamlined organisation, the level of safety in tunnels on Austria's network of motorways and expressways has been significantly increased since 1999.

The analysis of the data shows clearly that the use of safety equipment in tunnels, especially the emergency call system has not yet achieved the desired effect. In subsequent years, special attention should be paid to providing information to the users. As a first step in 2010 an information campaign will be started.

The large proportion of alarms by the police can be attributed to the fact that the road users inform with their mobile phone the police instead of the monitoring center. To improve the alerting a research project to locate mobile phone emergency calls in the tunnel was started 2009.

SAFETY IN ROAD TUNNELS / STATUARY REGULATIONS AND PRACTICAL IMPLEMENTATION

R. Hörhan
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ABSTRACT

The coming into effect of the "Straßentunnelsicherheitsgesetz (STSG)"; i. e. the Austrian Road Tunnel Safety Law, has brought with it precise regulations with regard to organisational, operational and infrastructural measures. The following presentation aims to communicate the implementation of these regulations and additionally to compare them with the regulations included in the national guidelines.

Keywords: safety procedure, risk assessment, risk analysis, training for tunnel staff

INTRODUCTION

In essence, the safety of roadway tunnels in Austria is based on the "Straßentunnel – Sicherheitsgesetz (STSG BGBl.54/2006)", i. e. the Austrian Road Tunnel Safety Law. As this law has now been in effect for four years, taking into consideration the general characteristics of EU Directive 2004/54/EG, we are now able to reference the current state of practical implementation and the relevant results:

1. PROCEDURES ACCORDING TO THE ROAD TUNNEL SAFETY LAW

The most important aim of both the European and the Austrian Road Tunnel Safety Law was to create a coordinated and consistent high level of safety for road tunnels in terms of planning, construction and operation. However this involves a major challenge in terms of organization and financing for countries with a high number of tunnels in operation such as Austria where 71 tunnels were in service as of May 2006. Some of the tunnels have been in operation for many years and therefore require extensive maintenance and renovation work. The construction of a second tunnel tube due to a great increase in traffic volume results in especially high investment costs which are included in the costs for tunnel safety.

In order to comply with these requirements, several procedures have already been standardized and included in the Road Tunnel Safety Law: the procedures outlined in §7 STSG "Approval of Tunnel Preliminary Draft", §8 STSG "Putting Tunnels into Operation" and §10 STSG "Changes to Tunnels". The procedures are initiated along with the application which has to be submitted by the tunnel manager and must include the following documents:

- Tunnel preliminary draft to the extent prescribed by the related regulation
- Tunnel safety documentation report
- Comment of the tunnel safety officer regarding the tunnel preliminary draft or concerning the putting of the tunnel into operation

For each procedure, an external tunnel safety expert examines the documents and prepares a safety evaluation report.

The tunnel preliminary draft or the activation is approved by the Tunnel Administration Authority by means of an official notification which is prepared according to the AVG, i. e. the Austrian General Administrative Procedure Law. In addition to statements regarding the safety evaluation report and the comment of the safety inspector, the notification may contain regulations and deadlines with regard to measures to be carried out in order to complete and improve the submitted tunnel preliminary draft.

Since the Road Tunnel Safety Law has been in effect, 13 tunnel preliminary draft approval procedures according to §7 STSG have been carried out for 20 tunnel structures, and 23 procedures according to §8 STSG for the putting into operation of a tunnel either for the first time or after renovation.

2. ADAPTATION PROCEDURE FOR CONFORMITY

In addition all tunnels on the highway and expressway network which are longer than 500m were subject to a first evaluation and an adaptation procedure aimed at reaching conformity. This procedure was based on a safety documentation report which has so far been prepared for 75 tunnels according to the regulations of the STSG and includes a description of the tunnel and construction plans as well as a traffic forecast and a specific risk analysis.
This safety documentation report also serves as a basis for preparing the time schedule for the adaptation to the regulations of the STSG which must be evaluated every second year and forwarded to Brussels. The improvement measures carried out so far consisted mainly of the construction of a second tunnel tube and the associated refurbishment or replacement of the existing tunnel equipment in the first tube. As far as existing twin-tube tunnel structures are concerned, the retrofitting consists of providing additional escape routes and additional emergency phone areas along with carrying out measures intended to improve fire prevention. In terms of tunnel equipment several tunnel structures must be retrofitted by installing video-based detection systems (CCTV) or different indication signs such as additional escape route indication signs, CCTV usage notifications, etc.

3. REGULATIONS REGARDING INFRASTRUCTURE

The regulations of the STSG regarding infrastructure mainly concern the placement of various safety equipment and the maximum allowed distances between escape routes, emergency phones and fire hose placements. However, there are few regulations regarding operating modes, safety level and quality of equipment, and when they exist they are minimal in their scope.

To give an example with regard to the lighting of a tunnel, the STSG only contains the note that *the lighting must be designed in such way that adequate visibility in both the entrance area and the interior zone is guaranteed for the driver both during the day and at night.* There are no specifications regarding the light density level in the entrance and interior zone, lighting control systems, longitudinal or transversal consistency or additional requirements for merging lanes in the entrance or exit area. With the exception of a few fundamental regulations according to the international CIE, the local sets of regulations and standards for the items referred to vary greatly from one European country to the next.

Emergency phone niches represent a very frequently discussed tunnel equipment topic. Comparing the regulations of the STSG with those of the related RVS 09.02.22, one can see that there are remarkable differences; to some extent this is due to the fact that emergency phone systems were formerly regarded as a crucial self-rescue tool.

According to the STSG only the following regulations for emergency phone facilities must be observed:

- Emergency phone facilities are intended to serve as a location where various safety equipment, e. g. phone devices and fire extinguishers, can be stored. They are not intended to protect the tunnel users from the dangers of a fire.
- Emergency phone facilities must be designed in such way that a person can enter – preferably they should be located in a niche or in a box. They must be provided with at least one telephone and two fire extinguishers.

- Emergency phone facilities which are separated from the tunnel interior zone by a door must be provided with a clearly legible sign in an adequate number of languages, minimally in German and English, saying that the emergency phone facility does not provide protection in case of a fire.
- Emergency phone facilities must be arranged near the tunnel portals and in the tunnel interior zone at maximum distances of 150m for new tunnels and 250m for existing tunnels.

The RVS 09.02.22 however contains regulations with regard to components as well as to requirements for and functions of emergency phone facilities. Additional detailed requirements for tunnels on the high-speed road network are given in the ASFINAG guideline manuals.

The components of emergency phone facilities are listed in detail in the RVS:

- Communication device (handset)
- Manually activated device producing an SOS alert and fire alarm
- Door for emergency phone niche with glass panels and door closing mechanism mounted above the door
- Standing fixture with a place for a fire extinguisher
- Electric control box
- Permanent niche lighting
- Permanent lighting of the fire extinguisher compartment
- Door contact sensor for the emergency phone niche door and the fire extinguisher cabin door
- Removal sensor for fire extinguisher
- Specification and labelling of the niche

The RVS contains the following requirements for emergency phone facilities:

- Full-duplex voice transmission
- Data transmission
- Ease of use
- Bus configured in a ring structure

Emergency phone facilities must provide the following functionality:

- Making an emergency call by activating a manual alarm device
- Making an emergency call by lifting the handset
- Calming text
- Visual information showing operational readiness
- Acoustic and visual signal sent to the operation centre and the control centre
- Active reception at the operator station
- Selection of each emergency call area from the operator station
- Call-waiting function
- Emergency call recording
- Regular check-ups of cable routes and buttons

The emergency call facilities provide both well-placed and immediate assistance and information for the tunnel user and the immediate notification of an event in the control centre which initiates the action of the tunnel operator. However in order to most effectively handle an event, it is necessary that tunnel users make use of the emergency call facilities. Unfortunately, people tend to use their own mobile phones rather than using emergency call facilities and so end up calling an unspecified police station. This normally leads to unwanted delays in delivering assistance, as detecting the location of the tunnel user calling for help is very laborious and takes some time. For this reason ASFINAG has initiated research and studies aimed at finding ways to achieve an effective locator system which works with mobile phones which are located within tunnels.

Another example illustrating the difference between regulations contained in the law and how they are put into practice according to national guidelines is tunnel ventilation:

The Road Tunnel Safety Law includes the following requirements:

- *Installation of a mechanical ventilation systems in tunnels longer than 1,000m which have an AADT of 2,000 vehicles per driving lane*
- *In tunnels with bidirectional traffic and/or slow moving unidirectional traffic, longitudinal ventilation systems may be installed only if their acceptability is confirmed by a tunnel risk analysis; otherwise a semi-transversal and a transversal ventilation systems must be installed.*
- *Transversal and/or semi-transversal ventilation systems must comply with the following minimum requirements:*
    - *Installation of exhaust fans which can be controlled individually or in groups*
    - *Longitudinal air speed must be constantly monitored and the control of the ventilation system must be adapted accordingly.*

The RVS 09.02.31 contains the following requirements:

- In tunnels longer than 500m and sometimes longer than 700m mechanical ventilation systems must be installed.
- In tunnels of lengths ranging between 1,500m and 3,000m with high traffic jam frequencies having either unidirectional or bidirectional traffic, longitudinal ventilation systems with localised extraction must be installed
- For tunnels longer than 3,000m exhaust extraction via an intermediate ceiling is required.

The law does not contain requirements for ventilation systems with regard to the following items:

- Dimensions (minimum air stream for longitudinal ventilation systems or exhaust performance for exhaust ventilation systems with intermediate ceiling)
- Technical requirements for ventilators and the associated additional equipment
- Control and operation of the ventilation system

Nonetheless, criteria for dimensioning and operating ventilation systems like those contained in the RVS 09.02.31 must be defined in order to guarantee adequate effectiveness of the ventilation system, especially when it comes to self-rescue. As the functionality of the ventilation system represents a decisive factor in determining the specific risk of a tunnel, the Austrian tunnel risk analysis model includes the following fundamental criteria for modelling the ventilation system according to possible fire events, deviation from which must be recorded:

- Profile of tunnel traffic space
- Speed limit for the tunnel
- Longitudinal gradient
- Fire load
- Detection delay
- Response time of the system
- Longitudinal air speed before fire outbreak
- Desired speed of longitudinal air flow
- Maximum allowed value for smoke release
- Maximum allowed fire load value

4. RISK EVALUATION

Introducing the risk analysis as a tool for risk evaluation, the Austrian Road Tunnel Safety Law allowed for an essential shift in the planning of tunnel safety measures. Since that time an Austrian tunnel risk analysis model has been developed and published in the form of RVS 09.03.11. This model is based on the evaluation of accidents in Austrian road tunnels, and takes into consideration the Austrian tunnel equipment standards which are defined in the RVS.
This method consists of analysing the normally occurring risks and carrying out a frequency analysis and/or a damage extent analysis. Fundamentally, using the tunnel risk analysis method, all decisive influencing factors may be quantitatively determined if the required input data are available.
The tunnel risk analysis method includes the examination of the following influencing factors according to RVS 09.03.11:

- Unidirectional and bidirectional traffic represented as different event trees
- Traffic volume having an impact on accident rate and the extent of damage in the case of a fire
- Tunnel length having an impact on accident frequency
- Tunnel ventilation system examined by means of an evacuation simulation
- Traffic jam occurrence having impact on the extent of damage in the case of a fire
- Length of escape route having impact on the extent of damage in the case of a fire
- Additional problematic areas impacting accident frequency
- Proportion of heavy vehicle traffic having an impact on accident frequency and the extent of damage in the case of mechanical failures or fires

The risk of dangerous goods transports for roadway tunnels is dealt with separately in RVS 09.03.12 using a suitable methodology based on DG-QRAM. Some other factors such as longitudinal gradients in and outside the tunnel, maximum allowed driving speed and operational aspects may be taken into account by carrying out additional testing and/or by introducing both enhancing and reducing factors to impact the extent of damage. The risk analysis has already been used for several procedures, primarily because it is prescribed in the Road Tunnel Safety Law for special tunnel parameters. Fundamentally it can be pointed out that the risk analysis includes substantial simplifications and modelling speculation and should mainly be used for the comparison of tunnel structures.
In addition the risk analysis serves as a method for examining and evaluating the cost effectiveness of single safety elements of a tunnel. It is currently used for this purpose to some extent and an adequate expansion of the existing tunnel risk analysis model is being

seriously considered. Examinations with regard to the following parameters may be referred to as examples: 100MW fire, different types of tunnel profiles, reliability of systems, impact of improved lighting systems/LED, impact of different driving lane widths, impact of different distances between emergency call areas, etc.

5. MEASURES TO BE TAKEN WITH REGARD TO OPERATION

The STSG defines operational measures as an important element of tunnel safety. Relatedly, point three of the annex of the STSG contains the following note: *Both the operational tunnel staff and the emergency services staff must take part in appropriate basic training courses and then later regular training courses.*

Accordingly the job profile and the training material for tunnel operators, operational technicians and safety personnel have been defined in RVS 14.02.15. On the basis of these regulations ASFINAG has prepared and carried out a training and exam programme. The entirety of the training subject matter was divided into four fields and tests were prepared containing a maximum of 60 test questions per field; these were to be answered by all of the 141 operators and technicians. The entire training and testing programme was carried out within the previous year. Refresher training courses, which are of course shorter than the basic training, are planned for the future, along with additional basic training and tests for new personnel.

The emergency services provide separate training for their staff. Emergency services staff also take part in fire tests which must be carried out in tunnels with mechanical ventilation systems before putting them into operation, in order to learn about the specific features of the tunnel. In addition, according to the §6 of the STSG, drills for both the emergency services and the operational staff are carried out at the prescribed time intervals.

6. CONCLUSIONS

The Road Tunnel Safety Law defines a series of organisational and structural measures and governs the responsibilities for road tunnel safety. In addition, risk evaluation allows for defining the requirements for sufficient tunnel safety. The putting into practice of the regulations is carried out through updating the national guidelines, creating an appropriate management structure and – last but not least – practical implementation in tunnel structures.

THE IMPACT OF FIXED FIRE FIGHTING SYSTEMS ON TUNNEL SAFETY – THE BURNLEY INCIDENT IN A CURRENT THEORETICAL PERSPECTIVE

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ABSTRACT

Renewed interest in FFFS has resulted in new scientific data on the effectiveness of FFFS and its interrelationship with ventilation, incident detection, water application rates and FFFS type. When this new data is compared with the real experience in the Burnley tunnel fire of 2007 the results appear consistent.
Keywords: Fire, ventilation, deluge, mist, FFFS, safety, asset protection

1. INTRODUCTION

Fixed fire fighting systems (FFFS) are the subject of renewed interest following recent recalculations of fire size and a series of extreme tunnel fire events. FFFS have been used extensively in Japan for more than 40 years and are also found in all of Australia's congested urban road tunnels.

However there remains little theoretical data in the literature about their performance. Recent investigations by both FFFS vendors and researchers are finally revealing some of the details of how FFFS work and how to optimise them in a tunnel.

The fatal Burnley Tunnel incident in Australia of 23 March 2007 provides a rare insight into the effectiveness of these fixed fire fighting systems. Unfortunately most of the technical details of the Burnley Incident remain secret. The detailed investigation report is subject to a legal suppression order and the "Report to the Victorian Coroner, The Fatal Burnley Tunnel Crashes Melbourne, Victoria, Australia (Arnold Dix 2008) cannot be made public. This paper uses evidence from the Supreme Court criminal proceedings of mid 2009 which is not suppressed to reveal some of the events of 2007.

Although it must be conceded that the statistical significance of the Japanese and Australian experience is unclear, neither Japan nor Australia has experienced a catastrophic tunnel fire despite numerous tunnel fire incidents. The Burnley fire provides a critical insight into how fires in Japanese and Australian tunnels are managed.

2. NEW LEARNINGS

Recently published literature is providing insights into the effects of FFFS and how to optimise its integration into tunnel safety systems.

2.1. Unshielded Fire Growth

Large scale tests by SP Technical Research Institute of Sweden examine the water discharge density, water pressure and its effect on cargo fires.[1]

The results of these tests clearly established a relationship between water application rates, fire growth rates and heat release rates. Importantly the research suggests that there are critical water application rates below which the FFFS has virtually no effect.[2]

Interestingly discharge densities of 15mm/min provided immediate fire suppression, 10mm/min fire suppression and 5mm/min fire control. This relationship was also influenced by operating pressure – the higher the pressure the better the performance. Mist systems were also investigated and as a general rule were found less effective than the same application rate in a sprinkler system. See Figure 1. Neither system was effective against shielded fires. [2]

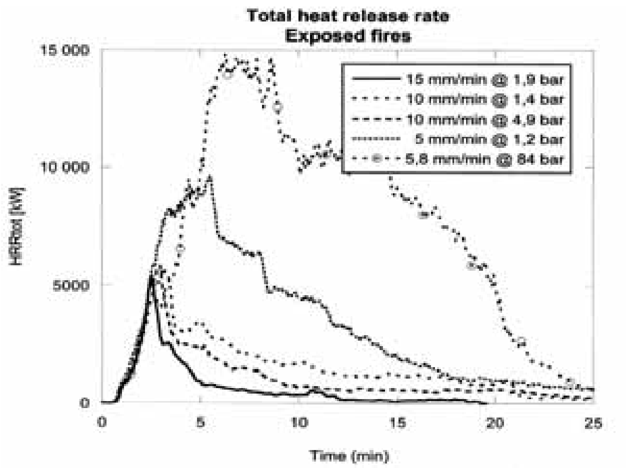

Figure 1:
Total heat release rate histories for the fire tests using various water application rates and pressures without shielding. (Arvidson 2010 [2])

However water mist systems are generally regarded as a viable alternative to sprinklers because they are able to achieve good attenuation of heat radiation and cooling although they have reduced fire suppression performance. Mist systems require early activation to minimise fire growth and reduce peak heat release rates. [3,4,5]

Computational analysis using CFD has recently been undertaken for varying FFFS water application rates.[6] The results of this analysis suggest that for an unshielded fire there is a critical water application rate under which fire growth is not significantly reduced. In this CFD analysis the authors suggest it is around 4mm/min, however review of their CFD results suggests it may be higher (perhaps around 6mm/min). Like the scaled experiment results (above) shielded fires perform poorly no matter what the application rates although in all instances fire spread is controlled.

A summary of predicted heat release rates with varying water application rates is found in Figure 2.

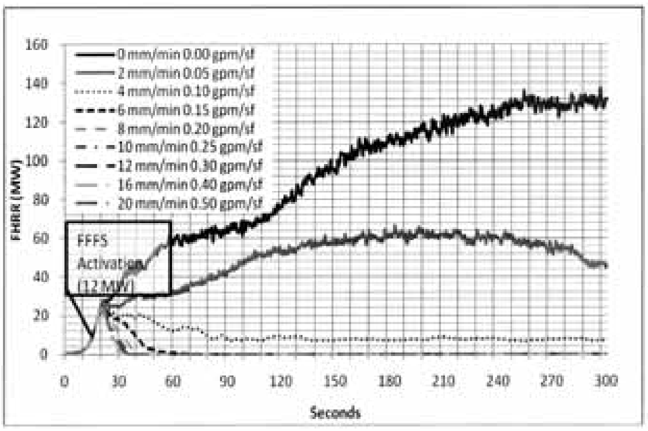

Figure 2:
Predicted CFD Fire Heat Release Rate for Varying Water Application Rates- Unshielded Fires (Harris 2010 [6])

This scale model and CFD experimental data is compared with the actual experience in the Burnley tunnel fire in the first section of this paper. In short it is consistent with the experience from Japan and Australia about the effectiveness of their deluge systems at fire fighting application rates of in the order of 10mm/min. The role of droplet size distribution in this performance warrants further investigation.

2.2. Shielded Fire Growth

All recent analysis suggests that FFFS has minimal impact on shielded fires. [6, 7]

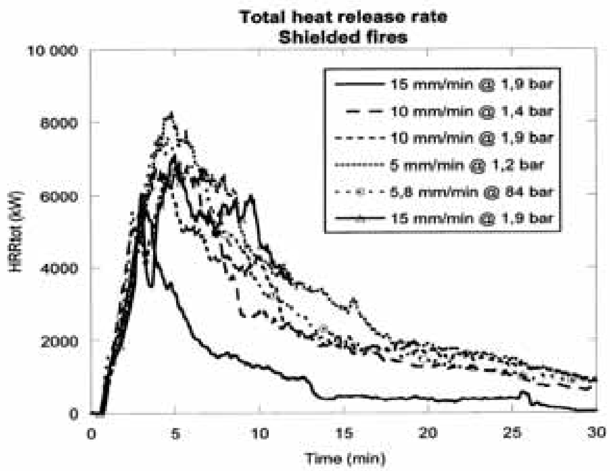

Figure 3:
Total heat release rate for shielded fires in full scale test (Arvidson 2010 [2])

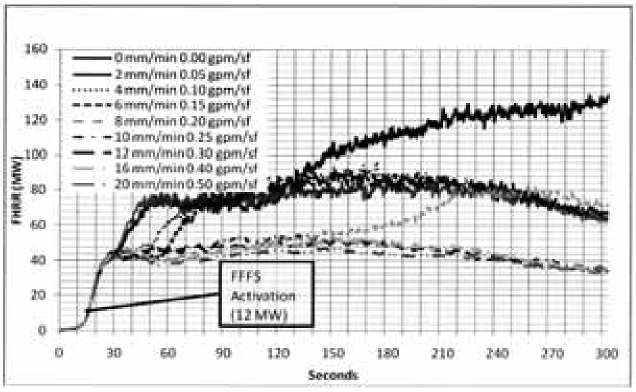

Figure 4:
Fire heat release rate for shielded tests using CFD analysis (Harris 2010 [6])

These results are consistent with earlier concerns by NFPA502 and PIARC that FFFS does not put out fires within vehicles. However in all instances fire spread is predicted to be substantially reduced despite the fire not being constrained when shielded. Furthermore the effects of FFFS activation upstream of an event and the migration of droplets horizontally beneath a shield have not yet been modelled in detail.

In practice multiple FFFS zones are operated in a real tunnel and the horizontal migration of water droplets under the effect of longitudinal ventilation may be the reason for enhanced FFFS performance even in shielded situations. This should be the subject of further research. The effects of FFFS in this regard are noted in the examination of the Burnley event in this paper. Fires were not extinguished by the FFFS in shielded environments nor in the Burnley fires.

One of the largest effects of FFFS is the reduction in radiated energy levels and the substantial reduction in the risk of flashover.

3. THE IMPACT OF FFFS ON TUNNEL VENTILATION

3.1. Backlayering

Increased interest in FFFS has rightly raised questions with respect to the management of backlayering during FFFS activation in an emergency. There has been literature on the phenomenon without FFFS but little or no published data with FFFS use.[8] Experimental data is now emerging which confirms that the control of backlayering is not an issue with FFFS activation. The longitudinal airflow is able to maintain backlayering because the FFFS reduced the smoke temperature thereby reducing the driving force propagating the smoke which reduces the amount of ventilation required to prevent backlayering.[7]

Although this is a theoretical study (based on a scale model) and does not take into full regard the effects of destratification it nonetheless is consistent with the experience from Japan and Australia that preventing backlayering is not an issue in tunnels with FFFS.

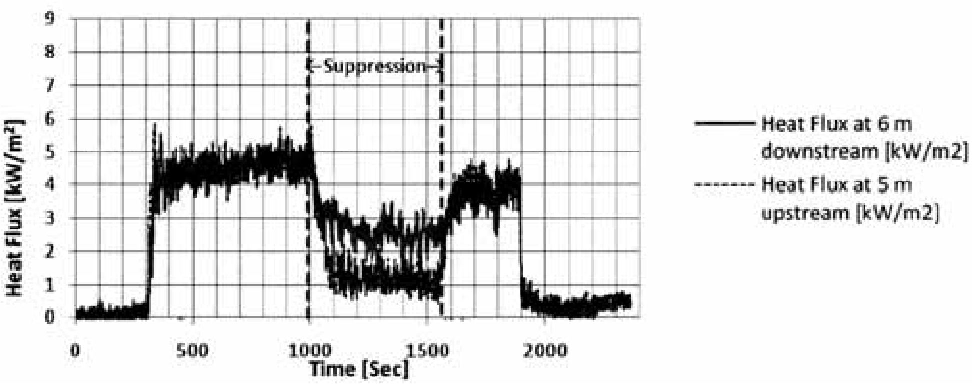

Figure 5: A comparison of heat fluxes measured 5m downstream and 6m upstream over time (Yoon J. Ko and George Hadjisophocleous 2010 [7])

The reduction in heat flux is thought to reduce the amount of energy required to stop backlayering.

3.2. Longitudinal Airflow

With a theoretical reduction in fire growth rates and heat release rates as a result of FFFS use it also follows that achieving critical airflow velocities remains a high priority in FFFS equipped tunnels. Indeed this is required in order to achieve both control of backlayering and not to increase the fire size by virtue of unnecessarily large longitudinal velocities.

It is already well established that increases in longitudinal ventilation velocity can increase heat release rates significantly. [9, 10, 11, 12]

Balancing the need to control backlayering with the undesirable acceleration of fire growth remains a high priority in real tunnels.

The most recent research suggests that the rate of burning of charring fuels (such as wood and thermo setting plastics) exhibits a clear dependence on ventilation velocity while pool fires are less sensitive to such changes. [13]

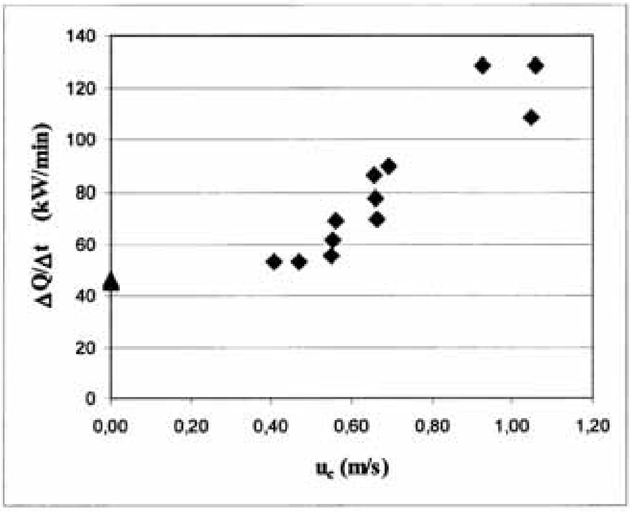

Figure 6:
The fire growth rate as a function of the longitudinal ventilation velocity [13, 14]

It is conceivable that early tests which relied upon pool fires for the test methodology would have failed to detect this phenomenon. Furthermore even where tests were conducted using non-charring fuels (the majority of synthetic polymers) they would have behaved like a pool fire. This may be an explanation for why such phenomenon has been poorly understood. The consequences of this are likely to have adversely impacted the size of fires in tunnels because of insistence by operators in operating high longitudinal velocities during emergency mode despite pleas from Fire Brigades to do otherwise. [15]

The positive impact of this phenomenon was revealed in the Burnley fire event where longitudinal velocities were rapidly reduced following the outbreak of fire and backlayering controlled while the FFFS concurrently operated successfully.

4. BURNLEY TUNNEL FIRE - MARCH 2007

The Burnley tunnel is a single direction, 3 lane tunnel of 2.9km length. It has a traffic flow of around 100,000 vehicles per day.

On 23 March 2007, at 09:52:30 am a truck travelling eastbound made an unscheduled stop in Melbourne’s CityLink Burnley tunnel. Over the next two minutes 103 vehicles passed the stopped truck without incident. Two minutes later, by 09:54:24 seconds several vehicles, including 4 HGVs and 7 light vehicles had crashed, 3 people were dead and fire and a series of explosions were initiated.

By 09:56:00am (two minutes after ignition) emergency ventilation and a fixed fire suppression system had been activated.

The following eye witness evidence from the criminal court case against the driver graphically illustrates the sequence of events:

- *---Essentially I heard the screeching of tyres. I looked in the rear vision mirror; saw the car careering into the back of the truck. The nose of the car went down, the car lifted up like that so - and then there was another smash from behind by a truck.*
- *---I saw the truck hit it and the - I can only assume that it was the gas tank of the vehicle that exploded.*

- *---I saw the explosion.*
- *---Well I continued to drive through the tunnel. There were - there was another explosion shortly after that which was a much bigger explosion. I remember the windows of my car vibrating as a result. There was also another announcement that came over the speaker saying that there had now been an incident in the tunnel and that vehicles were to slow down to 60 kilometres an hour… "*

This evidence graphically describes the crash, fires and subsequent explosions. The initiating events for this incident were large – large in the context of prior catastrophic events such as the engine compartment fire at Mont Blanc. Yet, despite the severity of these initiating events the fires were contained, with no flash over or other significant fire growth occurring once the deluge fixed fire fighting system was initiated.

However, it was not merely the presence of the fixed fire fighting system which was critical – it was that the ventilation system was effective in that it stopped backlayering (up a steep tunnel grade of 6%) and reduced the longitudinal airflow rapidly (to approximately 2m/sec) in order to optimize smoke extraction and minimize ventilation induced fire growth. It was the fire brigade that put the fires out – the deluge system merely kept the fires small enough to allow effective emergency services intervention.

Following is a summary of key events for the 2007 Burnley Tunnel Fires as given in evidence in the Supreme Court Proceedings DIRECTOR OF PUBLIC PROSECUTIONS v. DAVID LAWRENCE KALWIG 16/07/2009 [This evidence is indicative only of the events – the currently suppressed Technical Report for the Coroner (Dix 2008)] contains detailed technical information on the events):

- *"At 9:52:30 a truck stopped in the left (slow) of three lanes in the east bound Burnley Tunnel.*
- *Between 9:54:26 and 9:54:30 a series of collisions, explosions and fires occur when a truck crashes into several cars and HGVs in the region immediately behind the stopped truck. Eventually the truck which initiated the series of crashes hit the stopped truck and pushing it many metres forward.*
- *At 9:55:37 the tunnel operator enabled emergency mode in preparation for the smoke extraction, deluge operation and evacuation.*
- *At 9:55:50 the emergency response plan was initiated by the tunnel controller including activation of emergency smoke extraction and the deluge system.*
- *At 9:55:54 the smoke extraction system was activated.*
- *At 9:56 the fixed fire suppression (Deluge) was activated."*

Three people were killed in three different vehicles. Two of the three deaths were determined to be "effects of fire". The fires which killed these people were not, and could not, be extinguished by the deluge system as expected from the experimental results. [2, 6] All those killed suffered fatal serious physical injuries in the car crashes.

The lack of demand to the outsides of the vehicles involved in the fires, and the lack of fire spread by flashover is also to be expected from theoretical observations. [16]

The incident resulted in several hundred people being evacuated from the tunnel – and their vehicles. None of the evacuees or their vehicles was injured or damaged. The tunnel only suffered minor damage, and could have been re-opened 10's of hours later if the extent of the damage could have been more rapidly determined.

Mont Blanc Tunnel after fire (no suppression system.)

Burnley Tunnel after fire - road surface and tunnel walls and services still intact.

4.1. Discussion

In the Burnley incident the ventilation system rapidly reduced the longitudinal velocity to approximately 2m/sec. This low ventilation rate was sufficient to stop backlayering despite the buoyancy effect caused by the tunnels steep grade of in excess of 6.2% at the incident location.

The rapid activation of the FFFS and the comparatively low longitudinal velocities coincided with only minimal fire growth following the crash, explosions and subsequent fire.

This is entirely consistent with the theoretical results noted in this report.

The fire inside the structure of the prime mover was not extinguished by the FFFS but by the intervention of fire fighters. This is entirely consistent with the expectations derived from experiments involving shielded fires.

The absence of flashover and lack of accelerated fire growth is consistent with the experimental data on the effects of a FFFS with water application rates roughly in the order of 10mm/min.

5. CONCLUSIONS

The rapid and accurate use of Burnley's FFFS coupled with effective longitudinal air velocity control coincided with minimal tunnel damage, no non crash human victim fire related injuries and rapid reopening of the infrastructure.

There is now growing theoretical research which supports the view taken in Australia and in Japan that the use of FFFS coupled with advanced tunnel ventilation control, rapid incident detection and accurate response positively contributes to tunnel fire safety and asset protection. The differences in the performance of FFFS systems as a function of droplet size distribution warrants further analysis in the tunnel fires context.

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HOW SAFE CAN A TUNNEL BE – HOW SAFE WILL IT BE? – USERS' PERSPECTIVE

A Dangerous Driving Companion

Willy MATZKE; *ÖAMTC, A*

ABSTRACT

The Austrian motoring association ÖAMTC has analysed the safety measures which can limit the fear element in people and the extent to which such measures can be effective.

Fear can always be dangerous as it can paralyse the thought process. If there are real dangers present, people can be shocked to such an extent that they simply do not react or react inappropriately. This is apparent from analyses of plane, ship and train evacuations, and this is especially true of underground railways. As far as public transportation is concerned, there is the advantage that passengers are accompanied by trained personnel who, at least in theory, should be capable of dealing with extreme technical failures or accidents. They have to take command of the situation immediately in order to initiate appropriate rescue measures.

Figure 1: Smoke Accident in Tunnel Rannerdorf S1, March 2010

Roadway tunnels lack such advantages, moreover we may be solely responsible for our own rescue. Is it really possible to rescue oneself? Analyses of traffic accidents have shown that there are two primary extreme reactions: panicked flight and complete paralysis. People leap from bridges to their death or try to climb over noise protection barriers although it would have been possible to escape from the accident scene via the motorway. In tunnels people easily get lost if smoke coming from a fire impedes their view. Even the very distant and small explosion of an aerosol can quickly cause additional panic. This means fear is always driving us.... so what can we do?

Figure 2: Helicopter for Emergency must arrive very quickly

Nobody knows the driver`s mind better than the ÖAMTC. The motoring association has nearly two million members; this means that more than half of Austrian drivers are served by the ÖAMTC. Our experts deal with the changes regarding the aging driving population and we are getting ready for the future when older drivers, aged 80 or 90 will be part of our everyday lives. In future older people will represent the majority of drivers. How do they deal with modern tunnel equipment?

Fear: who has it, where does it come from and how could it be treated?

Since the tunnel catastrophes which occurred in recent years in single-tube tunnels which are similar in a way to black holes, we have had to accept that my warnings about tunnels being potential mass graves were no journalistic exaggerations but instead a bitter and sad reality. There is nothing which I would like to avoid more than causing panic, as this is exactly the thing which must certainly be avoided. Since the fire in the Tauern Tunnel fear has only grown among motorway users.

Figure 3: 30-50% of drivers do not have good eyesight when driving in dark tunnels

Of the people interviewed, 90% said that they have fear when driving through a tunnel and additionally they do not exactly know what to do in case of an emergency. They specifically mentioned bidirectional traffic in tunnels without escape routes, intermittent standstills in heavy traffic as well as bad tunnel air and bad tunnel lighting as being problematic. Many of us know that since 1999, there should have been no single tube tunnels on the Austrian highway network, even if at that time the tunnel guideline did not yet exist. The Tauern Tunnel catastrophe has shown us that there is a huge gap between theory and practice, and additionally we have learned that safety concerns can fall by the wayside, if politicians value the next election more than the safety of the citizens. The second tube of the Tauern Tunnel was only opened recently, but drivers will have to continue to deal with bidirectional traffic until the summer of 2011.

After upgrading both lighting and ventilation equipment as suggested by the tunnel committee, and after the utilisation of a tunnel inspector at the request of the ÖAMTC, the percentage of drivers affected by fear was reduced to 70 to 80 percent.

Figure 4: Emergency lane and escape doors reduce the percentage of fear to 50%

One single measure, adding second tunnel tubes to avoid bidirectional traffic, helps to reduce the percentage to not less than 50 percent. Additionally, if there are marked escape routes at distances of less than 500m, people automatically feel more safe. Obviously escape routes leading to a connection free of vehicles or to a rescue area rather than to the second tunnel tube are optimal. Such model tunnels already exist, for example in Madrid. Another solution would be the construction of secured emergency areas as it is included in the rescue protocol for the Arlberg Road Tunnel in combination with the associated railway tunnel. Both drivers and also firefighters are aware of the fact that the best solution consists of providing as many connections to the outside as possible. This is one of the reasons why the ÖAMTC, for the sake of all drivers, will never accept a 6 to 8km long tunnel running under the Lobau area which lacks an escape route to the outside.

Figure 5: Soft entrances make tunnels safer

Tunnels can be regarded as nearly perfect if they have portals which are designed with crash protection barriers (e.g. on the S1 expressway between Vösendorf and Schwechat) if they have breakdown lanes running throughout the entire tunnel length and if they are illuminated by white light, such as the Tanzenberg Tunnel. In such a tunnel, the proportion of drivers affected by fear decreases to approximately 30%. Our main aim should be to raise the safety level of tunnels to the extent that it is equal to that of open road sections. This is particularly important in view of the fact that a third of the drivers still feel fear when driving through a tunnel.

Figure 6: White light instead of yellow is much safer

It is widely known that portal areas may be extremely dangerous. Do we have to accept this? I believe that it is unacceptable that snow removal vehicles bring ice and snow into the tunnel and thus cover the LED lights along the edges with snow as these lights are very important in terms of safety. Often the snow remains in the tunnel for weeks and the melting water leads to

LED blackouts in areas. Roof overhangs and turning areas for snowplows no longer exist for reasons of cost savings; i.e. driving safety is compromised in order to reduce costs. Even simple frost in the tunnel portal area led to several accidents earlier this year. This is due to differences in air temperature and humidity and could be prevented by installing roof overhangs as well as through the installation of driving lane heating or automatic salt releasing devices, but both of these solutions would require intensive maintenance and both are prone to failure and expensive to install.

Lorry drivers represent a special risk as they often drive too fast and too close to the vehicle in front and, additionally, often behave in a criminal way. Flashing alert signals may prevent inattention but not criminal behaviour which has become everyday reality. In Italy lorry drivers have to keep a safe distance of 70m on an increasing number of open road tracks; in other countries lorry drivers and dangerous goods drivers have to keep safe distances of 100m and 200m respectively when driving through a tunnel.

Lorries and buses losing chunks of ice when going through a tunnel can cause fatal accidents breaking the windscreens of oncoming vehicles; in some cases, they may also damage cables and thus cause blackouts of the tunnel lighting.

As we know that broken lorries which are pulled from traffic circulation are often being used illegally and lack valid driving documents, we can see that financial gain can lead to criminal behaviour. However, drivers are often acting in this way because their fear of losing their jobs is greater than their fear of the penalties. Hence more control areas are required especially on sections including tunnels and the highway companies should be authorized to carry out safety checks with the help of appropriately trained personnel. Parking areas should not be closed and instead should be preserved for use as control and holding areas. As far as the Tauern Autobahn is concerned, the areas currently used for stop-and-go system, which next year will hopefully not be necessary any more, could be used for this purpose.

Figure 7: The red lights should flash in case of a traffic stop

Do vehicles really always stop at red traffic lights? Not all the time. Even bans on driving announced by means of remote systems are often ignored. The installation of barriers is not the optimal solution for an alpine country as they may be covered by snow. But what could really help? The green light should be dimmed as it is often blinding and drivers simply adapt to this repeated exposure to bright lights. Red light should be as glaring as possible and flash or blink as this has proven effective for yellow blinking alert lights. I do not consider the argument valid that this would require laborious changes to the existing regulations as I think that administrative authorities, which are generally cost-obsessed, must no longer ignore safety aspects. It is certainly a fact that in the past fatal accidents were caused by green traffic lights installed at both sides of single-tube tunnels as drivers considered the lane for the oncoming traffic as available for driving. I pointed this out in a former tunnel safety congress held here in Graz and the necessary changes were carried out immediately; I am grateful for that. But not all tunnel traffic lights have been changed in this way.

Figure 8: Green lights on both sides of Schmitten Tunnel in bidirectional traffic

The Schmitten Tunnel at Zell am See in the Austrian Salzburg region (5.1 km of opposing traffic and bad lighting) still has green traffic lights on both sides of the tunnel portal. Thus it is no wonder if there are repeated head-on collisions. But I would like to positively point out that wrong way lorry drivers, for example on the Arlberg roadway section, can be detected in a timely manner in order to successfully warn drivers – but a little bit of luck is needed.

As traffic accidents are mainly caused by driver error, what can the ÖAMTC do to prevent drivers from behaving incorrectly.

We will continue to carry out tunnel tests throughout Europe (EUROTAP), even after 2014, the extended deadline for the upgrading of tunnel equipment in Austria and Italy. Awarding of prizes for the best equipped tunnel is intended to encourage competition.

We have learned that even the best tunnel equipment cannot be efficient enough if the emergency service staff is not regularly trained to deal with incidents. We have the opportunity to attend every tunnel training, and we continue to learn more and more.

We thank you for the invitation to this tunnel congress - together we have already brought about many improvements.

We are always prepared to contribute if the topic is safety improvement as we believe that it is crucial to influence drivers in such a way that they stop being afraid and begin to think and act more clearly. Safety should be the first thing on their mind.

Figure 9: A Vision for the future: Tunnels Safety Awards for all Austrian tunnels

HOW SAFE CAN A TUNNEL BE – HOW SAFE WILL IT BE? DESIGNERS' PERSPECTIVE

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ABSTRACT

Tunnel system designers have to work with the locally-approved design approaches be it using the local design guidelines or using a risk or performance based approach. Some of the issues raised by the two approaches are discussed and a number of other issues faced by designers are identified.

Keywords: tunnel, design, guidelines, risk, performance, incident ventilation

1. INTRODUCTION

The options available to the designer with respect to the choice of safety-related equipment and systems depend on the country in which the tunnel is located and the relevant legislation that is applicable there. In a number of countries there are no real options as the local regulations define what is required for a particular length and type of tunnel. All the designer has to do is apply them; it's just a case of "sizing" to suit the particular conditions. In other countries – where a risk or performance based design approach is acceptable – the designer can, in theory, "choose" the most appropriate systems to achieve an acceptable level of safety. The approaches available to designers are discussed and some of the problems they face are identified.

2. DESIGN GUIDELINES

Since the Mont Blanc, Gotthard and Tauern incidents the EU has introduced the Directive on minimum safety requirements for road tunnels on the TERN[1] and this multi-national legislation is, in many countries, now being used for all tunnels. A number of countries have also revised and strengthened their design guidelines as a result of these and other incidents. One would have hoped that after all the experience accumulated throughout the world over the last 50+ years there would be some amount of similarity between the guidelines in different countries. In some things there are but in others there are not.

One of the classic differences concerns short tunnels or, when does a "long bridge" become a tunnel? The "definition" of a short tunnel and the safety measures required varies from country to country as illustrated in **Figure 1**.

The EU and half the countries shown have a set tunnel length beyond which all the safety measures for a tunnel in that country are required; less than that no particular measures are required. The length that this transition occurs varies from a maximum of 500 m down to just 150 m in the UK. The other countries listed define that some safety measures are necessary in tunnels which are shorter than "real tunnels".

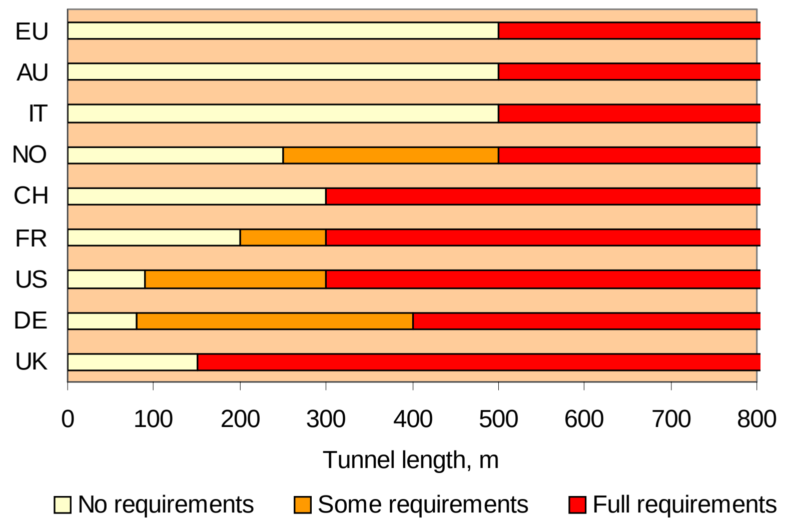

Figure 1: Tunnel safety requirements vs tunnel length in various countries

Passive safety measures such as emergency exits are effective in short tunnels as are some active systems such as emergency lighting but several countries also require that a mechanical ventilation system be provided for an emergency. The practical difficulties of providing such systems in short tunnels have been identified[2] especially when there is a longitudinal gradient and a large design fire. A classic issue occurs when the length of a tunnel is close to the transition between requiring and not requiring a ventilation system, usually a longitudinal system with jet fans. In one tunnel known to the author the original design was with just natural ventilation but this was rejected by one of the project's stakeholders because "it needs some jet fans to blow the smoke out of the tunnel". A second design with a longitudinal system was also challenged because "there are too many jet fans in the tunnel, we don't need that many". The second design was accepted, albeit reluctantly, once it was explained that you either had an emergency ventilation system or you did not, you could not have half a system, and that the system required that many fans.

One of the "problems" with design guidelines is that they change periodically, often within the relatively long time-span of a tunnel project. In many disciplines the relevant versions of the design guidelines are set at the start of the project and are not changed even if the guidelines themselves change during the course of the project. However this approach is not acceptable for safety-related issues and designers have to adapt their design to satisfy the new requirements. Sometimes those changes are minor and can easily be incorporated into design irrespective of the stage of the project. However some changes can and have had major impacts on projects, especially when they occur once the construction of the tunnel has started. One such example is changing the required ventilation system from a simple longitudinal one with jet fans to one requiring localised smoke extraction. The space available within the tunnel cross section is usually too small to allow a reasonably sized exhaust duct to be incorporated which results in high under-pressures in the exhaust duct, large leakages from the traffic space and high powered motors for the exhaust fans. Often, because of planning and/or environmental impact restrictions, there is also very limited space available for ventilation stations which further increases the pressure losses and, as a result, the motor power required for the ventilation system.

Guidelines usually also mean that the designer has little or no opportunity to optimise a design by improving one safety measure while reducing or replacing another even if the end result improves the safety for tunnel users. A simple example of this would be decreasing the spacing between emergency exits and installing a longitudinal ventilation system instead of one with localised smoke extraction. This approach is intended to be the realm of the risk or performance based design – but is that really the case?

3. RISK OR PERFORMANCE BASED DESIGN

The aforementioned EU Directive requires that a minimum level of safety measures be incorporated in tunnels. However the Directive has also introduced a requirement for risk analyses to be carried out to determine if more or enhanced safety measures are required in a number of specific instances including when the tunnel's longitudinal gradient is greater than 3%. Many of the countries directly affected by the Directive already require their tunnel design guidelines to be used to determine the necessary safety measures etc but most of the countries have no experience of using a risk-based design approach for road transport infrastructure.

In order for the risk based design approach to work, all of the interested stakeholders need to be involved in the design process so that they can "sign up" to the approach, the assessment of the risks and, as a result, the final design. But does this type of design process really work like that? Irrespective of whether a probabilistic or a deterministic approach is being used the design process should really start with the expected hazards due to the traffic, etc and an empty tunnel; the only safety measures that should be "added" are those necessary to achieve a required level of safety. In practice the starting point is usually not an empty tunnel but one with all the "normal" safety measures – emergency exits, lighting, radio, CCTV, drainage, fire hydrant system, SOS niches, etc as defined in many design guidelines – and the risk analysis process is carried out to demonstrate that these measures achieve the required level of safety. This is certainly the situation with respect to the EU Directive – certain safety measures must be incorporated which might have to be enhanced and/or augmented in certain circumstances depending on the results of the risk analyses. The thought of removing one of the "normal" measures – say the fire hydrant system – or of replacing one measure by improving another would almost certainly never be considered even if the result was that the required level of safety was still achieved.

But what is an "acceptable level of safety"? This is the aspect where the designers using a country's design guidelines have an easy task – if their design satisfies the guidelines then, by definition, the tunnel is safe enough. But how safe is that? Is it that the number of fatalities per year per kilometre in the tunnel should be no more than that on the open road on either side of the tunnel? Or is it that the tunnel is made to be as "safe as reasonably practicable" whatever that means. Although a number of suggestions have been put forward there appear to be no generally acceptable values for either societal or individual risk with respect to road tunnels; each project using this approach has to go through a process of determining values that the project's stakeholders believe would be acceptable. The EU Directive suggested that there would be a common risk analysis approach with, presumably, recommended levels of safety but, to date, nothing has been forthcoming.

4. OTHER ISSUES FACED BY DESIGNERS

The different design approaches required when using either design guidelines or the risk/performance based design are not the only issues that designers have to live and deal with. There are also groups, some from within the design community itself, that introduce further problems into the design process. For simplicity these have been identified as the "Bureaucrats", the "Modernisers", the "*Accumulators*", the "Universalists" and the "Automatons".

The "Bureaucrats"

A number of countries have introduced changes to their safety guidelines and/or the required safety measures without, it appears, a thorough understanding of the implications. It is only when the designers have to use them for a real tunnel that the implications of those changes become apparent. Even relatively simple changes such as the level of redundancy required for, say, the smoke exhaust fans have a significant impact on the layout, size and costs of ventilation stations. Furthermore the resulting design of the station is often far from optimal because of space restraints.

Additional safety-related equipment may be a new requirement but then, during the design of a real tunnel, questions arise about how this new equipment can be effectively and reliably integrated with all the other systems that are also required. A good example of this is smoke detectors. It is well known that the principal "problem" with fire detection systems is adjusting their sensitivity to minimise false alarms while giving a reasonable detection time. As a result there is an inevitable delay between the start of the fire and it being detected by such systems but, once detected, the location of the fire can usually be identified. Smoke detectors may detect quickly but the source of the smoke is unknown; is it stationary or is it still moving? Yes, smoke detectors can be a good early warning system but that is all they are. It is then almost impossible to do anything automatically with that information with respect to initiating and/or controlling the emergency ventilation system such as deciding reliably which smoke exhaust dampers to open.

The "Modernisers"

There are a number of instances where systems and approaches that have been shown to work well for many years are now being questioned simply because they are "old". The message that the "Modernisers" are giving is that this particular approach is old fashioned therefore it is no good today and there must be a better way.

There is a well known proverb which should be heeded by all – If it works don't fix it. Inventing "new" approaches or systems to "replace" older proven ones is not the way to make tunnels safer. Somebody might believe the message and actually install one of the new "wonder systems" and it might make the "Moderniser" quite wealthy. However, in the event of an incident, it is certain that the courts will determine if the "wonder system" really is an improvement over the old tried and tested one.

The "Accumulators"

This group want to equip tunnels with each and every conceivable piece of safety-related equipment that they can. Is this really done in the belief that it will make the tunnel safer or is it so that nobody can accuse them of not trying to make the tunnel as safe as possible? Do the "Accumulators" also insist that only those who have been suitably "trained" can use their tunnel?

There are two "sub-species", one usually owns or is responsible for one or more tunnels; the other is often a designer who also believes that the higher the costs of systems etc, they specify, the higher can be their honoraria,

The "Universalists"

These believe that, no matter where in the world a tunnel is located, it should be designed and equipped in the same way – which is usually in the same way it would be in their home country. They take no account of the local situation, resources and conditions. How can the design and facilities provided for an urban tunnel in Europe possibly be suitable for a tunnel 2'000 m up in the mountains of a 3rd world country? Who is going to service and maintain it? What about one organisation that provided a tunnel with systems that nobody in the particular country was capable of maintaining or servicing, it could only be done by bringing people and equipment from other countries. Or another where a sophisticated ventilation system was installed that needed significantly more power than was available at the tunnel's location?

The "Automatons"

This group believe that everything can be achieved by suitably programming the appropriate systems and that no account has to be taken of the idiosyncrasies of people, particularly when those people happen to be the drivers of the vehicles using their tunnel. There are numerous records of drivers taking what most would believe to be totally unreasonable actions, none of which could possibly have been taken into account in the system programming.

The safety provisions have to take account of the different behaviours of people, especially in a stressful situation. Some countries such as Switzerland, have successfully "trained" their tunnel users how to respond in a tunnel emergency. When are other countries going to follow suit and do the same? Yes, it costs money and time but it is valid for all the tunnels; it doesn't have to be done for each individual tunnel as is the case for most safety measures.

5. DISCUSSION

Society seems to accept that road accidents occur and some of them result in fatalities whereas they do not appear to accept any fatalities occurring in an incident involving a fire in a tunnel. Bearing in mind that less than 150 people have ever been killed anywhere in the world in road tunnel incidents involving a fire – and that includes those killed by any preceding accident – this means that the fire safety aspects of road tunnel design must be reasonable.

The current trend for trying to improve tunnel safety is towards providing ever more active safety systems almost all of which are directly concerned with reducing the consequences of a fire – as are many of the existing safety measures. The question has to be why are we not improving the passive safety measures which will always function and also have low maintenance costs? Is it because their capital costs can be high or is it because there is no "glamour" in these solutions; no fancy electronics and computers and, as a result, they cannot be "any good"? Although active safety systems may have a lower capital cost many of them have large whole life costs due to the testing, maintenance and replacement that is required and, after all that, they still may not function correctly on the rare occasions they are required. On the other hand they can always be blamed when they don't work correctly when required! Maybe that is the real reason why so many systems are now being installed – hoping that each will act as a back up for the other when one doesn't work!

This raises the question of how reliable are each of the systems and is there any confidence that each (or any) of them will work correctly when they are required? If there is not a reasonable level of confidence that they will function correctly when required then why are they being installed? Similarly, but more importantly, what should be done if one of the safety systems is out of commission. The design process – be it based on design guidelines or performance – has determined that each system needs to be installed to achieve the required level of safety in the tunnel so, when that system is not available, should the tunnel then be closed? Or does it depend on how long the particular system is not working? Who takes the decision that the tunnel is not "safe enough" so has to be closed – the operator, the owner, the designer? Has anybody even thought about what systems must be available in order to safely operate the tunnel?

Although no fatalities are acceptable it has to be accepted that in the real world some are inevitable. Resources should be used to achieve the maximum benefit (i.e. in this context, to save the maximum number of lives) and maybe the large sums of money being spent to "improve the safety" of road tunnels (particularly fire safety) could be better spent on other parts of the road network where the cost per life saved is much lower. The cost-effectiveness of different safety measures in road tunnels in the Netherlands – a country where the principles of risk-based design are generally accepted – have been assessed by Arends[3,4] and this approach could usefully be adopted in other countries, particularly those with large numbers of tunnels, to optimise their expenditure on tunnel safety measures.

6. CONCLUSIONS

Designers that are required to use guidelines to determine the safety measures needed in road tunnels do not know the level of safety that is actually achieved.

Risk/performance based design is hampered by the lack of generally agreed a) risk analysis process for road tunnels and b) values for acceptable societal and individual risk levels for road tunnels.

The responsible authorities should fully understand the implications of any new requirements before introducing them.

Safety measures that have been proven to be effective should not be challenged.

Equipping a tunnel with each and every safety measure does not mean that the tunnel is safe.

There is no universal design for road tunnels; it must depend on local conditions and resources.

The behaviour of tunnel users cannot be assumed; they have to be "trained".

The minimum acceptable level of operating safety measures should be determined for each tunnel and a tunnel should be closed when that level is not achieved.

Increased emphasis should be placed on improving passive safety measures rather than introducing more and more active systems.

The cost effectiveness of safety measures should be taken into account when equipping road tunnels.

7. DISCLAIMER

The opinions expressed in this paper are those of the author and do not necessarily reflect those of Pöyry Ltd

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RECENT DEVELOPMENTS AND APPLICATIONS OF TRACER GAS METHODS IN ROAD TUNNELS

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ABSTRACT

Determination of ventilation efficiency in buildings and tunnels is one of the leading skills of the Lucerne University of Applied Sciences and Arts. One favoured measurement technique is the tracer gas method, where sulphur hexafluoride (SF_6) or nitrous oxide (N_2O) is injected into the air flow and its concentration is measured downstream by infrared gas analysers at different locations through single- or multipoint-sampling. The commonly used method is the constant emission tracer gas method. Economical considerations initiated the authors of this paper to find a new method which needs less tracer gas with equal or more precise results as the constant emission method. These investigations have led to a new method called pulsed emission tracer gas method.

The present paper briefly recalls the experience gained in tunnels with the constant emission method, describes the method itself and presents the state of development of the new pulsed emission method.

Keywords: ventilation efficiency, tracer gas methods, pulsed emission, constant emission

1. INTRODUCTION

After several heavy accidents in tunnels in the last few years the guidelines for tunnel ventilation have become stricter, especially for safety installations. It has been recognized that emergency situations have to be better considered at the stage of the design of the ventilation system. It was realized however that there was not a lot of data available to fall back on. Therefore a Swiss Federal Road Authority research project led by Pöyry Infra Ltd. in collaboration with Lucerne University of Applied Sciences and Arts (LUASA) was started in Switzerland, running from 2007 to 2009, to determine the tightness of exhaust ducts in several road tunnels in which the constant emission tracer gas method (CEM) was successfully applied.

The application of several experimental set-ups for the determination of leakages and volume flows for different tunnel ventilation layouts has been described by Frei /2008/. The tracer gas is injected into an exhaust duct, dispersed by turbulent flow and the concentration measured downstream as shown in **Figure 1**. The mass of tracer gas and the concentration at the measuring point deliver the needed data for calculating the flow and leakage rates. First results were published by Buchmann /2008/ at the 4th International Conference Tunnel Safety and Ventilation. Further results, calculations, and recommendations are reported by Buchmann /2010/ in these conference proceedings.

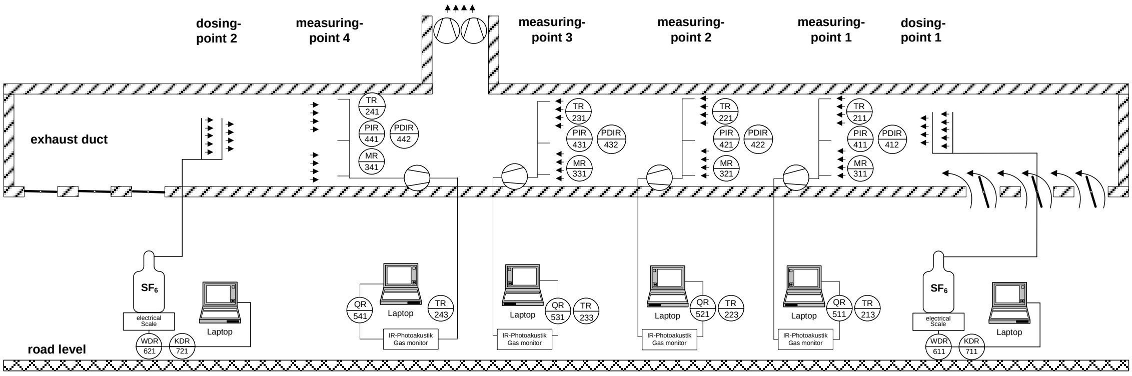

Figure 1: Experimental set-up for quantification of exhaust duct leakages

In road tunnels without an exhaust duct the exhaust gases are extracted from a ventilator on road level. However, a risk was identified that the motion of vehicles in the tunnel might generate a malfunction of the fan leading to increased concentrations of exhaust emissions from the vehicles. HBI Haerter Ltd. and LUASA quantified the volume flow rate and short circuits of air on road level in four road tunnels applying the CEM from 2005 to 2009. **Figure 2** depicts an example of the tunnel Spier, Switzerland, where the efficiency of the exhaust extraction system was successfully determined by means of the CEM.

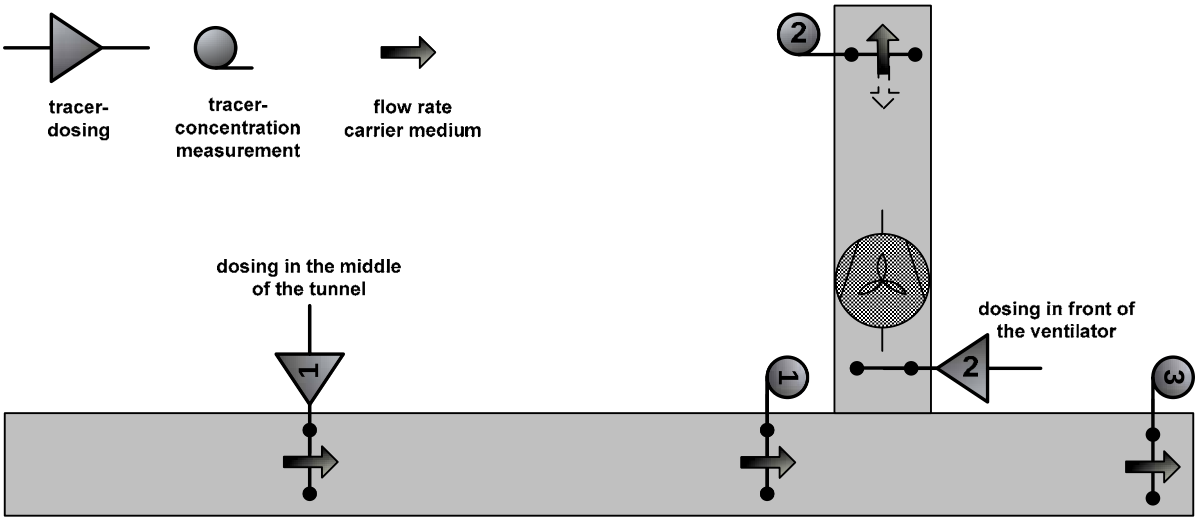

Figure 2: Experimental set-up to quantify ventilation efficiency in tunnel Spier, Switzerland

The CEM method is completely independent from flow profile disturbances and regarded by literature as reference compared to flow rate calculation methods based on velocity measurements. The drawback of the method is the big amount of tracer gas and the time-consuming measurement.

These drawbacks initiated the authors of this paper to find a new method which needs less tracer gas with equal or more precise results as the CEM. The idea of the alternative method was to replace the constant injection of tracer gas during the measurement period by a pulse of tracer gas. This would lead to a smaller amount of the gas used and a reduced time for measuring.

2. CONSTANT EMISSION TRACER GAS METHOD

The constant emission tracer method has been used by LUASA since 2002 to determine volume flow and leakage in exhaust ducts of sixteen road tunnels in Switzerland, Germany, and Slovakia. Tracer methods are completely independent from flow profile disturbances and are regarded by Bettelini /2008/ as reference method compared to flow rate calculation methods based on multipoint velocity measurements. Tracer gas, usually sulphur hexafluoride (SF_6) or nitrous oxide (N_2O), is injected into the carrier medium through mass flow meters, dispersed by turbulent flow and measured downstream at different locations through single- or multipoint-sampling. Due to leakages of the duct the measured tracer gas concentration is different at point 2 compared to point 1.

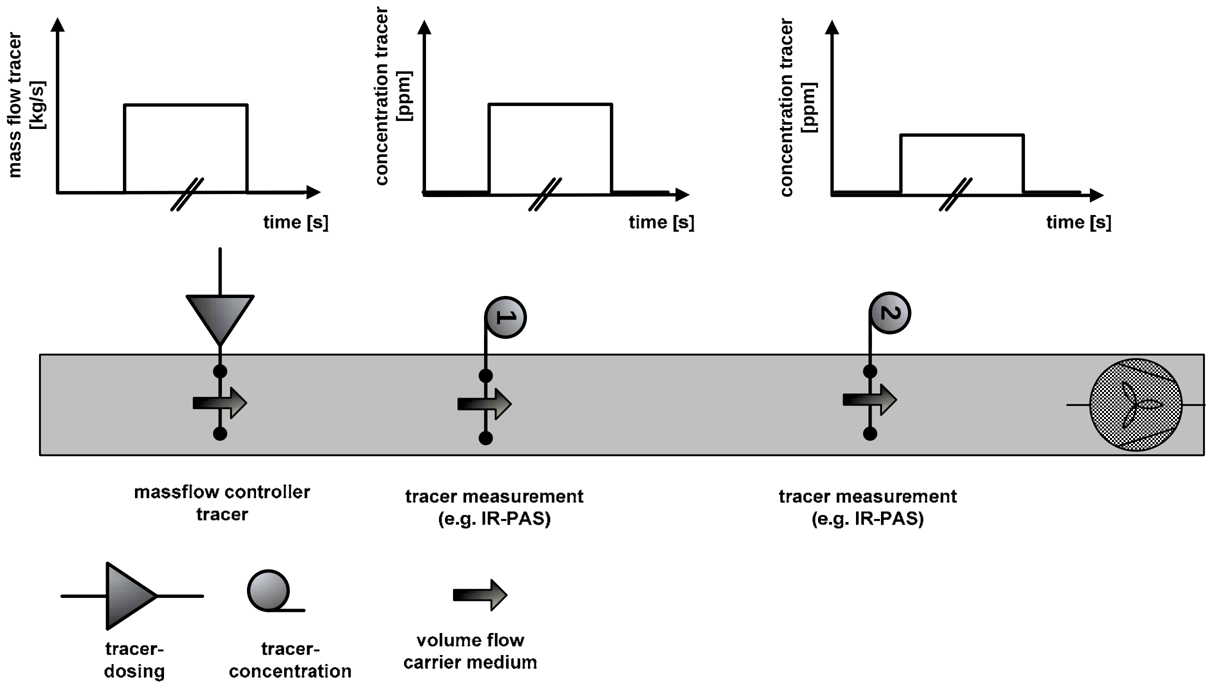

Figure 3: Experimental set-up of the constant emission tracer method in exhaust ducts

Equation 1 mentioned by Frei /2008/ allows to calculate the volume flow of air $q_{V\,Air}$ at the measuring point with the determined concentration of tracer gas and the mass flow of it at the dosing point.

$$q_{V\,Air} = 10^6\,ppm \cdot \frac{1}{\rho_{Air}} \cdot \frac{R_{Tracer}}{R_{Air}} \cdot \frac{q_{m\,\mathrm{Tracer}}}{c_V} \qquad \left[m^3/s\right] \qquad \textbf{(Eq. 1)}$$

$q_{m\,Tracer}$	mass flow of tracer at the dosing point	[kg/s]
R_{Tracer}	specific gas constant of the tracer	[J/(kg K)]
R_{Air}	specific gas constant of the air in the exhaust duct	[J/(kg K)]
c_V	determined volumetric concentration at the measuring point	[ppm]
ρ_{Air}	density of the moist air at the measuring point	[kg/m^3]

3. PULSED EMISSION TRACER GAS METHOD

The pulsed emission method (PEM) is not a new idea. Earlier applications of PEM were hindered by two important facts: Accurate tracer gas dosing and fast enough concentration measurements were nearly impossible due to technical limitations. Today, accurate dosing through mass flow controller/meters and fast tracer measurements by Fourier Transformation Infrared Spectroscopy (FTIR) and/or Non Dispersive Infrared Spectroscopy (NDIR) are both possible. The PEM basically applies two numerical integrations: Upstream the tracer mass flow over time and downstream the tracer gas concentration over time (see **Figure 4**).

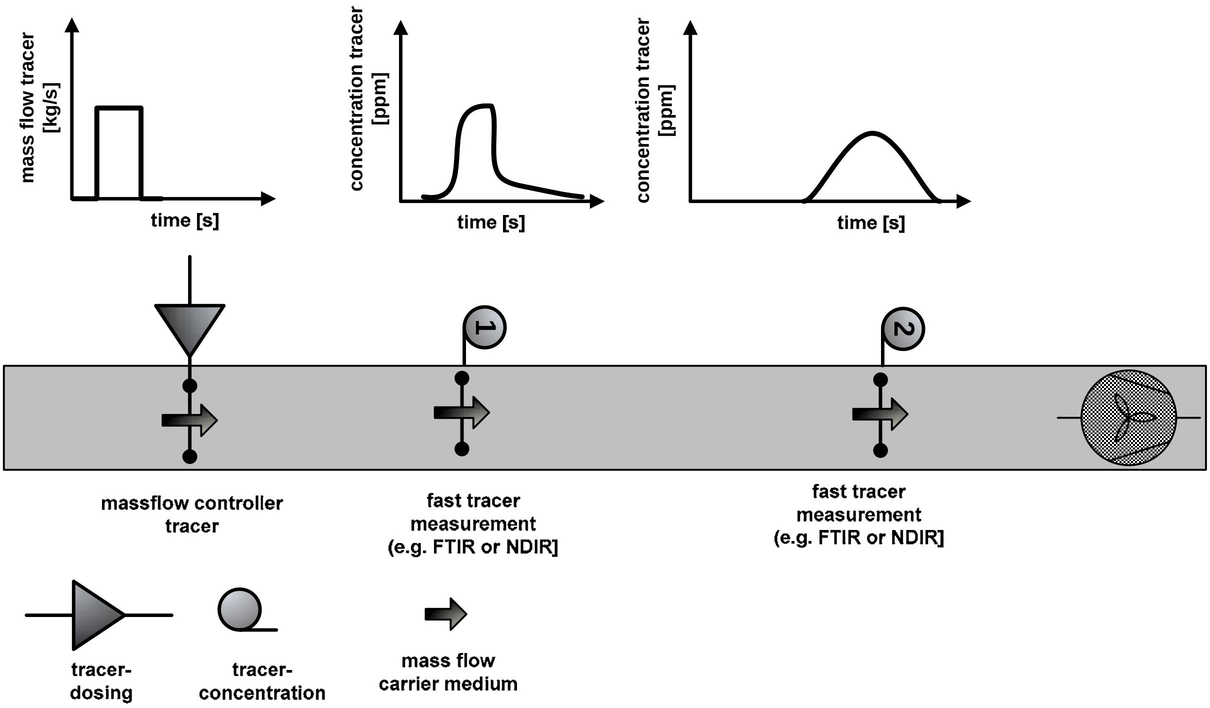

Figure 4: Experimental set-up of the pulsed emission tracer method in exhaust ducts

A tracer gas pulse with a mass flow rate of $q_{mTracer}(t)$ is injected upstream and the time varying tracer gas concentration c(t) is measured downstream at positions 1 and 2. It is essential that the tracer gas is well mixed with the air. Furthermore, the whole amount of tracer gas must have left the duct at the time t_2. If that is the case the following integral mass balance, **Equation 2**, reported by Persily /1990/ is applicable.

$$\int_{t1}^{t2} q_m(t) \cdot c(t) \cdot dt = \int_{t1}^{t2} q_{m\,Tracer}(t) \cdot dt; \quad q_m(t) \geq 0 \qquad \textbf{(Eq. 2)}$$

Concentration c(t) is a mass fraction

t_1: start injection

t_2: time at which the tracer gas has purged through the duct

Assuming a constant air mass flow during the observed time interval, and considering that the mass flow of the tracer gas is negligible compared to the air mass flow, the mass flow of air can be calculated according to **Equation 3**:

$$\overline{q}_m(\xi) = \frac{\int_{t1}^{t2} q_{m\,Tracer}(t)\cdot dt}{\int_{t1}^{t2} c(t)\cdot dt} \qquad t_1 \le \xi \le t_2 \qquad \textbf{(Eq. 3)}$$

Considering the volumetric concentration rather than the mass concentration of the tracer gas in the air, **Equation 3** is transformed to the following:

$$\overline{q}_{m\,Air} = 10^6\,ppm\ \frac{R_{Tracer}}{R_{Air}} \cdot \frac{\int_{t1}^{t2} q_{m\,Tracer}(t)\cdot dt}{\int_{t1}^{t2} c_V(t)\cdot dt} \qquad [kg/s] \qquad \textbf{(Eq. 4)}$$

$c_V(t)$:	volumetric tracer gas concentration at the time t	[ppm]
$q_{m\,Tracer}(t)$:	mass of tracer gas at the time t	[kg]

Equation 4 is equivalent to **Equation 1** with the difference that the mass flow of the tracer gas at the dosing point as well as the measured concentration are no longer constant and have to be integrated over time.

4. DEVELOPMENT OF THE PULSED EMISSION METHOD

4.1. Tracer gas dosing

The tracer gas pulse is injected by means of a fast mass flow controller valve. A special tool has been developed by LUASA in order to control the valve and to generate tracer gas pulses of varying shape. Recent investigations of the pulse design for the injection and the calculated test pulses from three different tunnels have shown that it is very important how the injection is accomplished. If a rectangular pulse is injected into the exhaust duct a similar shape of time varying concentration is measured at the measuring point. Since the time varying concentration profile needs to be integrated over time, the response time of the analyser is now the determining factor for the time interval dt between two points of the integration. If the gradient of the concentration profile is large, it is difficult to perform precise integrations. The tool therefore allows designing free selectable pulses. **Figure 5** displays a prepared pulse for an injection in a duct. If four of the interpolation points in the graph are set, the curve is automatically plotted. The tool communicates with the controller valve and governs the injection valve accordingly. Even more, the tool allows checking the actual position of the valve and the already dosed amount of tracer gas. Thus equipped, it is possible to inject the tracer gas as it is required in a specific situation and depending on the type of gas analyser used.

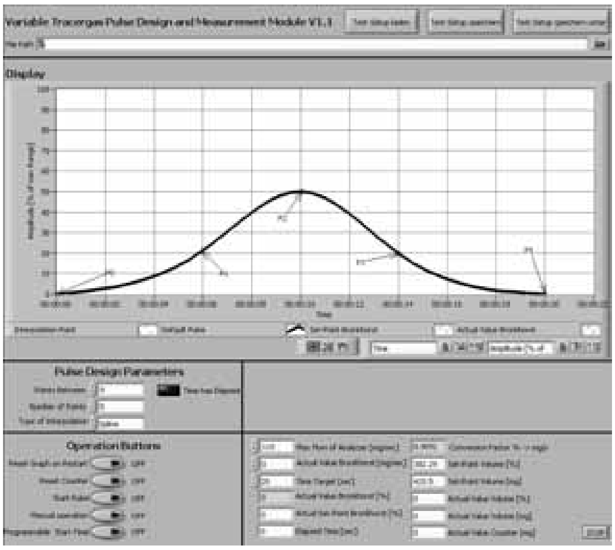

Figure 5: Design and numerical integration tool for individual pulses upstream

4.2. Calculation tool for the concentration signal integration

Working with a pulsed injection of the tracer gas implies having to integrate the downstream integration signal as indicated in **Equation (4)** in order to calculate the actual mass flow of the carrier medium. A specific tool was developed as shown in **Figure 6** to simplify the integration of the time varying concentration. The tool considers parameters as temperature, pressure, humidity and the mass of tracer gas. Four different types of integration methods are implemented (trapezoidal; Bode; Simpson's 3/8 and Simpson) but comparisons on sensitivity have shown that no significant differences in integration quality respectively in mass flow of air are identifiable.

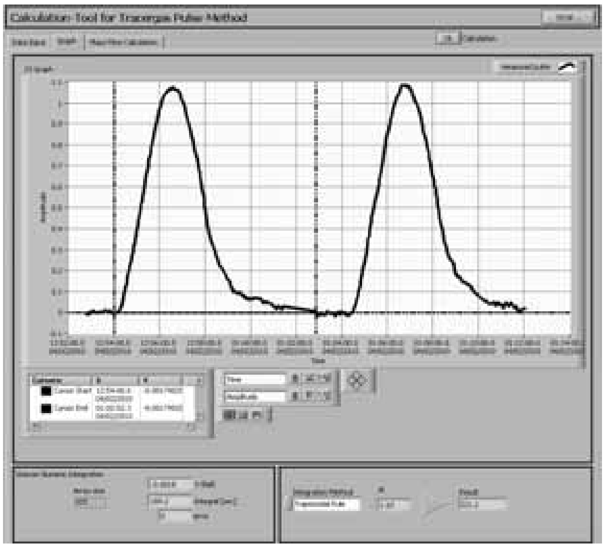

Figure 6: Numerical integration tool for measured pulses downstream

Once the concentration data are entered, the start point and the end point of the time interval t_1 to t_2 have to be specified with two cursers. In case of a background concentration this offset can also be corrected with the curser. A further advantage of this tool is its flexibility with regard to the tracer gas used, making the tool universally applicable.

5. FIRST EXPERIENCE WITH THE PULSED EMISSION METHOD

During the mentioned research project led by Pöyry Infra Ltd., first experiences with the new PEM were made in three tunnels, the Swiss road tunnels Kirchenwald (2008), Aescher (2009), and Islisberg (2009) and since Islisberg gradually further developed by means of experimental investigations in the LUASA laboratory by the authors of this paper.

Figure 7 show tracer gas pulses downstream at different distances originating from rectangular pulses from dosing points upstream. The dosed amount of tracer gas for one pulse is about eighty to hundred grams instead of two to four kilograms used with the constant emission method. For validation purposes tracer gas measurements were done through single- and multipoint sampling. Both sampling strategies show good agreements and therefore excellent mixing even shortly after dosing.

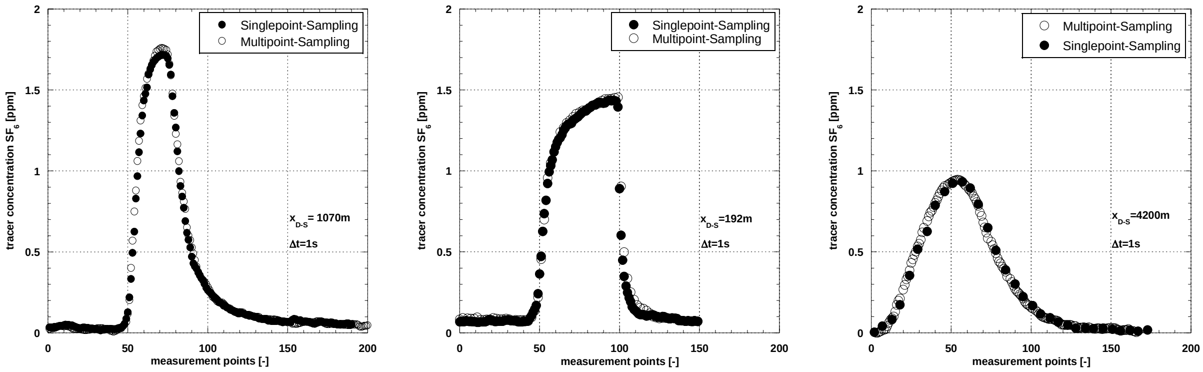

Figure 7: Tracer gas pulses downstream in exhaust ducts of road tunnels. From left to right: Kirchenwald, Aescher, Islisberg

The mass flows determined with the PEM in these three tunnels vary about ± 5% from those evaluated with the constant emission method. These preliminary results indicate the potential of the pulsed emission method to determine the mass flow of air in an exhaust duct reliably. They also indicate that it might be possible to detect insufficiently ventilated zones within the duct, resulting in stretched-out concentration profiles. In further steps these results have yet to be substantiated.

6. CONCLUSION AND OUTLOOK

Several flow and leakage rates in different road tunnels have been experimentally determined by LUASA with the constant emission tracer method in the last few years and have shown the advantages of this technique. The main findings are that the flow is well mixed also shortly after dosing and the method is insensitive to variable flow profile disturbances, cross sections and obstacles. The relatively small expenditure of time for a measuring campaign in a tunnel usually allows to carry out the campaign during one night and this fact shows how effective and practicable this method is. Nevertheless there are some points to enhance, particularly the ecological and economical aspects.

Recent efforts have demonstrated that the pulsed emission tracer method is the correct answer to upgrade these aspects. One important advantage is the reduced tracer gas consumption by factors of 50 to 100. The simultaneous development of the fast tracer gas concentration recorders furthermore reduce the overall duration of the measurement campaign. The developed tools permit to adapt to different requirements such as the tracer gas used or particular pulse shapes. It could well be that the method will also allow to quantify flow behaviour related to dead zones within the duct. However to apply the pulsed tracer gas method successfully and use all this advantages, further investigations are still necessary:

- The current research around the pulse emission method has to be brought to a level which allows using this method confidently to determine leakages and flow rates in ducts.
- This implies further evaluation of the pulse emission method in existing road tunnels compared to the synchronously measured results obtained with the constant emission method.
- The measurement uncertainty according to ISO-standards of the method needs to be defined and compared to other methods.

Lucerne University of Applied Sciences and Arts will continue this work during the coming months and when occasions arise to validate the results in measurement campaigns and will also investigate to what extent the method can be used to determine flow rates or leakages in applications such as within buildings.

7. ACKNOWLEDGEMENTS

We would like to thank Josef Böcklin, Matthias Häfliger, Tahsin Boyman and Tjeerd De Neef for their continuous support and advice.

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NUMERICAL INVESTIGATION OF THE FLOW BEHAVIOUR IN A MODERN TRAFFIC TUNNEL IN CASE OF FIRE INCIDENT

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ABSTRACT

A numerical study of the flow behaviour in the Limerick Tunnel in case of a fire incident was undertaken. Due to the construction requirements, a 100MW fire in one of the two tubes was considered. The analyses were focused on the smoke removal in the incident tube and on the present pressure difference at the passage doors for a predefined massflow of the ventilation system. The numerical study was meant to judge the risk of a smoke migration from the incident tube to the other one. With the obtained pressure distribution at the passage doors, it was also possible to investigate, whether the resulting pressure at the fire exit doors prevents an opening of them.

Keywords: Numerical simulation, Saccardo nozzle, tunnel flow, fire incident

1. INTRODUCTION

The Limerick tunnel in Ireland represents a state-of-the-art city tunnel. The installed ventilation fulfils modern standards and guarantees low emission values even for high traffic rates. The ventilation system consists of five jet fans and a Saccardo nozzle, installed next to the tunnel entry and exit. Furthermore, the ventilation performs quite well in case of a fire incident: A nozzle exit speed of more than 30 m/s permits a fast removal of the toxic gases.

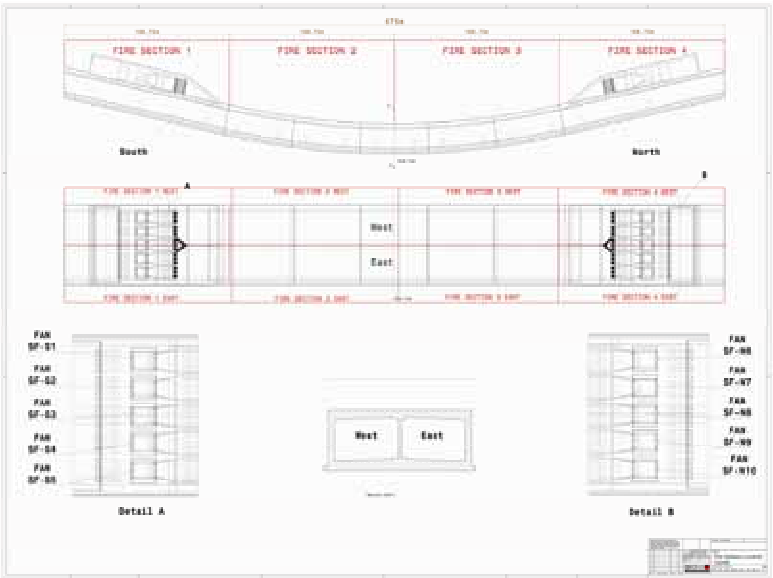

Figure 1: Tunnel building scheme with aerodynamic installations

Beside a fast smoke removal, a moderate pressure difference at the passage doors has to be maintained in order to permit an escape from the incident tube to the smoke-free tube. However, the setting of a reasonable pressure difference is quite challenging: One the one hand, the pressure difference should kept below a distinct level, permitting an opening of the door at any rate. On the other hand, the positive pressure gradient (directed from the incident to the non-incident tube) should be high enough to prevent the smoke from entering the non-incident tube, when the passage doors are open. Therefore an exact thrust setting is needed: A positive pressure gradient is realised by running only the fans in the incident tube at design speed. The rotational speed in the non-incident is then derived by the definition of a threshold pressure difference value. In the described case, the rotational speed was calculated analytically by considering global parameters of the tunnel and the ventilation. Aerodynamic losses were considered by defining distinct loss coefficients. In most cases, this represents a reasonable and fast method. However, local influences on the tunnel flow (like traffic sings) can be incorporated only in a rough way in such a study. So, if the pressure differences at the passage doors are influenced significantly by local flow phenomena, an analytical method would fail. Therefore, a complementary unsteady numerical study were undertaken to confirm the derived settings, using a state-of-the-art CFD method.

2. COMPUTATIONAL GRID AND BOUNDARY CONDITIONS

The computational model of the Limerick tunnel was based on the CAD-geometry, which includes the Saccardo nozzle, all traffic signs, the cable ducts mounted on the ceiling, and the fire exit doors. In order to predict the smoke movement and the pressure distribution on the escape doors accurately, a grid with more than 1e+06 elements was constructed. The burning truck was placed in the middle of the incident tube and therefore in the lowest part of the Tunnel. Thus, a smoke migration in both directions was possible. This corresponds to a worst case scenario. In accordance to older investigations, the wind speed was 3m/s. The maximum volume flow rate of the ventilation system was set to 258 m^3/s in the non incident tube and to 252.84 m^3/s in the remaining tube. The maximum heat release at the burning truck was 100MW. In order to predict the heat transfer accurately, a high grid resolution was defined around the truck (fig.2).

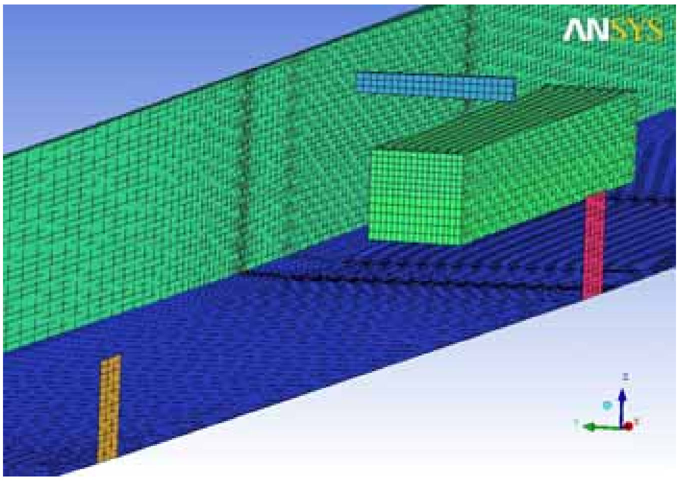

Figure 2: Computational grid nearby the burning truck

A high element number was also required at the passed through Saccardo nozzles, since high velocity gradient were assumed in this region. Additionally, the high grid resolution in this area permitted a quantitative evaluation concerning the influence of the electric ducts on the flow behaviour (fig.3). The ventilation system is run up 30 seconds after the fire inception. Since the run-up time of the fans was expected to be 60s, the maximum volume flow rate is attained after 1.5 minutes. According to the experimental data of the used fans, a linear increase of the volume flow rate was assumed. The increase of the heat flow rate at the burning truck was also considered to be linear with 40 MW per minute. The simulations were performed under the assumption, that the burning truck is the only vehicle in the whole tunnel.

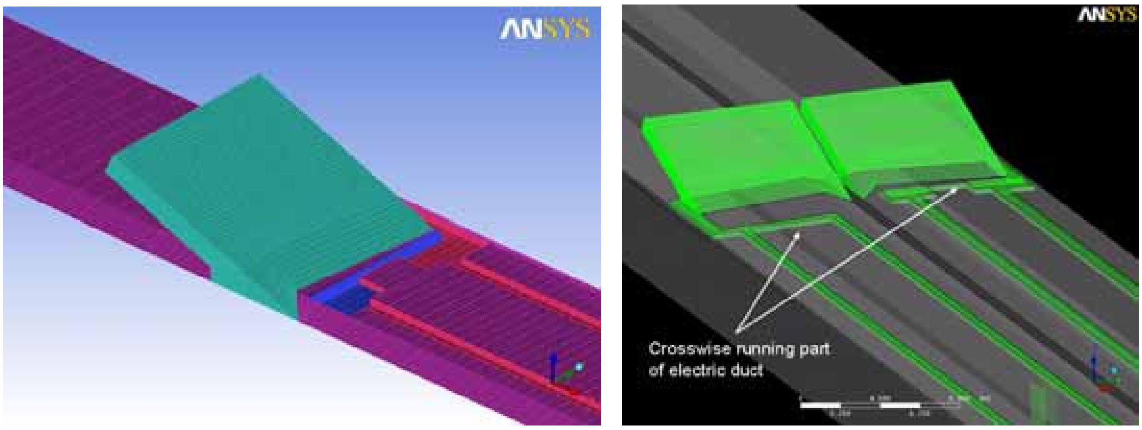

Figure 3: Computational grid nearby Saccardo nozzle

3. NUMERICAL RESULTS

Figure 4 shows the time dependent emission of smoke at the burning truck and its gradual removal. The smoke is visualized by isosurfaces for (concentration)-values between 100% and 30%. In order to get an impression of the changing flow behaviour, streamlines are also plotted into the figure. The streamlines start from the tube inlet and from the Saccardo nozzle. Additionally, they are coloured as a function of the flow velocity. In the very beginning, the flow behaviour is dominated by the wind contribution. According to the drag at the truck, a distinct curvature of the streamlines can be observed there. 20 seconds after the fire inception, high smoke concentration values are present next to the truck. Now, a significant streamline curvature can be seen in this region. The smoke acts as barrier, which forces the flow to go around. Thus, higher pressure losses are located here. Furthermore, the blockage leads to an increase of the static pressure in the upstream direction. After 100s, the ventilation system ensures an effective removal of the toxic gases. Downstream of the fire, higher velocity values can be seen which is a result of the increasing specific volume of the fluid due to the heat transfer. The fourth picture shows the flow behaviour after nearly 3 minutes. Now, the maximum heat flow rate of 100MW is present. As a consequence, a stronger flow-acceleration downstream of the truck is visible. Despite the high flow blockage next to the truck, the ventilation system guarantees a controlled smoke-removal.

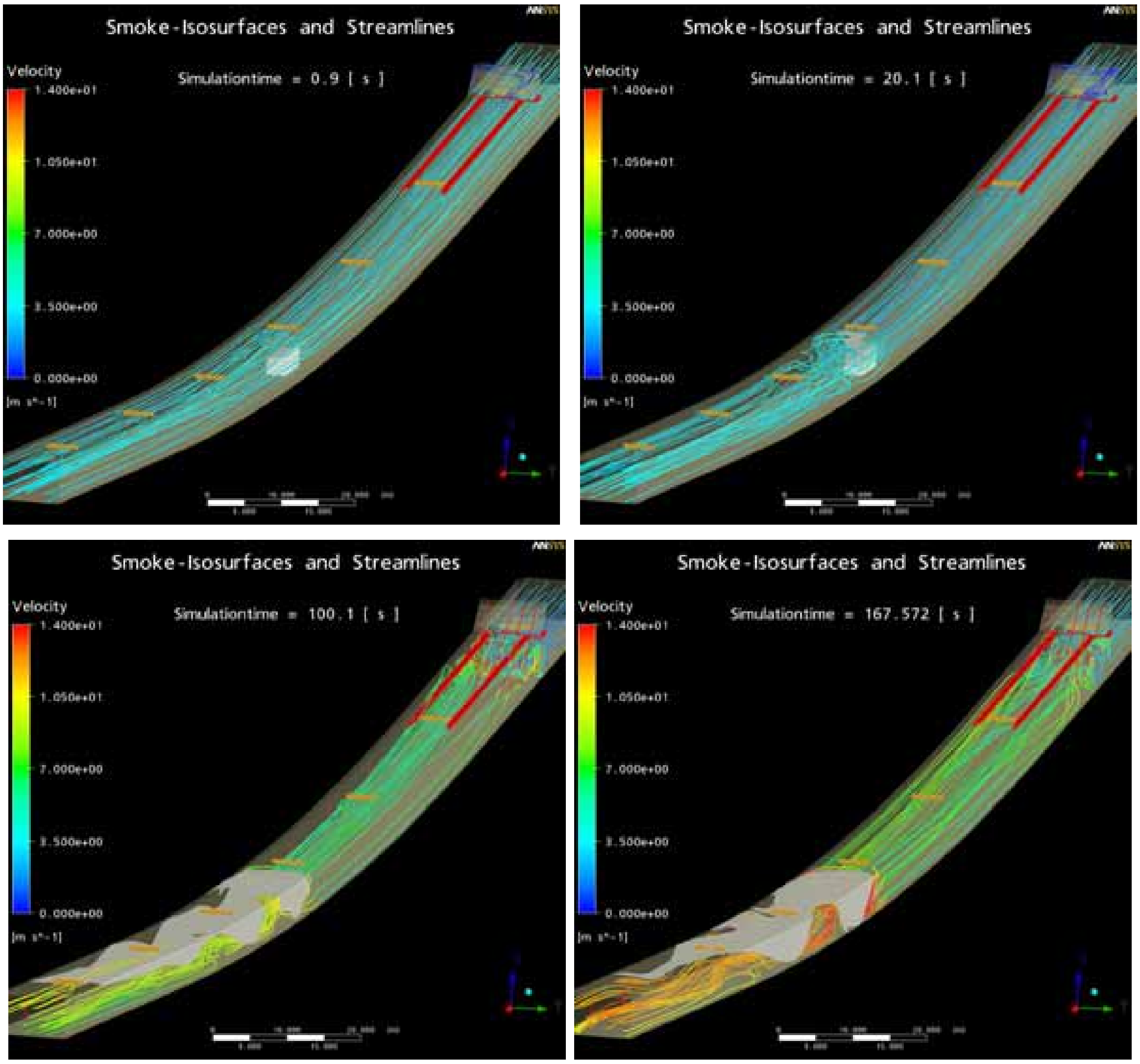

Figure 4: Time dependent smoke migration

Figure 5 shows the streamlines in both tubes next to the traffic signs (coloured in blue) near the end of the electric duct/light duct (left figure) and in front of the burning truck (right). The two pictures confirm the stated observation: The traffic signs influences the flow path only locally. A change of the global velocity field caused by the traffic signs can not be stated.

However, the ceiling lights and the electric ducts cause a bigger change of the velocity field nearby the Saccardo nozzle in the incident tube: The short distance between nozzle exit and the crosswise running part of the electric duct (see fig.3) results in a vertical directed displacement of the nozzle flow. As a consequence, the maximum velocity migrates also to lower heights. In the non-incident tube, the distance between nozzle outlet and duct is far greater. A distortion of the ventilation flow can not be observed. Thus the maximum velocity remains next to the ceiling in the smoke free tube.

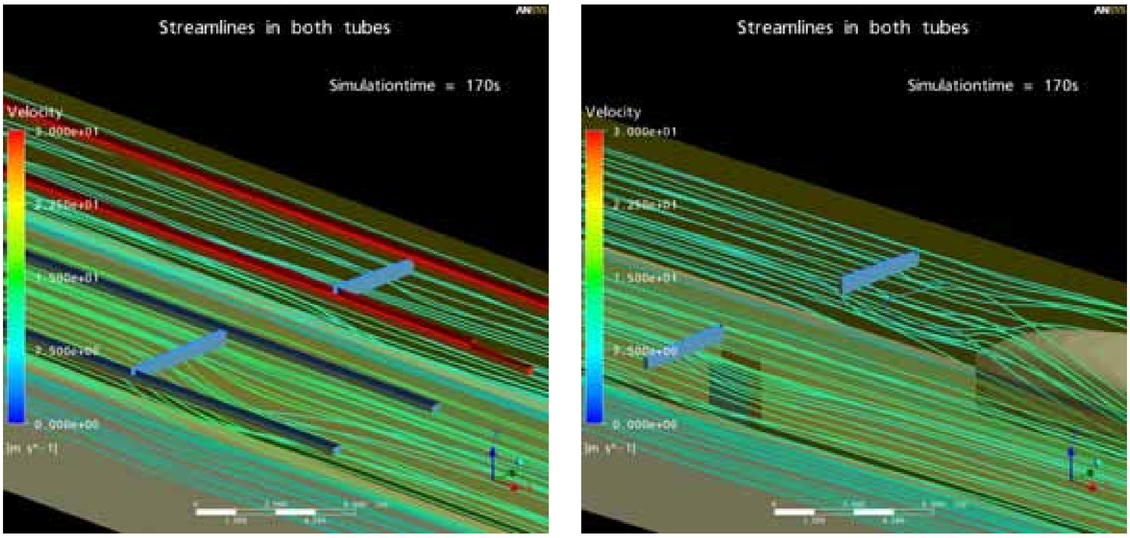

Figure 5: Flow behaviour at traffic signs

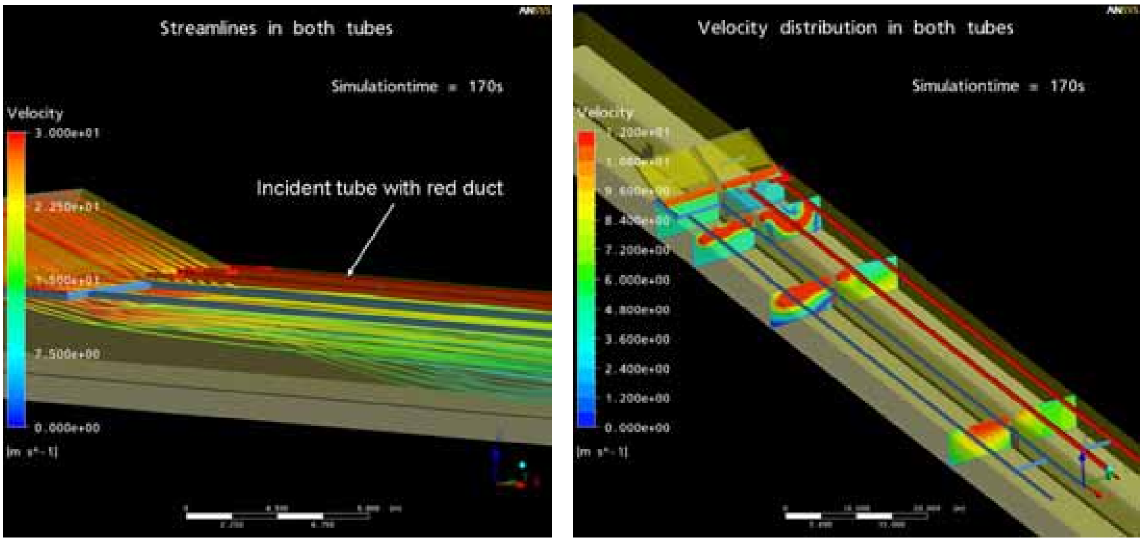

Figure 6: Streamlines and velocity distribution in both tubes near Saccardo nozzle

Beside an effective removal of the toxic gases, a moderate pressure difference at the passage doors is also in the field of interests. The following figures show the distribution of the pressure difference for all passage doors for the last timestep (170s). Positive values mean a positive pressure gradient with higher pressure values in the non-incident tube. The numbering of the doors is increasing from the southern to the northern portal. Door no.1 is positioned upstream of the passed through Saccardo nozzle, door no.2 is located about 30m downstream of the nozzle. Door no. 7 is located less than 10m upstream of the burning truck and door no.8 25m downstream of the vehicle.

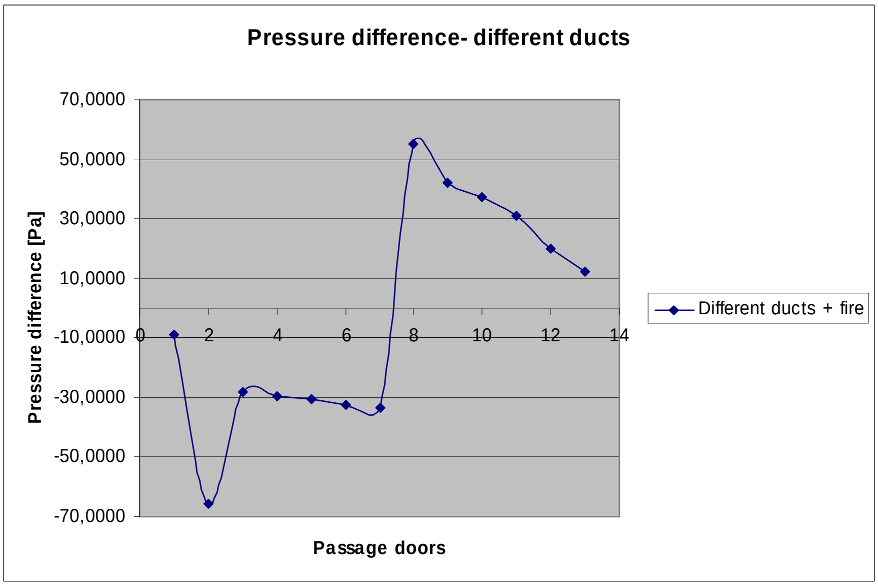

Figure 7: Distribution of pressure difference at passage doors

The pressure difference distribution results from three effects:

- Vertical displacement of the nozzle flow in the incident tube due to the crosswise running duct (door no.2)
- Upstream acting drag effect of the burning truck (door no.3 – no.7)
- Total pressure loss at the burning truck (incident tube) combined with gas expansion behind the truck

The vertical displacement of the nozzle flow nearby the cross running duct leads to a migration of the total pressure maximum to lower heights. As a result, the static pressure values are significant higher at ground level, than in the non-incident tube. This leads to a static pressure difference of $\Delta p = -65.4$Pa at passage door no.2 (fig.7). According to turbulent diffusion, this effect shrinks after a distinct distance from the nozzle. Therefore, a lower pressure difference is given between door no.3 and door no.7. The negative Δp between no.3 and door no.7 is mainly driven by the drag effect of the burning truck, whereas the smoke contribution is significant higher than the contribution by the truck itself. This in upstream direction acting stagnation leads to a decrease of the flow velocity and instantly to high static pressure values. Therefore, the static pressure differences remain negative up to the location of the truck.

According to the drag of the smoke and the truck, higher total pressure losses appear nearby the fire. As shown in figure 8, a higher portion of the fluid is convected to the sidewalls nearby the truck. This leads to a vortex creation and finally to flow losses. At the same time, the heat release at the truck results in an increase of the specific volume and in a rising flow velocity. According to a shrinking total pressure and a flow-acceleration, the static pressure is also shrinking. Since the pressure values in the non-incident tube vary only slightly, the pressure difference changes its sign downstream of the fire.

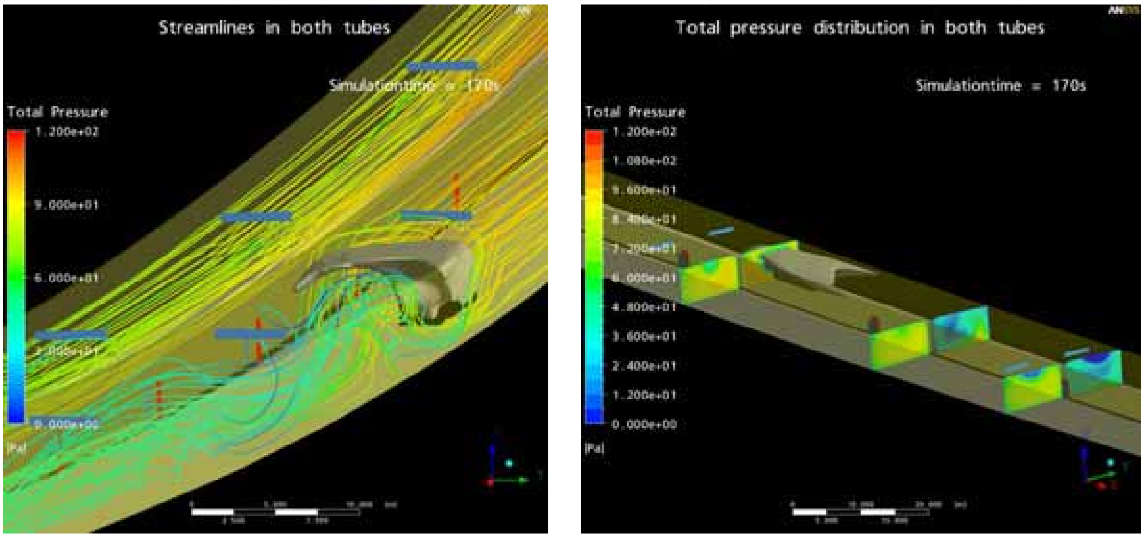

Figure 8: Influence of burning truck on flow behaviour

The highest values are obtained at door no.8, which means about 25m downstream of the burning truck. Here, the pressure difference is 55Pa. Downstream of that location, a steady decrease of the pressure difference can be stated. At the last passage door, Δp is 12.4Pa. Since the smoke reveals a movement to the northern portal, a migration of the smoke from the incident to the non-incident tube is unlikely. At the same time, the pressure difference remains mostly at an acceptable level ensuring an opening of the doors in the smoke-filled part. Only nearby the burning truck, a difference slightly beyond the threshold value of 50Pa exists.

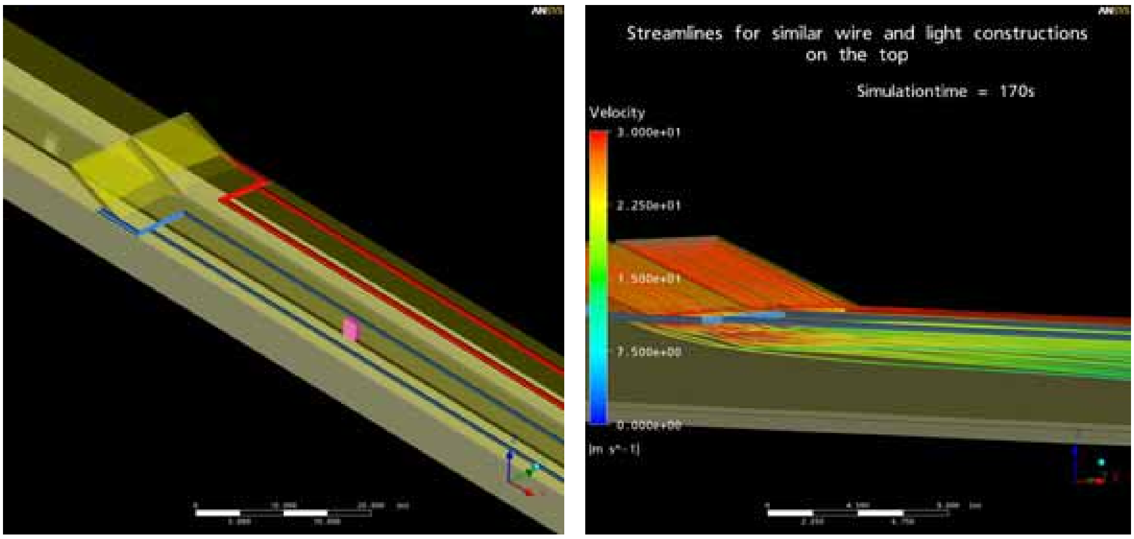

Figure 9: Flow simulation for similar ducts

In order to get an idea of the individual effects like the electric duct or drag of the burning truck, further investigations were undertaken. First, the influence of the duct was analysed. For that reason, the duct in the incident tube was constructed in a similar way to the duct in the non-incident tube. As a result, the distance between crosswise duct and nozzle changed from 0.6m to 3m. The data for the ventilation system and the heat release were defined identically. According to the right picture of figure 9, the adaption of the ducts leads to a similar flow behaviour in both tubes nearby the nozzle.

Figure 10 shows the distribution of the static pressure difference for the original geometry (magenta line) and for similar electric ducts. The plot reveals that the differences between the two lines remain below 3 Pa from passage door no.3 to no.13. Downstream of the fire position (door no.8-13) the values of both lines are nearly identical. The actual impact on the pressure difference appears at door no.2. Here the delta is nearly up to 30Pa. In other word, the influence of the duct on the flow behaviour is limited on the passage door next to the Saccardo nozzle.

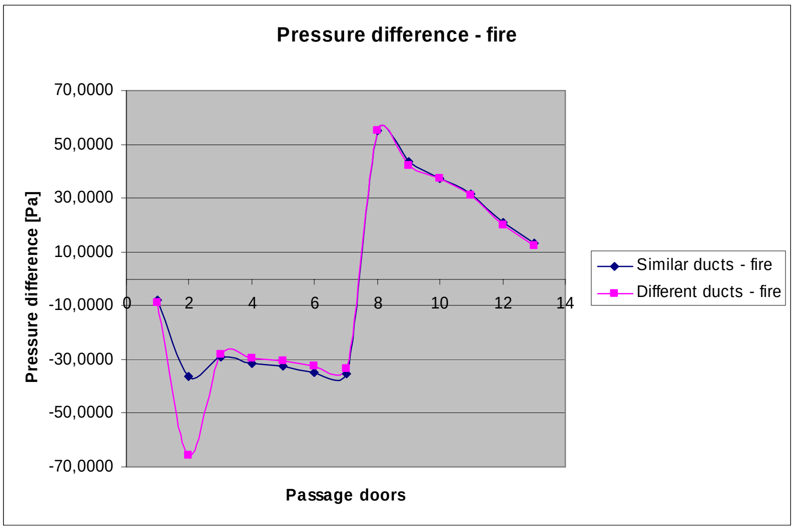

Figure 10: Influence of installed ducts on the pressure difference

The last figure shows the distribution of the pressure difference for a burning and a not-burning truck (blue line). In both cases, one can clearly identify the local influence of the different duct geometries on the flow behaviour (minimum at door no.2). The figure also clarifies the enormous impact of the fire on the tunnel flow: At all passage doors, significant higher pressure differences (absolute values) are given. Actually, the fire influence seems to scale the pressure difference. The biggest deviation appears downstream of the truck at door no.8. Here, the pressure difference has increased from 2.8Pa to 55Pa.

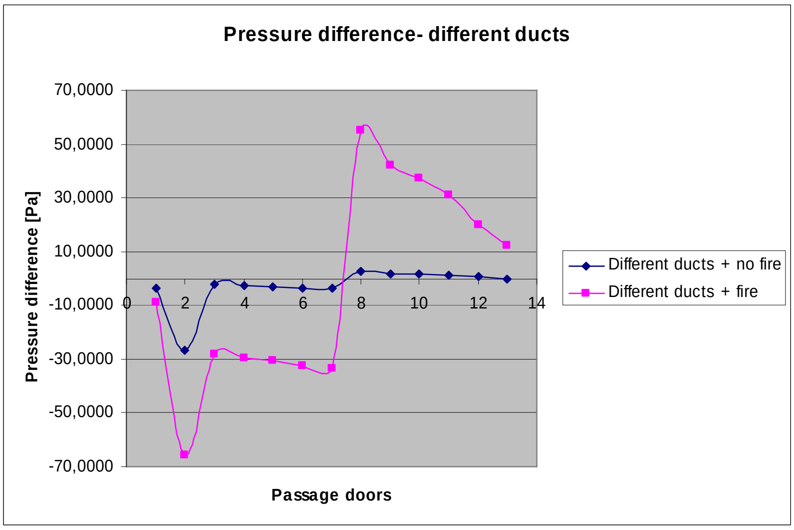

Figure 11: Impact of the fire on pressure difference

4. SUMMARY

A numerical study of the flow behaviour in the Limerick tunnel was undertaken. All geometric details like traffic signs and electric ducts were integrated in the numeric model. Furthermore, a burning truck with a heat release of 100MW located in the middle of the tunnel was considered. The numerical results proved that the toxic gases are removed under the given conditions. Furthermore the results reveal a minor impact on the flow behaviour by the installed traffic signs. Changes in the flow field are only visible nearby the signs. However, the electric duct in the west tube influences the flow field significantly since the distance between nozzle and the crosswise running part of the duct is less than 1m. The short distance leads to a forced displacement of the nozzle flow to lower height and to high static pressure values near the ground. As a result, the pressure difference at the passage door no.2 nearby the nozzle is up to Δp = -65.4Pa. The pressure difference at the passage doors is driven by overall three effects. A shown in the last chapter, the pressure difference is mainly influenced by the drag of the smoke and the heat release at the burning truck. According to the obtained distribution of the pressure difference, a migration of the smoke from the incident to the non-incident tube is unlikely. The maximum pressure difference of +55Pa exceeds the threshold value of 50Pa only by little.

5. AKNOWLEDGEMENTS

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AUTOMATIC RE-CALIBRATION OF VIDEO-DETECTION-SYSTEMS

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ABSTRACT

To enhance safety in modern traffic tunnels, automatic incident-detection via video is increasingly used. Mounted and calibrated cameras in tunnel-tubes are often misaligned by purification and maintenance works. With the help of extended algorithms, changed camera positions can be recognized and the detection software is automatically adjusted to the new constraints without manual calibration of operators.

Keywords: automatical recalibration, video detection, incident detection, single frame, traffic tunnel, camera

1. PROBLEM

With the help of automatic incident detection via video, operators can directly be advised on predefined incidents like smoke formation, breakdown vans, traffic jams or ghost drivers. The enormous flood of information of actual traffic situations is getting manageable with the help of such devices. Tunnel operators can very fast and reliable appraise complex and safety-imperilling situations and take corresponding arrangements.

Caused by the reason of intense contamination in traffic tunnels, imperative purification in constant intervals is needed. The mounted and calibrated cameras in the tunnel-tube are often misaligned by those purification and maintenance works. Every camera position change requires a new adjustment and fine-calibration of the image acquisition devices. In the case of no fine-calibration, detection-failures can occur and the operating company is accompanied by an immense safety-risk. Additional it's impossible to collect and measure traffic information, like vehicle distances or velocities, by the use of misaligned cameras. For this reason ancillary costs for the anew adjustment of the video-detection-system occur besides the tunnel purification. These operations can in most instances be accomplished by the manufacturer only.

Figure 1: Typical tunnel purification (with friendly acceptance of Andreas Kienzler)

A simple example illustrates the demand towards an alternative approach. According to the statement of the Austrian highway operating company - ASFiNAG, street tunnels are cleaned two times a year. The experience of the control room employee’s says that on average every tunnel cleaning, three to four cameras have to be re-adjusted. At an averaged expenditure of time, about 100 to 120 minutes per camera, this accumulates to about 16 to 20 hours recalibration work per year and tunnel. Additional to the operational hours, efforts for the obstructions of traffic have to be taken into account.

These numbers point out the imperative of an automated procedure. Operating companies should minimize the safety hazard via detection blackouts and decrease the incidental costs. Operators should not bother time consuming tasks. Manufacturer of video-detection systems should not misplan specialized employees for permanently new- and re-calibration.

2. METHOD OF RESOLUTION

2.1. Operating mode

The operating of street tunnels distinguishes different modes. Besides the normal operating, in more tube constructions normally one-way traffic, when failures or maintenance occur, the tunnel can be controlled in an opposing traffic way. Additional to tunnel blocking at accidents and flexible lane allocation, the maintenance mode exists. In this mode, traffic is reduced to one lane or the tube is completely closed.

In a modern tunnel-monitoring different operating modes are known. Especially for incident detections of the video surveillance systems it is mandatory to get the actual operating mode. In this way the generation of reasonable incident announcement can be guaranteed. This is e.g. essential in a non-ordinary opposing traffic service, when wrong way drivers should not be detected or at camera cleaning work, where the occlusion should not cause an alarm etc.

2.2. Activation of the control sequences

The easiest and most safe approach to check camera misalignment is, to tell the video detection software the operating mode of the tunnel. After a certain operating mode, the software advises an automatic check, to be sure that the cameras are in a correct alignment. A permanent inspection of the camera adjustment via the software is also possible.

2.3. Algorithmical solution

Calibrating a camera means to find the projective linear transform that maps coordinates from the image plane onto the road surface and back.

The usual calibration process involves initial reference points on the road surface whose relative distances and coordinates are determined in both, real-life and in the image plane. This restricts calibrations to static camera views, where it is ensured that the position of the reference points is kept constant.

As soon as the camera is panned or tilted, in such a way that the previous and current view overlap sufficiently, the new location of the reference points can be obtained by state-of-the-art image processing algorithms.

These involve the robust detection of so-called interest points or keypoints in the images. The visual surroundings of these keypoints are described by scale- and rotation-invariant features, which make it possible to match points across both images. Ideally, the locations of those keypoints are spread uniformly across the overlapping parts of the images and are not concentrated within a small region. This ensures that e.g. a rotation is correctly determined and not mistaken for a simple shift. This can be overcome by choosing adequate detector parameters.

Once the set of matched points is known, their locations in both images are used to obtain a projective linear transformation matrix, which describes the coordinate change of the matched points. The precision of this matrix is influenced by keypoint mismatches. One way to get rid of mismatches is, to use the computed matrix to detect and remove outliers, what results in a more precise transformation model after recomputation.

Finally, this matrix is used to obtain the new location of the reference points for actual recalibration.

To further avoid keypoint mismatches in the process, one has to avoid taking those points into account that are placed on moving objects in the image. Therefore, the reference image is obtained from a background model of the original camera view, ensuring that no moving objects are present among the described keypoints. This way the matches are only calculated between static visual features across the images.

2.4. Conversion and implementation

The configuration of the video detection system with the aforementioned additional feature can occur via two different ways. On the one hand it is possible to provide software updates for established systems in order to bring them to the technologically state of the art. On the other hand the feature of the automatical-recalibration of cameras can be acquired as an additional module at a new detection system.

3. ADVANTAGES

Center Systems achieved a measurable improvement in incident detection quality at highways and street tunnels. This is achieved via the use of a new developed method, the so called “Single Frame” procedure. The manifold requirements in daily handling of complex traffic situations demonstrate additional challenges, to enhance the usability of such systems for the operators.

Furthermore it is possible with the tool of automatical-recalibration, to focus human capacities on paying more attention on efficient surveillance. With the help of automated sequences at the readjusting of cameras, error sources, e.g. through manually adjusting, are minimized. Thereby failure detection rates after mechanically displacement are still very low. Ancillary the video detection is considerably fast available after tunnel purification.

4. SUMMARY

Using the operation of automatic recalibration, a displacement of cameras can immediately be recognized without manual testing. At the same time the detection software makes a new alignment. This advantage reflects in an increased traffic safety, because the detection rates offer furthermore a high output. At least the saving of time, because there is no need to check the cameras and readjust the software any longer, is a trailblazing benefit.

BAFFLES AS A MEANS OF STATION PROTECTION FROM HIGH AIR VELOCITIES - COMPARISON OF ANALYTICAL AND FIELD MEASUREMENTS RESULTS

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ABSTRACT

Draught relief shafts at certain distance from an underground station are used as a means to relieve pressure waves and to control air velocities at the platforms. Shafts location is usually spaced based on the information on train speed, breaking distance and geometry. As in most cases shafts determine the station limits, their location is a critical factor for project costs. Shafts located adjacent to the platform ends can substantially reduce the project costs however special attention shall be given to their effectiveness to control platform air velocities. Baffles were tested and proved as a means to direct air to improve draught relief shafts effectiveness. Field measurement results of air velocity at the platform and in the draught relief shaft were compared against the analytical and CFD approaches for the Beacon Hill light rail tunnel and station in Seattle and proved the design approach.

Keywords: baffles, platform air velocities, draught relief shaft

1. INTRODUCTION

National and international guidelines require the installation of draught relief shafts at certain distance from an underground station for effective reduction of pressure waves and air velocities at the platforms for passenger's comfort. Air velocities at the platform should not exceed 5 m/s for comfort and safety. The maximum airflow from tunnel to station depends on ratio of tunnel air velocity to train speed and resistances to airflow.

Geological conditions of the Beacon Hill Light Rail Station did not allow for draught relief shaft location at a typically acceptable distance (20 m – 90 m) from the station ends. Shafts had to be constructed as close as 4.5 m from the end of the platform of the Beacon Hill station. A short length of tunnel between the draught (blast) relief shaft and the station headwall is used for baffle installation to increase the overall impedance and to direct tunnel air into the draught relief shafts. Based on the result of studies and analysis, baffles were designed and installed in Beacon Hill tunnel (Seattle) between the station headwall and draught relief shafts. (1)

While analytical calculations and results of CFD analysis showed that the proposed solution can reduce platform air velocities to meet the comfort requirements, there was no practical evidence, and field measurements and verifications were required. A set of tests with running trains was performed in June 2009 to validate the design solution.

2. BAFFLE PLATES AS A MEANS TO IMPROVE EFFICIENCY OF THE DRAUGHT RELIEF SHAFTS

Design calculations and CFD analysis showed the problems with platform air velocities which will exceed the comfort level of 5 m/s when trains will pass the station at 64 km/hr if the draught relief shafts will be constructed as close as 4.5 m from the platform ends with no baffles. However pressure changes (pressure transients) will be insignificant due to the relatively slow train speeds.

Baffles were proposed at the draught relief chamber area to reduce platform air velocities. Baffle plates are good for both – reduction of station air velocity and reduction of pressure waves. They also reduce steepening of the pressure waves. (2) The ability to use baffle plates is usually constrained by the size of an existing tunnel since plates will reduce the available tunnel cross-section area locally. The remaining tunnel area must allow for sufficient space for the train vehicle dynamic envelope, catenaries equipment, fire standpipe and walkway.

We designed and installed baffle plates (orifice plates) spaced at a distance of 2.5 m along the draught relief chamber of the Beacon Hill station. Plates have been constructed as part of the tunnel wall designed to constrict the flow locally and provide friction losses increasing the overall impedance to the tunnel airflow in the draught relief chamber. Design includes an extension of the platform tunnel in order to create a draught relief chamber which shall accommodate a track damper and baffles (Fig. 1). Baffles were installed in the inbound tunnels damper chamber only. In the outbound damper chamber baffles may create additional pressure to the airflow for further escape, which reduces the effectiveness of the overall station pressure reduction, and thus were not installed.

Fig. 1: Baffles as installed in the Beacon Hill Tunnel in Seattle, WA (looking from the tunnel)

Due to baffles, tunnel airflow faces a set of sudden expansions and contractions in the draft relief chamber. This leads to increased pressure losses and eventually to direction of airflow into the draught relief ventilation shaft. Increased tunnel area will locally reduce tunnel air velocity, while plates will increase turbulence, creating secondary airflows behind them and leading to increased pressure drops. The platform headwall will serve dual purpose. First, it will serve as the last barrier (resistance) to airflow before the station. It shall protect platform adjacent to the headwall from high air velocities. Second, it serves as an architectural and security feature that will hide the track dampers, baffles, and fire equipment from public. The platform headwall will create local increase of air velocity, however the resistance it creates to the airflow will eventually reduce average airflow through the station and hence platform air velocities. Figure 2 shows results of CFD analysis and complicated aerodynamics in the draught relief chamber with lots of turbulence caused by the baffles.

However there was no practical evidence and field measurements to support the CFD analysis results and design decisions, and field verifications were required. A set of tests with running trains was performed in June 2009 to validate the design solution.

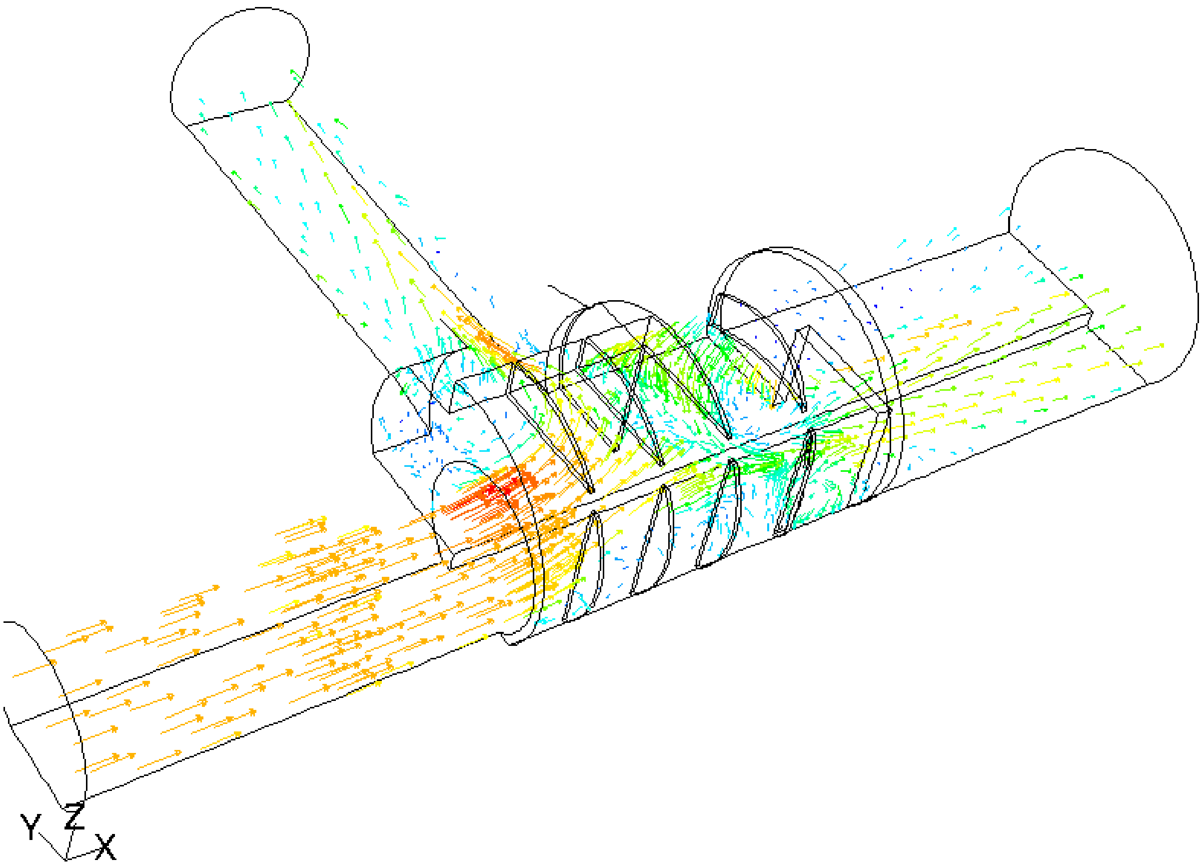

Fig. 2: Aerodynamics in draught relief shaft caused by the baffles - CFD analysis results

3. FIELD TESTS

Air velocity measurements were taken at the northbound platform and in the draught relief shaft simultaneously. Trains in southbound track were operating at low frequency. We established communication with train operators during the tests in order to control their operation and speed.

Two sets of tests were made:

- With trains operating as scheduled decelerating from 64 km/hr to 24 km/hr before entering the station and stopping at the Beacon Hill station (northbound platform)
- With trains passing through the station at 64 km/hr with no stopping at the station

Air velocity measurements were taken at the following locations:

- At the northbound platform east end at approximately 0.6 m from the edge of the platform at the height of 1.7 m from the top of platform and approximately 8 m from the platform headwall.
- In the east horizontal part of the draught relief shaft between the track damper and the vertical shaft.

Additional measurements were taken in the center of the platform and at the central concourse doors openings to verify the chosen locations. At the center of the platform the maximum air velocity were measured of 1.5 m/s, which confirmed that the location initially chosen represented the highest platform air velocity readings. Air velocity at the central concourse door openings showed the highest reading of 2.5 m/s, which is also well below the criteria of 5 m/s. It should be noted that measurements were taken while construction was still on-going at the central concourse and field conditions do not exactly represent the station operating conditions.

For air velocity measurements we used ADM 870C and ADM 870 with VeloGrid. The "speed read" mode allows registering air velocities at the intervals not exceeding two seconds.

Data was recorded as follows:

- Maximum air velocities in the vent adit
- Air velocities at the vent shaft when train passes the track damper
- Additional measurements as noted
- Tests were video recorded (Fig. 3).

Fig. 3: Measurements taken at the platform of Beacon Hill Station (1FP = 1fpm = 0.005 m/s)

It shall be noted that trains entering opposite platform impacted measurement results. Also trains started braking (slowing) at different distance from the station, which impacted the results as well.

4. FIELD MEASUREMENTS RESULTS

Air velocity measurements history on Fig. 4 shows that platform air velocities are less than 5 m/s with the exception of two cases when trains passed the station at 64 km/hr with no stopping at the station.

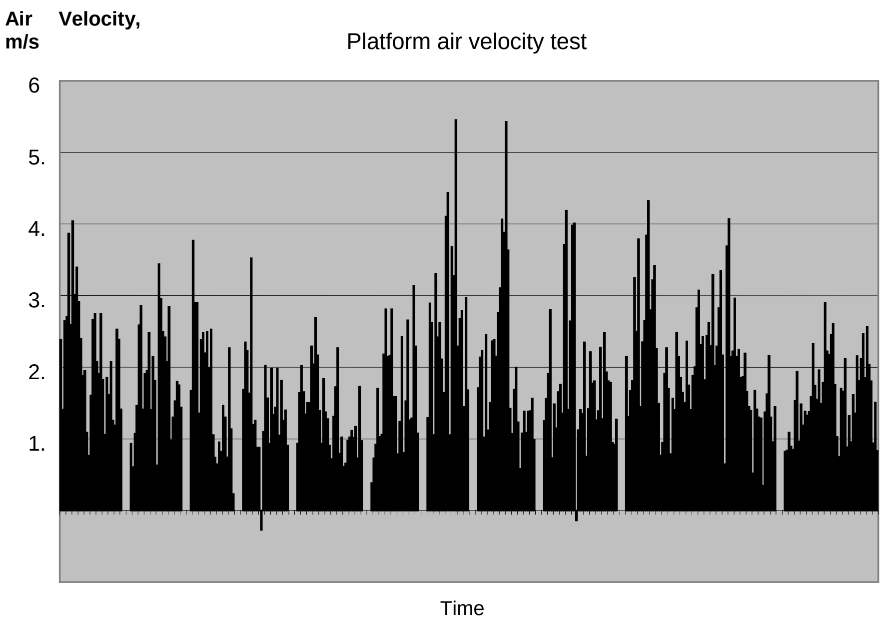

Fig. 4: Air Velocity readings at the platform with operation of 14 trains

CFD analysis results were compared against the field measurements. The broken curve on Fig 5 shows CFD predictions of platform air velocities with NO baffles. Those velocities could reach 5 m/s. The solid curve shows CFD predicted platform air velocities at the platforms with baffles, which are significantly lower. Platform air velocities measurements represented by points show reasonably good correlation with CFD predicted velocities, which are in the range of 3 m/s and less. Platform air velocities were always measured less than 5 m/s with trains operating as scheduled by decelerating from 64 km/hr to 24 km/hr before entering the station and stopping.

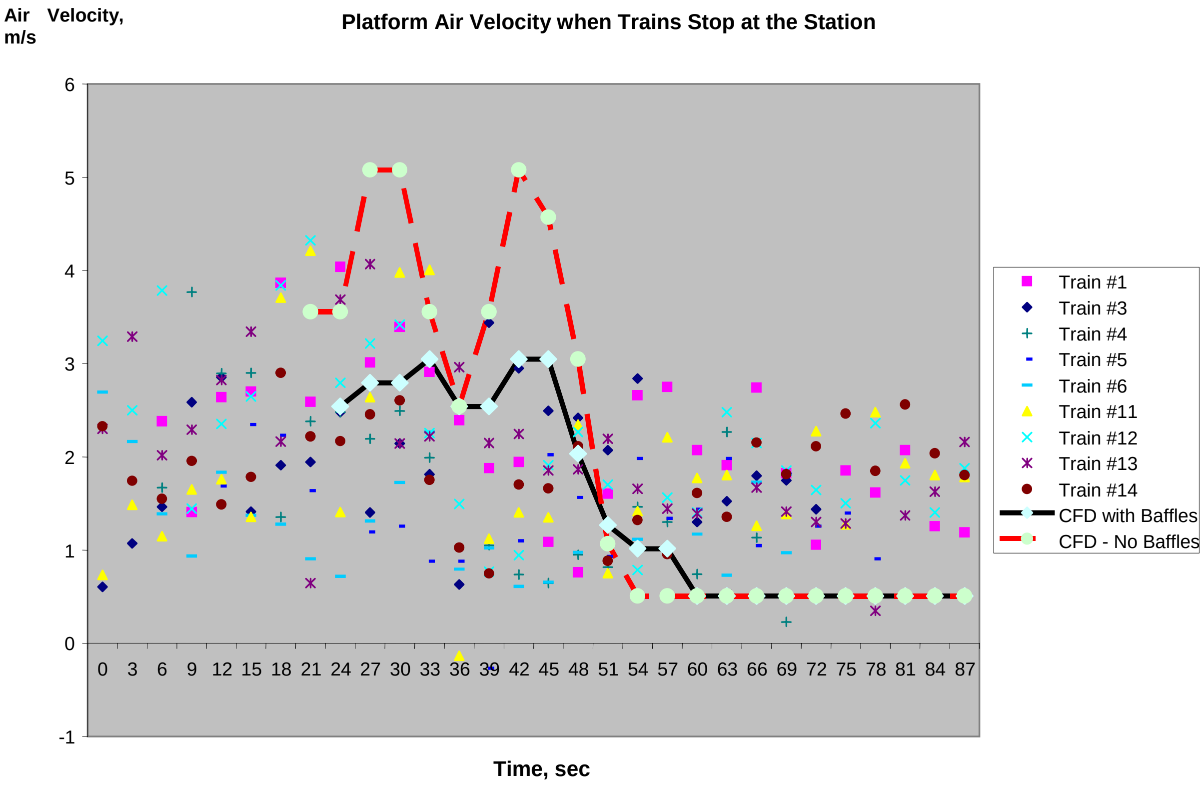

Fig. 5: Comparison of CFD analysis results against the field measurements when trains stop at the station

Fig. 6 represents platform air velocities when trains pass through the station at 64 km/hr with no stopping at the station. In this case, the actual maximum platform air velocities represented by bars slightly (by 9%) exceed 5 m/s for a few seconds. The broken curve on Fig 5 shows CFD predictions of platform air velocities with NO baffles. Those velocities could reach 8 m/s. The solid curve shows CFD predicted platform air velocities at the platforms with baffles, which are lower than measured. However velocities could be much higher exceeding the comfort level by over 50% if baffles were not installed. The peak platform air velocities are shown on Fig. 7. Three tests were performed when trains did not stop at the station. These testes demonstrated the effectiveness of baffles in reduction of platform air velocities.

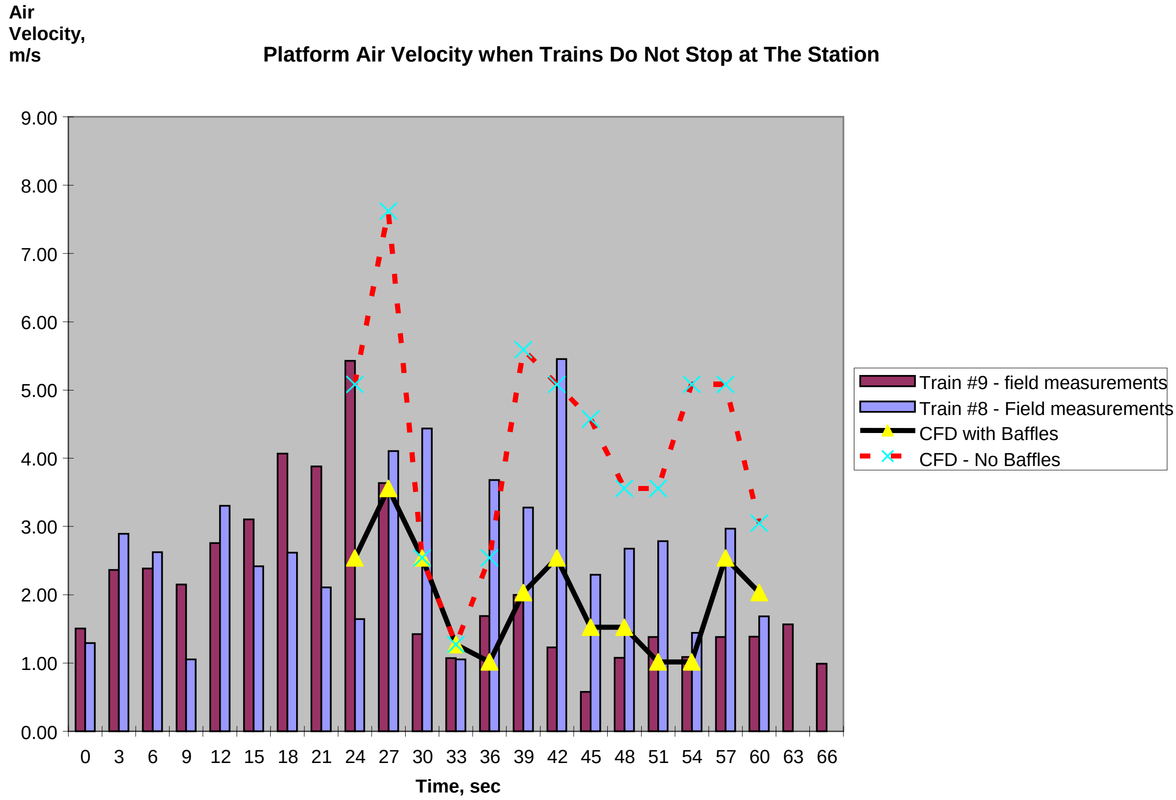

Fig. 6: Comparison of CFD analysis results against the field measurements when trains do NOT stop at the station

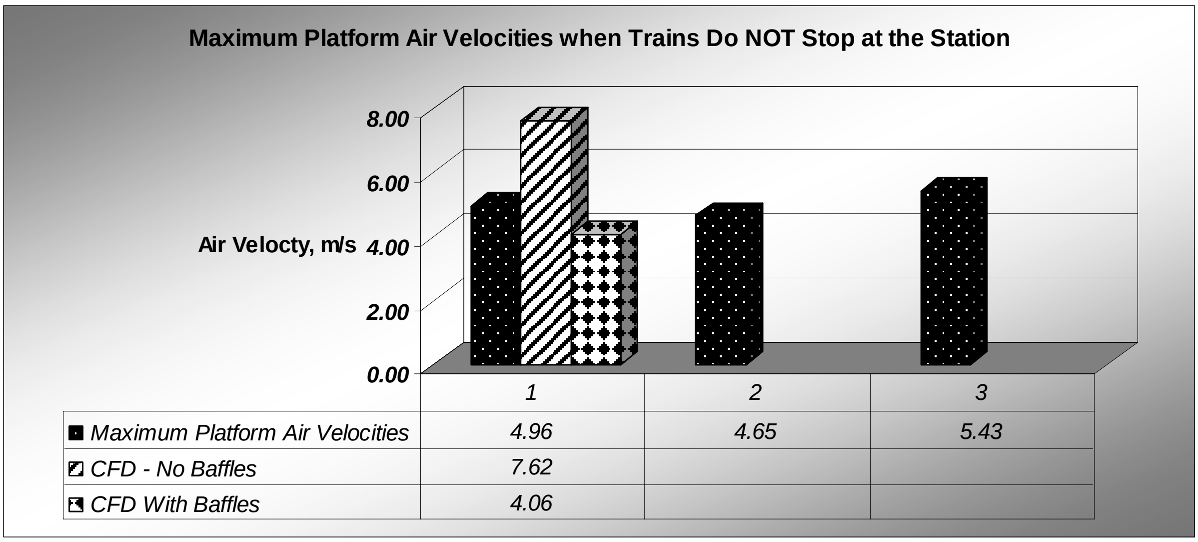

Fig. 7: Peak platform air velocities

Comparison of CFD analysis results against the field measurements when trains do NOT stop at the station. V max at the platforms – maximum gust air velocity registered at the measurement locations for a few seconds.

Simultaneously, measurements were taken in the draft relief shaft and presented on Fig. 8 and 9. The draught relief shaft has cross section area of 23 – 26 m^2. Maximum air velocities in the draught relief shaft vary from 1 to 2.4 m/s. Measurements were compared against the CFD analysis. Fig 8 indicates that while CFD slightly over predicted air velocities in the draught relief shaft with baffles, the obvious benefits of baffles was proven. Resultant air velocity measurements over time are shown on 9.

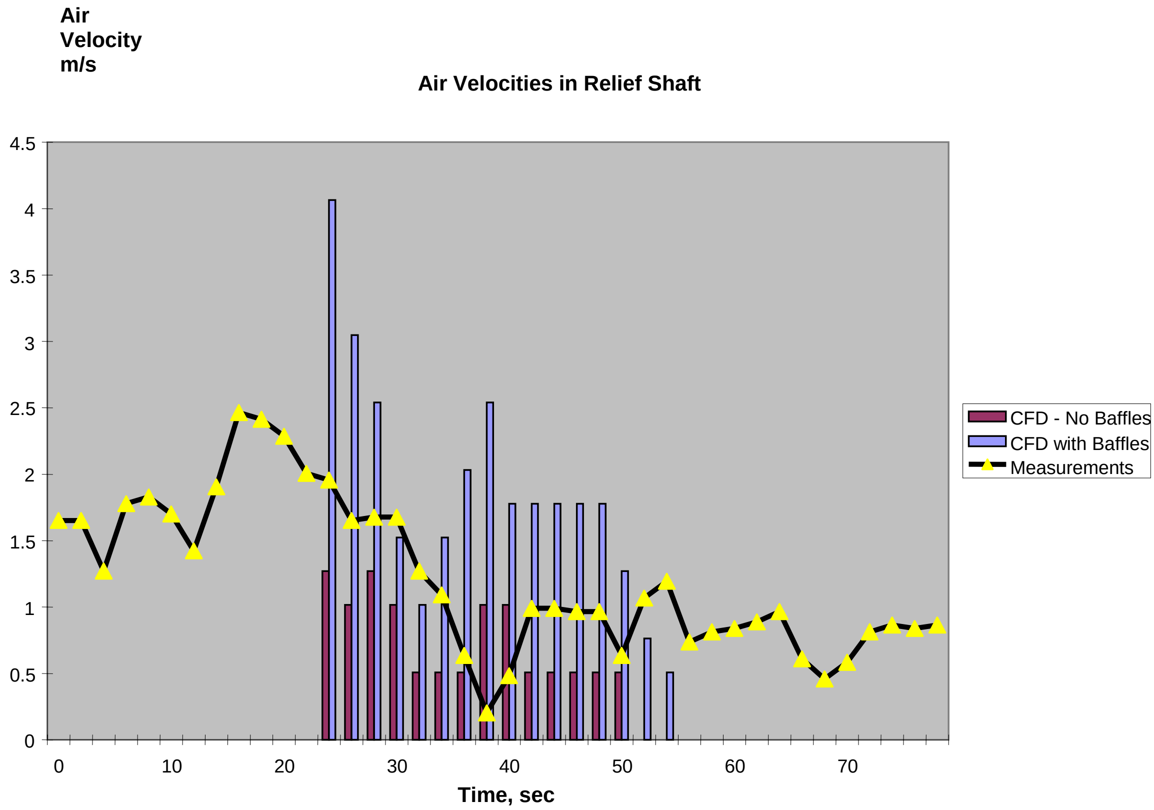

Fig 8: Comparison of CFD results against measurements in draught relief shaft

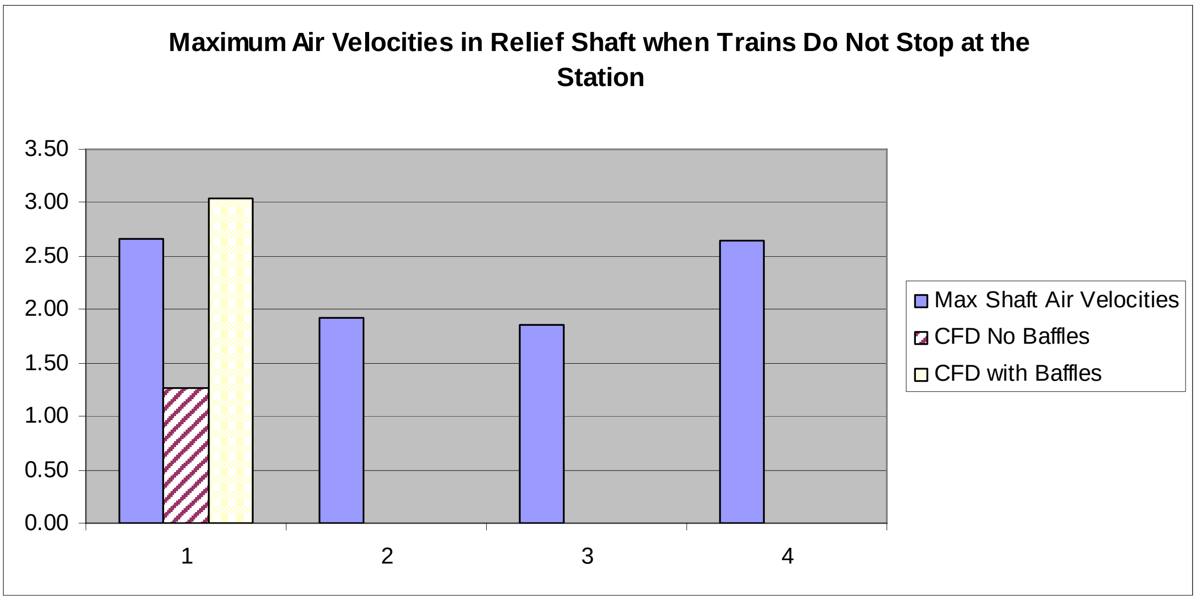

Fig 9: Air velocities in the draught relief shaft – measurements results when trains do not stop

5. CONCLUSIONS

Air velocity measurements confirmed the effectiveness of the baffles design and verified that gust air velocities at the Beacon Hill station were within the comfort level when trains operate in accordance with the schedule at 64 km/hr and stop at the station.

Higher gust air velocities were registered when trains do not stop at the station. Under those circumstances gust air velocities may exceed 5 m/s. However they do not exceed by more than 7% for a few seconds which should not create any problems for patrons at the platform.

Draught relief shaft relieves significant amount of air and effectively control air velocity at the platform. Baffles design is effective for protection of station from pressure waves and high air velocities when draught relief shafts are close to platform ends.

6. ACKNOWLEDGEMENTS

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REVIEW OF ROAD TUNNEL STANDARDS - THE SAFETY IMPLICATIONS ON URBAN ROAD TUNNELS IN SINGAPORE

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ABSTRACT

Urban road tunnels in Singapore are complex in design and its traffic volume is many times higher as compared to most overseas long tunnels. The Kallang-Paya Lebar Expressway (KPE) in Singapore is the longest underground road tunnel in South-East Asia, with an estimated traffic volume of 400 million vehicle kilometers per year. In addition, there is an ongoing construction of Marina Coastal Expressway (MCE), which is an extension of KPE. To ensure the safe operation of all existing and new tunnel projects, international road tunnel design standards are adopted by the Land Transport Authority (LTA) of Singapore.

LTA and the National University of Singapore (NUS) collaborated through a joint research in developing a Quantitative Risk Analysis (QRA) software tool to evaluate the risks of road tunnels design. This software tool is used as part of our study where the international standards specified different requirements or did not cover certain design applicable to urban tunnels such as those in Singapore. This paper will discuss some of the design safety challenges encountered in the application of these standards to road tunnels in Singapore and the usefulness of a QRA software tool in the safety study on areas which are not addressed by the international standards.

1. INTRODUCTION

Road tunnels are critical road infrastructure, especially in land scarcity Singapore, as it helps to improve road accessibility and capacity and at the same time, reducing air and noise pollutions. Urban road tunnels in Singapore are generally complex in design and have high traffic volumes. One such road tunnel is the 12 kilometers (km) KPE which comprises of a 9km underground section. KPE started operation in September 2008 and it has improved the connectivity between three major expressways – East Coast Parkway Expressway, Tampines Expressway and Pan-Island Expressway. KPE will be further extended with the ongoing development of a 3.6km MCE, comprising of a 420 meters (m) section constructed below the seabed.

The likelihood of major tunnel incidents such as huge fire from vehicles may be low. However, the consequences could be severe and costly in terms of casualties, damage to tunnel structures and equipment, environmental degradation, repair works and the impact on the transport economy. As safety is of utmost importance, international road tunnel design standards have been adopted by the LTA to ensure the safe design and operation of all road tunnel projects.

LTA and NUS collaborated to develop a QRA software tool to evaluate the risk of the road tunnels design. This QRA software tool is adopted as part of our study where the international standards specified different requirements or did not cover certain areas related to Singapore road tunnels. For example, the tool is being used to study the risk level of motorist evacuation emergency exits located at different intervals for the combined KPE/MPE tunnel configure-tion. Moreover, the feasibility of hazardous material (Hazmat) transportation in the road tunnel can also be evaluated with the aid of the software.

2. INTERNATIONAL STANDARDS FOR DESIGN OF ROAD TUNNEL

International road tunnel design standards such as the National Fire Protection Association (NFPA 502) Standard for Road Tunnels, Bridges and Other Limited Access Highways 2008 Edition from the United States, the Design Manual for Roads and Bridges (BD 78/99) from the United Kingdom and the European Union (EU) Directive 2004/54/EC are the most commonly adopted guidelines for the design and operation of road tunnels in Singapore.

The NFPA 502 provides fire protection and fire life safety requirements for limited access highways, road tunnels, bridges, elevated highways, depressed highways, and roadways that are located beneath air-tight structures. It establishes minimum criteria that provided fire protection and its related hazards. It is necessary to prevent loss of life and property due to the occurrence of fire [1]. BD 78/99 covers the procedures required for the design of new and refurbished road tunnels located within motorways and other trunk roads. It provides guidance on the necessary equipment and operational and maintenance systems that are required for consideration by the tunnel designer so as to facilitate continued effective and safe operation [2]. EU Directive 2004/54/EC aims at ensuring a minimum level of safety for road users in tunnels in the trans-European road network by the prevention of critical events that may endanger human life, the environment and tunnel installations, as well as by the provision of protection in case of accidents [3].

Relevant chapters from these international standards are adopted and formed the Design Safety Principles (DSP) for the safety design of road tunnels in Singapore. The design of the Singapore road tunnel would have to conform to the clauses stated in the DSP. NFPA 502 is the main standard adopted, supplemented by BD 78/99 and the EU Directive. Not all clauses in these standards are being used. This is attributed to the fact that these international standards are more applicable for most overseas tunnels. In general, overseas tunnels are constructed in the mountainous regions with one entrance and exit. For KPE/MCE tunnel, it has multiple slip roads for entrances and exits. Figure 1 gives an illustration of the entry slip road denoted by I and exit slip road denoted by II. In addition, KPE/MCE is constructed in the urban area of Singapore and the traffic volume is expected to be at least 600 million vehicle kilometers per year when in operation, which is many times higher than that of most European tunnels.

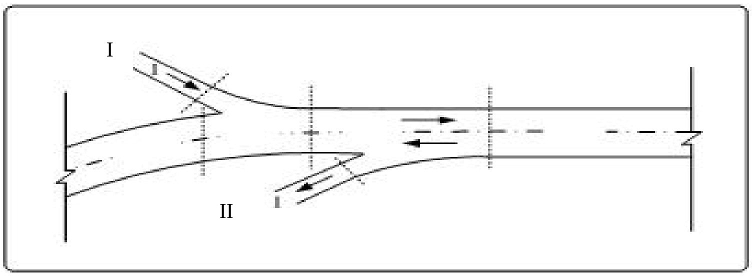

Figure 1: Illustration of Slip Roads

3. QUANTITATIVE RISK ANALYSIS (QRA) SOFTWARE TOOL

LTA and NUS have collaborated to develop a QRA software tool in evaluating the risk of road tunnels design, especially for urban road tunnels which have multiple entrances and exits.

The risk assessment of road tunnel safety focused on the use of Cause Consequence Analysis (CCA). CCA risk model integrated the causes, mitigations, initiators and consequences. The major top events (e.g. fire in tunnel, flood in tunnel, toxic gases generated by traffic congestion, etc.) are identified. Fault trees are constructed to identify the contributing events which led to the top events. Event trees are subsequently constructed by relating the possible sequence of events and outcomes. By performing quantification (in terms of probability and/or frequency) of the initiating events and all outcomes, the overall risk level of the operation of the road tunnel can be determined through aggregating the quantified Fault Tree Analysis (FTA) and Event Tree Analysis (ETA). For probabilistic safety analysis, the software is able to generate results in terms of societal risk, individual risk and the estimated number of fatalities per year in the tunnel. [4]

For urban road tunnels, which have multiple entrances and exits, manual calculation of the risk assessment would be time consuming and prone to human error. However, with the aid of the QRA software, it has become more efficient and accurate in generating the result. This tool is used as part of our study where the international standards specified different requirements or do not cover certain areas related to MCE.

4. DESIGN SAFETY CHALLENGES

4.1. Adoption of International Standards

For the various reasons described below, there are deviations from the DSP for the MCE project. These deviations are justified by using alternative design, compliance to Singapore codes and standards, or approved by the relevant authorities in Singapore. Some of these deviations are discussed:-

a) NFPA Clause 7.14.1.2

It is stated that "reflective or lighted directional signs indicating the distance to the two nearest emergency exits shall be provided on the side walls at distances of no more than 25m". In MCE, cross passage doors are provided at every 100m interval in the tunnel. Lighted exit signs and strobe lights, which are able to provide sufficient directional guidance to the emergency exit, are also provided at each passenger cross passage door and escape staircase door. Hence, reflective or lighted directional signs are not required as motorists are well-informed of the location of the emergency exits.

b) BD78/99 Clause 9.54

It is stated that "when Closed Circuit Television (CCTV) Alert is provided, the fire point and cross connection passage door alarms shall be linked into the CCTV Alert system in order to focus a camera on the area where the alarm originated or where the pedestrians may be situated. This enables the Traffic Control Centre (TCC) to quickly assess the situation and take any necessary safety measures required". For MCE, the Operator preferred to manually patch from the Graphical User Interface (GUI) as automatic patching of CCTV camera to where the alarm originated will cause distraction to the tunnel operator and could be a potential hazard if the CCTV camera is used to monitor an on-going incident.

c) EU Directive Clause 2.2

It is stated that "tunnel gradient to be less than or equal to 5%". In MCE, this clause is considered as partially complied. The main tunnel maximum gradient is 3% but for slip roads, the maximum gradient is 6%, which did not comply with the EU directive. However, this is in line with the local code requirements of a desirable maximum gradient of 6% and absolute maximum gradient of 8%.

4.2. Intervals of Motorist Evacuation Emergency Exit at Slip Roads

The specification of different requirements for the intervals of motorist evacuation emergency exits by the international standards is one of the design safety challenges encountered. NFPA 502 Clause 7.14.6.1 states that "emergency exits shall be provided throughout the tunnel spaced not more than 300m apart" [1], BD78/99 Clause 3.16 states that "single bore tunnel escape route and safe refuge requirements shall be examined and established by the Design Organisation" [2] while EU Directive Clause 2.3.8 specifies that "distance between emergency exits shall not exceed 500m" [3]. In addition, based on a Fire and Life Safety Report recommendation and the provision at KPE tunnel, escape staircases will be provided at nominal distance of 100m in the slip road. In addition, LTA's Civil Design Criteria specified the maximum interval between adjacent escape staircases is at 200m interval.

With the variation in requirements, it is challenging for LTA to determine the most suitable interval for the emergency exits in the slip road for MCE. LTA would like to ensure the safety of the motorists and at the same time, to optimise the number of escape staircases needed. LTA proposed the interval of escape staircase to be at 200m, which met the requirements of the LTA's Civil Design Criteria and at the same time, it reduced the land space needed for the construction of the escape staircases in the Marina East area. Meanwhile, simulation was conducted to evaluate the evacuation performance of motorists when the escape staircases were located at 200m interval. Two major factors – evacuating time and the waiting time for queuing at the staircase were taken into consideration. The simulation result obtained was considered as reasonable [6]. For further analysis and understanding, the QRA software tool was also used to study the level of risk for emergency exits to be located at 200m interval. Results showed that the risk was tolerable.

4.3. Suitable Tunnel Fire Fighting System

NFPA 502 Clause 7.9.1 states a requirement that "fixed water-based fire-fighting systems shall be permitted in road tunnels as part of an integrated approach to the management of fire and life safety" [1]. The main function of having fixed water-based fire-fighting system in road tunnel is to reduce the rate of fire growth as well as heat-release rate, i.e. fire suppression, but not fire extinguishing. With this system, the tunnel fire site temperature should be significantly lower for safe access by the firemen.

There are a few types of fixed water-based fire-fighting systems, such as sprinkler system, deluge systems, mist systems, and foam systems. The table below shows some of the properties of different fire-fighting systems.

Table 1: Properties of Fire-Fighting Systems

	Deluge System	**Sprinkler System**	**Water Mist System**	**Water Foam System**
Fire Suppression Principle	Water droplets for fire suppression	Water droplets for fire suppression	Water mist for isolating the fire contact and radiation reduction	Use chemical water to suppress the fire
Maintainability	Easy	Easy	Nozzle	Regular replacement of the chemical solution
Reliability	High	High	Moderate	Moderate
Discharge Principle	Open typed sprinkler head for water discharge	Sprinkler head for water discharge	Nozzle for creating the fine water mist	Sprinkler head for chemical water discharge

This is one of design safety challenges faced by LTA as this is the first time that a deluge system is being used in Singapore road tunnels. Furthermore, not many countries have used deluge system in their tunnels, except Australia and Sweden. Comparison and study are being carried out to decide which suitable system. Foam system is not applicable as it is installed only in tunnels that allow dangerous goods vehicles to pass through. Singapore has stringent control over the transport of dangerous goods in the tunnel.

An integrated approach is being adopted to understand how the selection of the system will have influences on the other E&M systems in the tunnel, such as tunnel ventilation system (TVS), fire detection system (FDS) etc. The deluge system has no impact on the TVS operation, whereas the rest of the fixed water-based fire-fighting systems will affect the operation of the TVS. In addition, TVS is considered as a safety-critical system in the tunnel as it prevents back layering of smoke.

It is noted that the steam generated from the water suppression system as well as the smoke from the fire would need to be properly controlled by the longitudinal tunnel ventilation system. The TVS will have to maintain its operation to blow the smoke and stream in one direction so as to prevent back layering of smoke. Without sacrificing the performance of the fire suppression system, only the deluge system will work well under a high tunnel air flow speed. Taking into consideration the tunnel design and other systems provision, the deluge system is chosen to be installed in MCE. [7]

5. FUTURE CONSIDERATION

An example use of the QRA software tool is the impact analyses performed on the proportion of hazmat transportation and traffic volume. This is an initial study that would require further analysis. According to the Road Traffic Act in Singapore, hazmat transportation is not allowed in all Singapore road tunnels. Impact analyses based on proportion of hazmat transportation and traffic volume were performed by using the QRA software tool [5]. The results are shown in Figures 2 and 3 during off-peak when the traffic volume is 1200 and during peak period when the traffic volume is 1800 vehicles per hour per lane respectively.

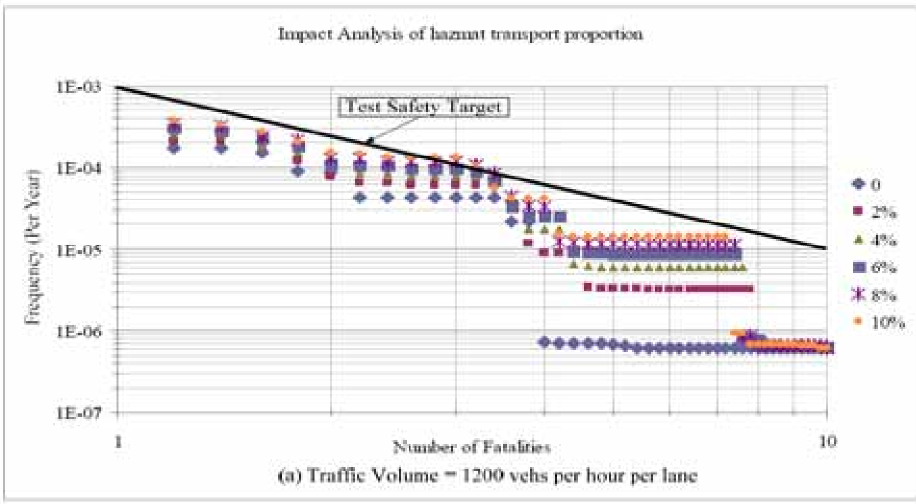

Figure 2: F/N Curve on Impact Analysis of Hazmat Transportation during Off-Peak Hours

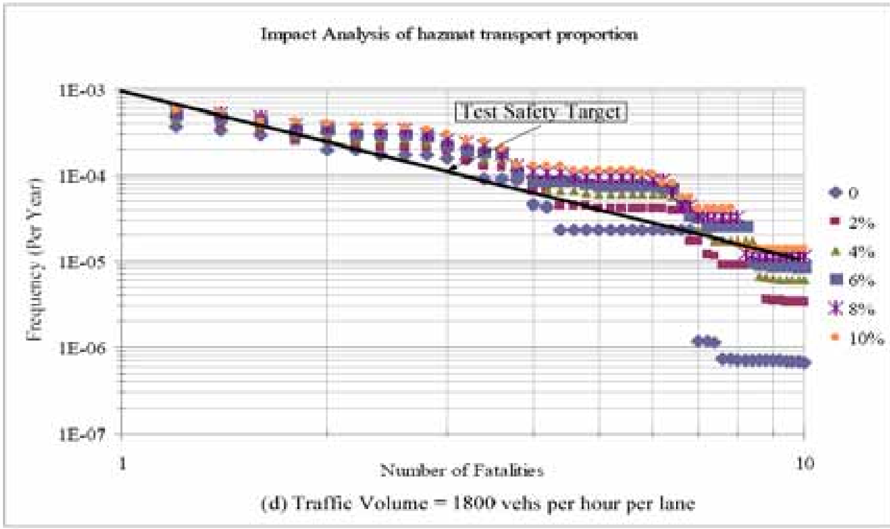

Figure 3: F/N Curve on Impact Analysis of Hazmat Transportation during Peak Hours

From Figures 2 and 3, analysis showed that when the traffic volume is relatively small, the frequency versus number of fatalities (F/N) curve can satisfy the test safety target, with a hazmat transportation of 6%. However, during the peak hours when the traffic volume is high, no hazmat transportation is allowed.

Thus, hazmat transportation may be considered feasible if the excessive risk is minimized through effective operational procedures such as allowing the transport of hazmat materials in the tunnel during off-peak hours when the traffic volume is low.

6. CONCLUSION

International standards are adopted for the design and operation of road tunnels in Singapore to ensure a minimum level of safety. However, different requirements arise from different international standards because they are more applicable for local context of which the standard was published. Risk based approach together with the QRA software would be useful to resolve some of the technical issues. Furthermore, there is a need for the development of standards for future urban road tunnels, taking into consideration the higher traffic volume in urban road tunnels.

7. ACKNOWLEDGEMENT

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