EUROPEAN STANDARDS FOR ROAD TUNNELS AND THEIR IMPLEMENTATION FOR AUSTRIA

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ABSTRACT

With the entry into force of the EU-Directive "on minimum safety requirements for tunnels in the Trans-European Road Network" an important step towards the aim of reaching a harmonization of safety requirements for European road tunnels has been made. This directive defines – among other things – the aims which have to be pursued in order to ensure higher safety standards. Uniform organisational structures in all member states shall ensure that the measures indicated in the Directive are translated into practice and shall also assess the conformity of each individual tunnel with safety standards on the basis of a safety documentation. The safety measures which have to be taken are given in *Annex I* of the Directive. Several of the mentioned parameters differentiate between tunnel in design stage and tunnels already in operation as well as between various traffic volumes. Additionally, uniform traffic and information signs shall ensure that in case of danger or break downs escape routes and emergency stations can be found easily by tunnel users.

1. INTRODUCTION

The disasters which occurred in 1999 and the following years have led to far-reaching changes as far as dealing with questions of safety in road tunnels is concerned. Because of the intensive public discussion of the above mentioned events nowadays these issues are subjects of great political interest whereas in earlier times they were left up mainly to experts. As a result, the importance of aiming at a harmonization of measures to improve tunnel safety has been recognised and has led to a revision of national guidelines as well as to the drawing up of national rules and international regulations and guidelines. At first, on European recommendation a group of experts has been established within the frame of the economic commission of the UNO (UN/ECE). The experts of this group have worked out *a programme of measures* to improve tunnel safety which was published in December 2001. But the Directive of the European Parliament and of the Council on minimum safety requirements for tunnels in the Trans-European Road Network has a far more binding character. In December 2002 the European Commission presented a first draft of this Directive which in the meantime has been discussed in the European Parliament and Council so that the Directive probably will enter into force in spring 2004.

Furthermore, a series of other initiatives consisting in new guidelines, European research programmes and thematic networks have been taken in various European countries.

2. AIMS OF THE DIRECTIVE

The European Union considers it to be its task to ensure a high, standardized and constant level of safety on the Trans-European Road Network. Tunnels of over 500 m in length are considered important structures which facilitate communication between large areas of Europe and play a decisive role in the functioning and development of regional economies. Therefore the Directive includes minimum safety requirements for tunnel users which are aimed at

- preventing events that may endanger human life, the environment and tunnel installations.
- reducing the consequences of incidents and fires. To achieve this objective the measures which have to be taken shall
  - enable people involved in incidents to rescue themselves
  - allow immediate intervention of road users to prevent greater consequences
  - ensure efficient action by emergency services and
  - limit material damage.

3. ORGANISATIONAL STRUCTURE

The Directive has to be applied on tunnels being in design, construction or operating stage which are longer than 500 m and are situated on the Trans-European Road Network. Each member state has to convert the regulations of this Directive within 24 months after its entry into force into national rules (law). In order to reach this aim, every single member state shall designate an Administrative Authority which shall present a link to the European Commission. This Administrative Authority shall ensure that all safety conditions are met and therefore shall have the power to suspend or restrict the operation of a tunnel. Additionally, it shall ensure that tunnels are tested and inspected on a regular basis and organise the training and equipping of emergency services.

The Administrative Authority shall identify as <u>tunnel manager</u> the public or private body responsible for the safety of a tunnel under all aspects whether it is in the design, construction or operating stage. Furthermore, every significant incident or accident occurring in a tunnel shall be the subject of a report prepared by the tunnel manager which shall be forwarded to the Administrative Authority.

Finally, every two years each member state shall compile reports on fires and accidents occurring in a tunnel, analyse and evaluate them in terms of effectiveness of safety facilities and measures, and transmit the reports to the European Commission. In order to exchange experiences these reports shall be available for all member states.

Furthermore, the tunnel manager shall nominate for each tunnel one *Safety Officer* who shall coordinate all preventive and safeguard measures. The Safety Officer shall take part in the definition of safety schemes and the specification of structure, equipment and operation in respect of both new tunnels and modifications to existing tunnels and shall also be responsible for maintenance and repairing of the tunnel installations. In addition to that, the Safety Officer shall ensure the coordination with emergency services and take part in the preparation of operational schemes. Moreover, he shall verify that operational staff and emergency services are trained and take part in the organisation of exercises.

Inspections, evaluations and tests shall be carried out by *Inspection Entities* which must be functionally independent from the Tunnel Manager.

4. PROCEDURES FOR APPROVAL AND COMMISSIONING OF A TUNNEL

An important new aspect of the Directive of the European Union is represented by the regulation that all tunnels which fall within its scope have to be assessed in terms of safety in every stage by exactly defined procedures which are given in *Annex II* of the Directive. The fundamental basis in every stage is the safety documentation of the respective tunnel which has to be compiled and continuously updated by the tunnel manager.

The safety documentation for a tunnel in the design stage shall include

- a technical description of the planned structure
- a description of preventive and safety measures for tunnel users with respect of people with reduced mobility and disabled people
- a traffic forecast study specifying and justifying the conditions expected for the transport of dangerous goods, together with a risk analysis
- a specific hazard investigation which specify and substantiate measures for reducing the likelihood of accidents and their consequences
- an opinion on safety from an expert not involved
- a description of the organisational structure in terms of operation and maintenance of a tunnel
- an emergency response plan which also shall take into account people with reduced mobility and disabled people
- a description of the system of permanent feedback of experience through which significant incidents and accidents can be recorded and analysed

The safety documentation of tunnels already in operation shall additionally include

- a report and analysis on significant incidents and accidents
- a list of the safety exercises carried out and an analysis of the lessons learned from them

The above mentioned safety documentation for a tunnel in design stage shall be submitted to the appropriate authority before the construction of the tunnel begins. As far as tunnels in construction stage are concerned, on the basis of the safety documentation the Administrative Authority shall assess the tunnel in terms of its conformity with the requirements of the Directive. Tunnels already in operation are assessed on the basis of the safety documentation and of an inspection in terms of their conformity with the requirements of the Directive. In Austria the documentation of the design and the facilities of a tunnel can be compiled on the basis of an already existing data bank which will have to be adapted in an appropriate way.

The assessment of all tunnels already in operation must be carried out by the Administrative Authority within 30 months after the entry into force of the Directive. If necessary, the tunnel manager shall draw schemes for modifying the tunnel in order to fulfil the regulations of the Directive.

Every member state shall present a report including the schemes of all necessary modifications within 36 months after the entry into force of the Directive.

The inspection entity shall carry out inspections at regular intervals of at most 6 years in order to ensure a standard of tunnel safety corresponding to the Directive of the European Union.

5. RISK ANALYSIS

The risk analysis represents a special issue of the Directive of the European Union. It is on the one hand an obligatory part of the safety documentation of a tunnel but on the other hand the method to carry out the risk analysis is not defined and each member state is required to work out on national level a precise and clearly defined procedure and to revise it within the following five years with the aim of reaching agreement with the other member states of the European Union.

The risk analysis shall include all aspects of the system consisting of infrastructure, operation, users and cars. All parameters relevant in this respect are defined in *Annex I* of the Directive; they range from the length to the geographical and meteorological conditions of a tunnel.

In Austria the already existing Austrian Guideline Code for the Planning, Construction and Maintenance of Roads (RVS) with regard to ventilation systems and operating and safety facilities in tunnels includes a risk analysis which on the basis of four parameters analyses the risk potential and the safety coefficient of a given tunnel. The procedure of assessment shall be re-examined and redefined taking into account the latest recognitions. The RVS shall include also in future a more simplified method of assessment.

In order to evaluate the existing risks in Austrian road tunnels and to analyse the effectiveness of each individual measure a quantitative risk analysis is being worked out. Its main emphasis is laid on the relative comparison of the risks existing in tunnels of various configurations and frame conditions. In order to evaluate the extent of damages the most frequent accidents and incidents are analysed. To evaluate the existing risk of accidents involving dangerous goods transports the QRA-method regarding the transport of dangerous goods worked out on the basis of the OECD/PIARC study shall be applied.

6. SAFETY MEASURES

The safety measures corresponding to the minimum requirements of tunnel safety are indicated in *Annex I* of the Directive. They mainly regard infrastructure and operation of a tunnel. Important measures regarding vehicles and driving lessons for tunnel users - as defined in the report of the group of experts of the UN/ECE - shall be regulated on the basis of other EU-Directives. In Austria in this regard several initiatives have already been taken (informative material, revision of documents used in driving schools etc).

The requirements mentioned in *Annex I* are subdivided in requirements regarding measures of construction and requirements regarding operating and safety facilities such as ventilation systems, lighting, surveillance systems, communication systems and fire resistance of operating facilities. Since several measures - above all those regarding construction - show a negative benefit-cost relation and some modifications cannot be carried out in a tunnel already built, e.g. diminishing a too high longitudinal gradient of a tunnel, the Directive differentiates between tunnels being designed and tunnels already in operation.

Furthermore, the Directive may accept the implementation of risk reduction measures as an alternative to the requirements laid down in *Annex I*, provided that the alternative measures will result in equivalent or improved protection. The efficiency of these measures shall be demonstrated through a risk analysis.

Most part of the individual regulations governing the implementation of constructional measures to improve infrastructure are exactly defined. They range from laying down the degree of prognosticated traffic volume which in case it is exceeded requires the construction of two tubes to regulations regarding tunnel drainage in case of dangerous goods transports. As far as safety facilities are concerned all relevant components are mentioned but the technical specifications in this regard are only a few e.g. minimum required waste air exhaustion or luminance. These specifications have to be laid down in the respective national guideline codes (standards). However, in future the effectiveness of the individual measures will have to be analysed and assessed in a more detailed way.

Austria has taken part actively at the Consultations about the Directive of the European Union. Therefore, most part of the Austrian guidelines already correspond to the regulations defined in *Annex I* or have even set higher standards, e.g. regarding electrical equipment

7. SIGNING FOR TUNNELS

The Commission of the European Union is particularly interested in the harmonization of signs and symbols used in a tunnel, especially as far as forms and colours characteristic of individual classes of signs are concerned. In *Annex III* all member states are required to indicate escape routes using the sign for emergency exits corresponding to the Vienna Convention, and to indicate the two nearest emergency exits and the respective distances. The emergency stations and lay-bys shall be indicated by uniform signs, too.

8. CONCLUSION

On the basis of the experiences made because of the tunnel disasters occurred in the last few years in Europe activities in order to harmonize directives and regulations regarding safety of road tunnels have increased. In this context the publications of the PIARC working group which form also the basis of many national regulations have to be mentioned in particular. Another important step in this regard has been made by the group of experts of the UN/ECE publishing its report on measures to improve tunnel safety.

But the most important contribution to reach the aim of harmonization is represented by the recently published Directive of the European Parliament and of the Council on minimum safety requirements for tunnels in the Trans-European Road Network. This Directive makes clear that tunnel safety can be defined only considering the entirety of many aspects which are connected with each other. Above all, the long tunnels situated in the alpine member states have to be dealt with applying specific requirements and measures which have been laid down in the Directive of the European Council and have been realized in collaboration with the member states involved. As far as Austrian standards are concerned, it has to be emphasized that they already correspond to a high level so that the translating into practice of measures regarding infrastructure will not be a problem. The structural reorganisation and the related points of view yet call for continuing with detailed work. However, in view of the important aim to increase tunnel safety for all users this should only be another incentive to go on.

OVERVIEW OF WORK PERFORMED BY PIARC C5 WORKING GROUP 6 ON FIRE AND SMOKE CONTROL

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ABSTRACT

The World Road Association (PIARC) has long included the subject of tunnel safety and ventilation as part of its quadrennial activities. The subject of fire life safety is addressed by its Technical Committee (C-5) and in turn by its Working Group 6 "Fire and Smoke Control in Road Tunnels". This paper provides a brief overview of the activities of PIARC Working Group 6 principally during the most recent four year PIARC cycle which culminated with the World Road Congress held in Durban, South Africa in October 2003.

1. INTRODUCTION

There are more road tunnels being built to provide access routes across waterways, through mountains or to simply to avoid urban environmental and construction difficulties.

As a result of the significant tunnel fires occurring during the recent years in the European alpine tunnels (Mont Blanc, Tauern and St. Gotthard Tunnels), worldwide interest in road tunnel fire life safety has intensified.

Vehicle fires give rise to particular concern because their consequences can be far greater in a road tunnel than on the open road if no appropriate mitigation measures are taken.

The continuing decrease in road vehicle pollutant emissions is such that the capacity of today's ventilation systems and equipment is usually determined by fire and smoke control considerations. This makes the planning and design decisions regarding the fire emergency extremely critical to the road tunnel construction process.

2. TECHNICAL COMMITTEE

Since it was created in 1957, the PIARC Committee on Road Tunnels (now known as the PIARC Technical Committee on Road Tunnel Operation C-5) has been engaged in the consideration of fire life safety and emergency ventilation (related to fire smoke control) systems and equipment. Information and recommendations in these fields have appeared in the reports C-5 produced for the PIARC World Road Congresses in Rio (1959), Tokyo (1967), Vienna (1979), Sydney (1983), Brussels (1987) and Marrakech (1991).

World Road Association (PIARC)
World Congress Reports on Ventilation

Report to the XVth World Road Congress, Mexico City, Mexico, 1975
Report to the XVIth World Road Congress, Vienna, Austria, 1979
Report to the XVIIth World Road Congress, Sydney, Australia, 1983
Report to the XVIIIth World Road Congress, Brussels, Belgium, 1987
Report to the XIXth World Road Congress, Marrakech, Morocco, 1991, [19.05.B]
Report to the XXth World Road Congress, Montreal, Canada, 1995, [20.05.B]
Report to the XXIst World Road Congress, Kuala Lumpur, Malaysia, 1999, [21.05.B]
Report to the XXIInd World Road Congress, Durban, South Africa, 2003, [22.05.B]

Until the Marrakech Congress the subject of fire and smoke control had been addressed by various working groups within the technical committee, especially those devoted to Operation-Maintenance-Management and to Pollution-Environment-Ventilation.

The working groups aligned with Technical Committee C-5, during the recent PIARC cycle, related to road tunnels were as follows:

Working Group 1 Operation
Working Group 2 Pollution, Ventilation, Environment
Working Group 3 Human Factors of Safety
Working Group 4 Communication Systems and Geometry
Working Group 5 Dangerous Goods
Working Group 6 Fire and Smoke Control

3. WORKING GROUP

In 1992 the Committee on Road Tunnels (C-5) determined that the importance of this subject justified the establishment of a specific working group devoted to fire and smoke control. This new working group, Working Group 6, has, since starting operation, participated in the Congress Reports for the World Road Congresses in Montreal (1995), Kuala Lumpur (1999) and Durban (2003).

This working group has met twice a year since its formation in 1992. The working group meetings have been held in Austria, Finland, France, Germany, Italy, the Netherlands, Norway, Spain, Sweden, Switzerland, the United Kingdom and the United States.

During its initial meetings the working group deemed it necessary to draw up a "state-of-the-art" summary of the primary subjects connected to fire and smoke control in road tunnels. The results of much research, experiences, reflections and even regulatory documents had been published worldwide, but a synthesis was lacking. Early results were published in the report prepared by the Committee on Road Tunnels for the XXth World Road Congress in Montreal in 1995. [1]

The inter-congress report, entitled "Fire and Smoke Control in Road Tunnels" (Figure 1) was published in 1999 in conjunction with the XXIst World Road Congress in Kuala Lumpur [2]. This 1999 report provided the "state-of-the-art" assessment prepared by the working group (a copy of the Table of Contents is at Appendix B). It was intended for all those who are interested in road tunnel planning, design, construction, operation or safety: owners, consultants, operators, researchers, regulators, fire brigades, etc. It provides an overview and recommendations, as well as the background on the way to provide reasonably efficient and cost-effective systems to protect against fire and smoke in road tunnels. It also provides references that are useful to obtain further details.

INTRODUCTION

I OBJECTIVES OF FIRE AND SMOKE CONTROL
II FIRE RISK AND DESIGN FIRES
III SMOKE BEHAVIOUR
IV STUDY METHODS
V VENTILATION FOR FIRE AND SMOKE CONTROL
VI EXITS AND OTHER SAFETY FACILITIES
VII TUNNEL REACTION AND RESISTANCE TO FIRE
VIII FIRE RESPONSE MANAGEMENT
IX REFERENCES

Figure 1 "Fire and Smoke Control in Road Tunnels" [2]

However, despite the enormous amount of data and information contained in this book experience and research are still needed because the field is quite large and the issues extremely complex: fires in tunnels involve numerous varing and interacting physical phenomena, which have been particularly difficult to investigate.

We do not yet have a complete understanding of the behaviour of a fire in a tunnel, even though our knowledge is quickly improving through numerous research projects. As a consequence further effort will be needed to achieve complete, well-founded and universally accepted guidelines. The PIARC Technical Committee on Road Tunnel Operation (C-5) has continued its efforts towards this goal.

The recent fire incidents in the Mont Blanc, Tauern and St. Gotthard Tunnels during the last few years have led to a situation where safety in transport tunnels, particularly evacuation, rescue and suppression concepts are being scrutinised both in the affected countries as well as worldwide.

3.1. The PIARC Cycle

The PIARC operational cycle is four years in length. Therefore, all committees and working groups have a life of four years. It then follows that all work programs also have a life of four years. Each cycle ends with a World Road Congress which is held every four (4) years. The most recent was held in Durban, South Africa in October 2003. After each World Road Congress PIARC leadership determines which committees and which working groups will be reconstituted for the next cycle base on the PIARC conceptual themes for the upcoming cycle.

3.2. Working Group Meetings

Working Group 6 held eight (8) Meetings in the 2000-2003 cycle in the following locations:

	City	Date
1.	Lyon	April 2000
2.	Helsinki	December 2000
3.	Madrid	April 2001
4.	Essen	October 2001
5.	Graz ++	April 2002
6.	Bad Ragaz ++	September 2002
7.	Turin ++	January 2003
8.	Amsterdam ++	April 2003

++Joint Collaborative Meetings were also held with Working Group 2.

3.3. Working Group Members

The following countries were represented within Working Group 6 Membership during the 1999-2003 cycle:

Members of PIARC Working Group 6 during the 1999-2003 Cycle

- **Australia**
  - Arnold Dix
- **Austria**
  - Rudolf Hörhan
  - Karl Pucher
  - Peter Sturm
- **Finland**
  - Marko Järvinen
- **France**
  - Eric Casale
  - Didier Lacroix
  - Anne Voeltzel
- **Germany**
  - Alfred Haack
  - Dieter Tetzner
  - Werner Foit
- **Italy**
  - Roberto Arditi
  - Giulio Gecchele
- **Japan**
  - Toshinori Mizutani
- **The Netherlands**
  - Hans Huijben
- **Norway**
  - Harald Buvik
- **Spain**
  - Alberto Abella
  - Samuel Estefania
  - Fernando Hacar
- **Sweden**
  - Bernt Freiholtz
- **Switzerland**
  - Ingo Riess
  - Martin Alleman
- **United Kingdom**
  - Norman Rhodes
- **United States of America**
  - Art Bendelius
  - Tony Caserta

3.4. Member Participation

The total Working Group 6 membership during this cycle was 23 members representing 14 countries. The member meeting participation is shown below:

Location City	Meeting Date	Members Present	Countries Represented
Lyon	April 2000	12	10
Helsinki	December 2000	14	12
Madrid	April 2001	18	12
Essen	October 2001	13	10
Graz	April2002	16	13
Bad Ragaz	September 2002	13	12
Turin	January 2003	12	10
Amsterdam	April 2003	14	12

4. APPROVED WORK PLAN

At the beginning of each PIARC cycle each working group must, in conjunction with its respective technical committee develop a work plan to be approved by the respective managing committee.

The approved work plan for WG6 for the 1999-2003 cycle contained the following work tasks:

Work Plan Task 1. Lessons from Past Disasters
Work Plan Task 2. Safety Concept for Tunnel Fires
Work Plan Task 3. Structures Resistance to Fire
Work Plan Task 4. (Semi-) Transverse Ventilation
Work Plan Task 5. Emergency Exits
Work Plan Task 6. Fire Specific Safety Equipment
Work Plan Task 7. Fire Response Management
Work Plan Task 9. Emergency Ventilation System Operation/Control

Each of these work plan tasks is briefly described below:

4.1. Work Plan Task 1 - Lessons from Past Disasters

The scope of this work task initially included the creation of a comprehensive data base of tunnel fires which would include tunnel characteristics and response to fire in addition to an in-depth comparative analysis of the recent Mont Blanc and Tauern tunnel fires.

At a later date the data base development was deleted as one of the new thematic networks, Fires in Tunnels (FIT), was planning to develop such a data base. Also as events unfolded with time and another serious road tunnel fire occurred the scope was adjusted to include the fire that occurred in the St. Gotthard Tunnel on 24 October 2001.

The output was intended to be an article in Routes/Roads and a short PIARC report on these fires to be published in 2003. Eventually it was determined that all work of Working Group 6 would be incorporated into a comprehensive inter-congress report to be published in 2004 [3].

4.2. Work Plan Task 2 - Safety Concept for Tunnel Fires

The purpose of this work Plan Task was to develop a set of objectives and design scenarios to address the overall concept of tunnel safety in the event of a tunnel fire. This was intended to include fire development.

The output of this task was intended to be included in a PIARC report to be published in 2003. Eventually it was determined that all work of Working Group 6 would be incorporated into a comprehensive inter-congress report to be published in 2004 [3].

4.3. Work Plan Task 3 - Structures Resistance to Fire

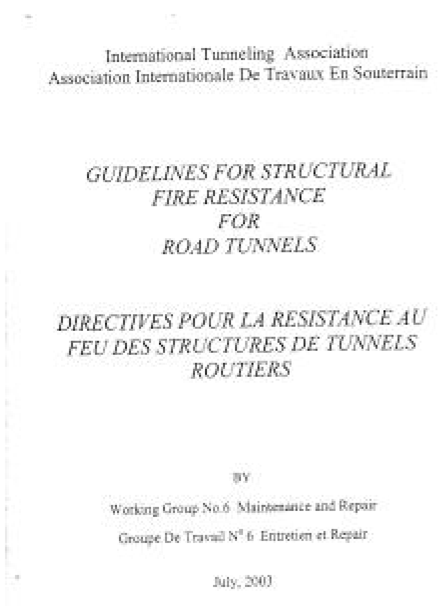
In order to advance all aspects of tunnel structures resistance to fire, the PIARC Technical Committee on Road Tunnels established a collaborative venture with the International Tunneling Association (ITA).

PIARC Working Group 6 on "Fire and Smoke Control" will more specifically determine and present the design fires and resistance objectives, while the ITA through its Working Group 6 on "Repair and Maintenance of Underground Structures" will examine and document the construction methods and material to meet these objectives.

Therefore, the scope of Work Plan Task 3 included continuing work on the collaborative effort with ITA Working Group 6 "Repair and Maintenance of Underground Structures" regarding structures resistance to fire. This work included, as noted above, the development of temperature-time curves for tunnel fires as quantified objectives for both safety and risk of traffic disruption

The output was to be intended to be a paper published simultaneously in Routes/Roads, Tunneling and Underground Space Technology, and Tunnels in 2001 along with the publication of the joint PIARC - ITA recommendations in 2002-2003

The Routes/Roads article is currently pending publication. The work will also be presented in ITA's "Guidelines for Structural Resistance for Road Tunnels to be formally published by ITA in 2004 [4]. This document is currently in draft form (Figure 2). In addition, the work of PIARC Working Group 6 in this area will be incorporated into a comprehensive inter-congress report to be published in 2004 [3].



International Tunneling Association
Association Internationale De Travaux En Souterrain

GUIDELINES FOR STRUCTURAL FIRE RESISTANCE FOR ROAD TUNNELS

DIRECTIVES POUR LA RESISTANCE AU FEU DES STRUCTURES DE TUNNELS ROUTIERS

BY

Working Group No.6 Maintenance and Repair
Groupe De Travail N° 6 Entretien et Repair

July, 2003

Figure 2: "Guidelines for Structural Fire Resistance for Road Tunnels" [4]

4.4. Work Plan Task 4 - (Semi-) Transverse Ventilation

Work Plan Task 4 included discussion of transverse ventilation systems for road tunnels. This scope initially included consideration of both system design and system operation. The output was intended to be a short PIARC report to be published in 2002-2003. Eventually all work of Working Group 6 will be incorporated into a comprehensive inter-congress report to be published in 2004 [3].

4.5. Work Plan Task 5 - Emergency Exits

The purpose of this Work Plan Task was to include consideration of the types and characteristics of emergency exits in road tunnels including how to deal with disabled people. Also included was the consideration of the necessary spacing between exits according to people behaviour and tunnel ventilation including escape modeling. This section includes a documented PIARC survey on emergency exits in road tunnels.

The output of this was intended to be included in a short PIARC report to be published in 2002/2003. Eventually it was determined that all work of Working Group 6 would be incorporated into a comprehensive inter-congress report to be published in 2004 [3].

4.6. Work Plan Task 6 - Fire Specific Safety Equipment

Work Plan Task 6 included discussion of fire specific safety equipment for road tunnels. This included fire suppression systems such as Sprinklers, water mists and others in addition to automatic fire detection systems. A unique aspect of this section is the documented PIARC survey on fire detection and automatic fire suppression in road tunnels conducted in 2000.

The output of this task was intended to be included in a PIARC "State-of-the-Art report to be published in 2003, however, eventually it was determined that all work of Working Group 6 would be incorporated into a comprehensive inter-congress report to be published in 2004 [3].

4.7. Work Plan Task 7 - Fire Response Management

The purpose of this Work Plan Task was to include discussion of the organisation of fire tests for both tunnel commissioning and for staff training (exercises) and of the behaviour expected from users in case of a fire in a road tunnel.

After much discussion within the working group Work Plan Task 9 was combined with Work Plan Task 7 under the title of "Fire Response Management".

The output of this task was originally intended to be included in a PIARC report to be published in 2003, however eventually it was determined that all work of Working Group 6 would be incorporated into a comprehensive inter-congress report to be published in 2004 [3].

4.8. Work Plan Task 9 - Emergency Ventilation System Operation-Control

Work Plan Task 9 was initially to include discussion of methods and systems required to properly operate and control a road tunnel ventilation system during a fire emergency.
Work Plan Task 9 was incorporated into a modified Work Plan Task 7.

5. PIARC PUBLICATIONS

As noted in conjunction with the Working Group 6 Work Plan Tasks outlined above the following publication plans are underway:

- Routes-Roads Article on Structures Resistance to Fire. {pending publication in 2004}
- Routes/Roads Article on Lessons Learned from Recent Tunnel Fires. {pending publication in 2004}
- Inter-Congress Report titled "Systems and Equipment for Fire and Smoke Control in Road Tunnels" is currently programmed to be published in 2004 [3]. (Figure 3) The proposed Table of Contents is shown at Appendix D. The Table of Contents shows the source (Work Plan Task) of each Section in brackets. This report was prepared in collaboration with PIARC Working Group 2.

World Road Association

SYSTEMS AND EQUIPMENT FOR FIRE AND SMOKE CONTROL IN ROAD TUNNELS

2004 PIARC Technical Committee on Road Tunnel Operation (C5)

FOREWORD
INTRODUCTION
1. **SMOKE PROGRESS AT THE BEGINNING OF A FIRE** [Results of Work Plan Task 7]
2. **SAFETY CONCEPT FOR ROAD TUNNELS** [Results of Work Plan Task 2]
3. **LESSONS LEARNED** [Results of Work Plan Task 1]
4. **VENTILATION** [Results of Work Plan Task 4]
5. **EMERGENCY EXITS** [Results of Work Plan Task 5]
6. **FIRE SPECIFIC EQUIPMENT** [Results of Work Plan Task 6]
7. **STRUCTURE RESISTANCE TO FIRE** [Results of Work Plan Task 3]
8. **OPERATIONAL RESPONSIBILITIES FOR EMERGENCIES** [Results of Work Plan Task 7]
9. **SUMMARY**
10. **REFERENCES**
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12. **APPENDICES**

Figure 3 "Systems & Equipment for Fire and Smoke Control in Road Tunnels" [3]

5.1. New Inter-congress Report

The comprehensive PIARC Inter-Congress Report titled "Systems and Equipment for Fire and Smoke Control in Road Tunnels" [3] is composed of eight (8) key technical sections. Each section begins with an introduction subsection which identifies the objectives and if appropriate, addresses earlier work performed by PIARC.

This report should be considered as a supplement to the 1999 report [2] as it supplements the material contained therein it does not replace the earlier publication.

The key technical sections of this document include:

- Section 1 presents an introduction to the effects of smoke propagation at the beginning of a road tunnel fire.
- Section 2 develops some sound safety concepts for the road tunnel. In
- Section 3 addresses the most severe of the recent tunnel fires. These fires are examined and a set of lessons that the industry should learn from these unfortunate incidents are included.
- Section 4 covers aspects of both transverse and longitudinal ventilation along with some of the equipment required for the ventilation system to function properly.
- Section 5 addresses the issue of emergency exits for evacuation, escape and rescue.
- Section 6 contains discussion of the latest technological advancements in fire detection and suppression.
- Section 7 contains the written material that PIARC Working Group 6 provided to ITA as a part of the collaboration agreement noted above related to the criteria to be applied in the development of methods to furnish structural resistance to fire.
- Section 8 includes a discussion of the objectives for smoke control and how these objectives can be achieved by the designers and operators, the factors affecting emergency response teams, the requirement for an Emergency Response Plan, and the importance of maintenance and testing of equipment. The issue of operational responsibilities during a fire based emergency is addressed in
- Section 9 contains a list of suggested subjects to be considered for future research and study.

6. COLLABORATIVE EFFORTS

Collaboration was one of the key themes of the Working Group 6 approved work plan. The purpose was the interact with the organizations from whom the working group could obtain the best input

The collaboration with ITA and its Working Group 6 had been ongoing for several years before the most recent cycle and therefore had been a most fruitful continuation. We now see, in draft form, the resulting document "Guidelines for Structural Fire Resistance for Road Tunnels".

Collaboration within the PIARC organisation included fellow working groups such as Working Group 2 "Pollution, Ventilation, Environment", Working Group 3 "Human Factors of Safety" and Working Group 4 "Communications Systems and Geometry".
The collaboration with Working Group 2 included deliberations on the following subjects of joint interest:

- Smoke Dampers
- Jet Fans
- Maintenance and Testing
- Ventilation Control

The results of these joint deliberations will appear as jointly written material in the new PIARC publication [3] in Sections 4 & 8 and the Appendices.

The collaborations with Working Groups 3 and 4 related to the work done by Working Group 6 in the area of emergency exits and human behaviour as related to emergency response and evacuation.

7. CONCLUSION

The primary purpose of this paper was to briefly present the results of the activities of the PIARC Working Group 6 "Fire and Smoke Control in Road Tunnels" during the recent cycle. The paper has shown the work performed and the resulting publications produced by this working group. It is clear that the resulting efforts of the working group are a key element in the continuing battle again the impact of fires in road tunnels. This was the result of the over 20 members from 14 countries working together toward a common goal "to improve fire life safety in road tunnels". The strong participation by all representatives made this cycle's efforts extremely productive and will result in an excellent documentation of the goals achieved.

The final section, Section 9 as noted above contains a comprehensive list of suggested issues for further study and research. Listed below is a brief abstract of a few of the key items from that list:

- Develop standards for in-situ fire tests for all tunnel ventilation system types to permit comparison of tests.
- Develop event management system availability – fire – police – rescue – ambulance.
- Conduct further study of evacuation procedures.
- Develop sample response plans.
- Evaluate the effects on motorists of smoke back-layering.
- Develop clear and reasonable criteria for tenable environment.
- Perform a detailed review of evolving technologies in fire suppression.

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NEW EMISSION DATA FOR VENTILATION DESIGN FOR ROAD TUNNELS

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ABSTRACT

In 1990 and 1995 PIARC published the calculation methodology and the emission factors for ventilation design. The old version described the emission situation up to the year 1995. An update of the existing PIARC methodology was necessary, as the emission standards of the vehicles are becoming more stringent and hence the vehicle cleaner. Carbon Monoxide (CO) is no longer the dominating factor in ventilation design in many countries, as the CO emissions per vehicle have reduced significantly, in addition diesel powered vehicles have penetrated the passenger car fleet and become in some countries almost as important as gasoline fuelled cars. As heavy duty vehicles are mostly powered by diesel engines the visibility issue has become in many cases the driving force in ventilation design for normal operation. As the emission quantities per vehicle have decreased for almost all pollutants the issue of the non exhaust particulate matter emissions due to tyre and brake wear as well as road abrasion and resuspended dust have become important factors. Some countries have also introduced nitrogen dioxide as the target pollutant for in-tunnel air monitoring. To reflect this situation updated emission tables for CO and turbidity, NOx emissions, and non-exhaust PM emissions have been introduced in the new PIARC calculation scheme.

The background for the new PIARC document is described and the the application of the new PIARC guidelines to the Austrian Standards on ventilation design discussed.

Keywords: ventilation design, emission factors, visibility

1. INTRODUCTION

Ventilation design for normal operation of a road tunnel is based on in – tunnel air quality. That means, that the ventilation has to provide sufficient fresh air to dilute the exhaust gases to a tolerable level. The in – tunnel air quality is defined by the concentration of Carbon Monoxide (CO) or the visibility inside the tunnel. In many countries CO is no longer the domination factor, the necessary fresh air amount is driven by the visibility. However, especially in urba areas another pollutant is playing an important role. Nitrogen Dioxide (NO2) is one of the pollutants in cities with the highest number of violations of threshold levels. Road traffic is one of the major emitter of Nitrogen Oxides (NOx) in urban areas. Hence, portals of road tunnels are major sources of NOx emission and reduced air quality in the close vicinity. To reduce this burden, the ventilation can provide a pre – delution of NOx and hence lower NO2 impact levels.

Emission legislation forces the car manufactures to produce cleaner vehicles. This results in lower polltuant emissions and hence in a reduced fresh air demand for each single vehicle. However, as soon as visibility is concidered the exhaust particle emissions are not the only emission source which has to be taken into account. Dust inside the tunnel plays a more and more important role. As the exhaust particle emissions have been reduced considerably the non – exhaust become (in relation) more and more important. Sources for non – exhaust particle emissions are abreation of road surface, tyre wear, break wear and resuspended road dust. Contrary to the exhaust PM emissions which are related to vehicles with diesel engines the non – exhaust PM emissions concern all vehicles. While abreation is a matter of each single vehicle, the resuspension might be non linear with the number of vehicles, as a certain number of vehicles or a certain vehicle speed may be sufficient for resuspension. However, up to now the data base for this type of emissions is very poor and does not allow for a non linear vehicle or speed dependent emission factor.

2. DEVELOPMENT IN VEHICLE EMISSIONS

2.1. Exhaust emissions

Permanent problems with air quality and a constant increasee in traffic volume are the driving facts behind the implementation of more and more stringent emission standards for road vehicles. Table 1and Table 2 show the development for passenger cars and heavy goods vehicles in Europe.

Table 1: Emission standards for passenger cars according to EU regulations, values in [g/km]

Passenger cars		Test	CO	HC	NOx	HC+NOx	PM
ECE 15/04 gasoline**	1982	R15	16.5			5.1	
Euro 1 gasoline	1992	NEDC	2.72			0.97	
Euro 1 diesel	1992	NEDC	2.72			0.97	0.14
Euro 2 gasoline	1997	NEDC	2.0			0.5	
Euro 2 diesel	1997	NEDC	1			0.7	0.08 (IDI) 0.10 (DI)
Euro 3 gasoline	2000	NEDC*	2.3	0.2	0.15		
Euro 3 diesel	2000	NEDC*	0.64		0.5	0.56	0.05
Euro 4 gasoline	2005	NEDC*	1.0	0.1	0.08		
Euro 4 diesel	2005	NEDC*	0.5		0.25	0.30	0.025

* modified test cycle; ** mass dependent values given are for mass class < 1020 kg

Table 2: Emission standards for heavy vehicles according to EU regulations. values in [g/kWh]

HGV		Test	CO	HC	NOx	Partikel
ECE R49	1982	R49	14.0	3.5	18.0	
Pre Euro*	1991	R49	12.3	2.6	15.8	
ECE R 49/02 (Euro 1)	1992	R49	4.9	1.23	9.0	0.4 (> 85kW) 0.68 (<85 kW)
Euro 2	1997	R49	4.0	1.1	7.0	0.15
Euro 3	2000	EST	2.1	0.66	5.0	0.10
Euro 4	2005	EST/ECT	1.5	0.46	3.5	0.02
Euro 5	2008	EST/ECT	1.5	0.46	2.0	0.02

*88/77/EWG

Unfortunately, developments in emission standards (to be fulfilled under test conditions) and real world behaviour are two different things. Extensive investigations within the framework of international resaerch projects show a totally different behaviour between test bed and reality. Table 3shows the differences between developments in emission standards and real worl behaviour for heavy duty vehicles. Taking the emission situation EURO 1 (1992) as 100% there is little improvement in the NOx – emissions and reduced improvments in PM emissions.

Table 3: Emission reductions of heavy duty vehicles under real world conditions vs. emission standards (Hausberger, 2003)

		EURO1	EURO2	EURO3
		1992	1997	2001
NOx	E-standard	100%	78%	55%
	on - road	100%	105% – 145%	75% - 110%
PM	E-standard	100%	38%	25%
	on - road	100%	35% - 110%	50% - 80%
HC	E-standard	100%	90%	50%
	on - road	100%	50% - 80%	60% - 90%

More or less the same results are visible in the US. Taking the UDDS cycle a a basis there is no improvment in NOx – emissions visible for the US heavy-heavy duty trucks (Clark et al, 2003). Similar trends have been reported for particulate matter (PM) emissions.

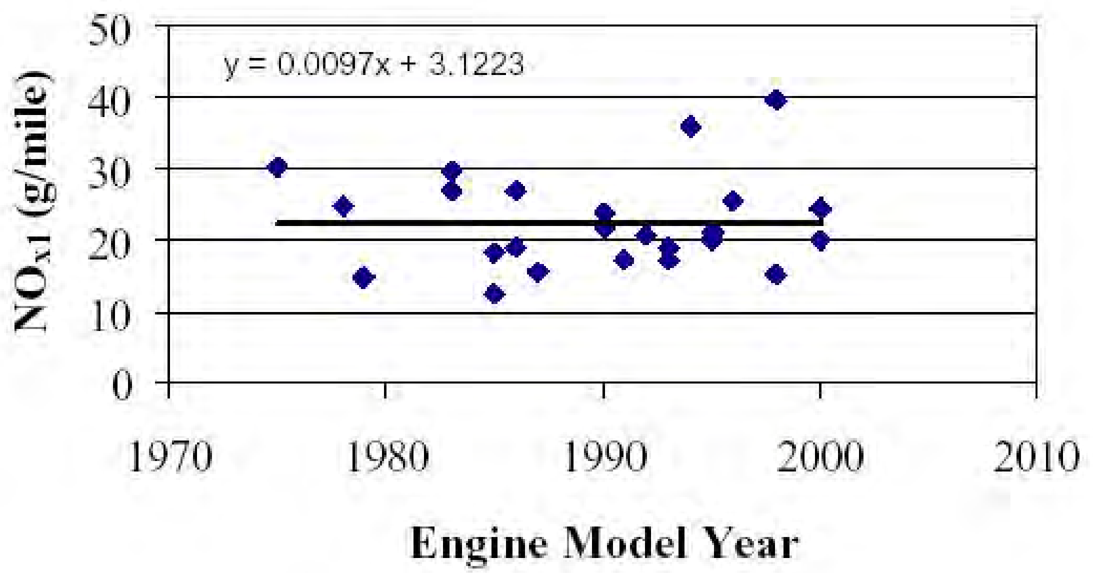

Figure 1: NOx – Emissions of heavy-heavy duty diesel trucks (HHDDV) according to the UDDS-cycle (Clark et al, 2003)

Based on the data produced by the various international activities for emission factor development (ARTEMIS, COST 346, Particulates) new emission tables have been proposed within the PIARC document which includes now vehicles up to EURO 4 (passenger cars) and EURO 5 (heavy duty vehicles).

2.2. Non - exhaust emissions

When considering PM emissions and hence visibility, two different sources have to be tackled. The first is the so called exhaust emission, i.e. the PM emission produced in the engine. The second one is the so called non-exhaust emission, i. e. PM emission from tyre and brake wear, road abrasion and resuspended dust. While the quality of the emission data for the first group is good, that for the second group is poor. For tunnel ventilation the light extinction is of importance. Therefore a correlation between PM mass emission and light extinction is needed. Such correlation factors are available for the exhaust part (although they are relatively old), but for the non-exhaust part such factors are missing.

2.2.1. Mass emissions

Figure 2 shows the correlation between calculated exhaust PM emissions (based on emission factors and traffic volume) and measurements undertaken for PM2.5 and PM10 in the Plabutsch tunnel. As it can be seen, there is a big discrepancy between calculated and observed PM emissions. This difference has two reasons. First of all, the calculation do not account for non – exhaust PM, and second there might be an inacurracy in the emission estimates for the exhaust part. However, as the majority of the exhaust emissions is smaller than PM1, a big part of the PM emission inside a tunnel is missed. Concerning PM 2.5 rougly 40% can be explained by the emission factors for exhaust PM emissions. Regarding PM10 only 10% account for the exhaust PM part. Thus it is obvious that a big part of PM emissions in road tunnels is missing.

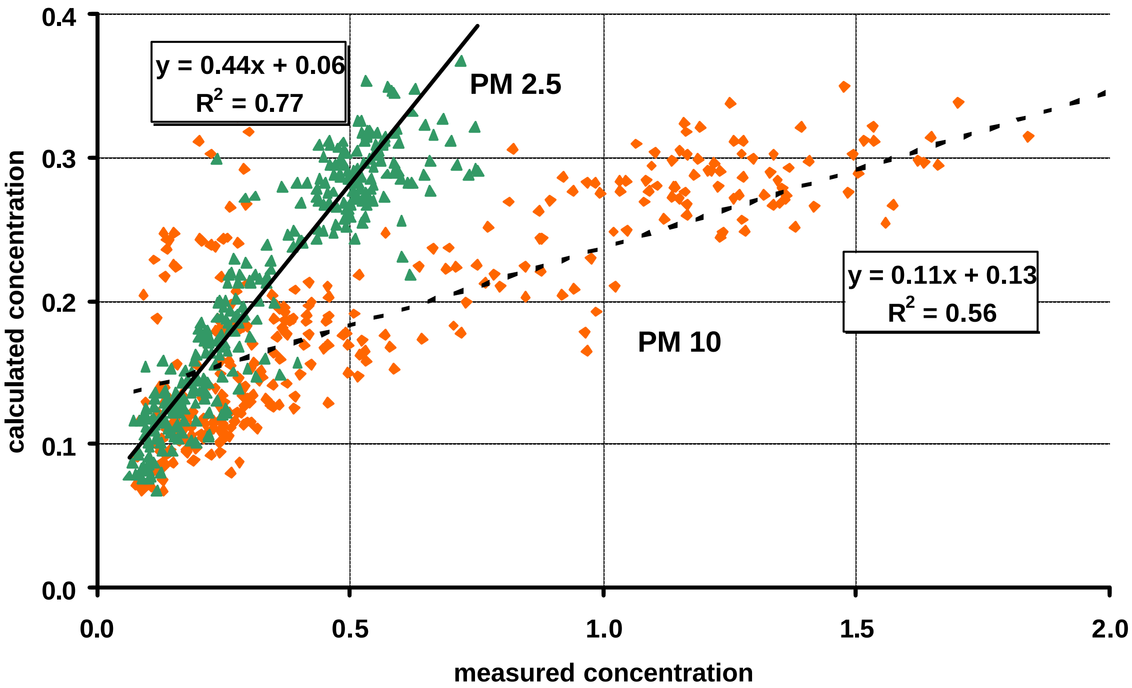

Figure 2: Correlation between measured and calculated values for PM10 and PM2.5 (note that the calculation do not distinguish between PM10 and PM2.5

Different investigations in road tunnels came up with emission factors for tyre and break wear (Abu-Allaban et al, 2003; Garg, 2000; Rauterberg-Wulff, 1999) as well as indications about road dust (Abu-Allaban et al, 2003). However, non of them looked at the combination between PM emission and light extinction.

2.2.2. Correlation mass – light extinction

The reason for light extinction is the scattering and absorption of radiation in the visible wave length range. In general sulfates, nitrates, organics, soot and soil are the major components that scatter and absorb light in the atmosphere. Except for the soil, most of these components are abundant in the 0.3 to 0.7 µm size range that approximates the wave length of visible light where they have their greatest effect on visibility impairment (Chow 2002). In road tunnels the two source types “exhaust” and “non-exhaust” emissions are relevant. The problem is that both have a different extinction behavior and have therefore to be treated different.

The extinction coefficient

The extinction coefficient (k) is defined as a factor describing the proportion between reduction in radiation flux (ϕ) and a layer thickness (dl).

$$d\phi = - k.\phi.dl \qquad (1)$$

An integration of equation (1) yields to the Beer-Lambert law.

$$\phi = \phi_0.e^{-kl}$$

ϕ…Intensity exit side

ϕ_0…Intensity inlet side

k… Extinction coefficient (log.)

l…Path length

The extinction coefficient is the sum of the scattering coefficient (σ) and the absorption coefficient (α)

$$k = \alpha + \sigma \qquad (2)$$

The relation between scattering and absorption is likely to vary, but mostly scattering dominates.

The different relations between exhaust (tail pipe) and non exhaust PM in the tunnel atmosphere result in different optical situations. This is shown in Figure 3 where results from tunnel and laboratory measurements are depicted (Pischinger 1977, Basel 2000, Leeb 2003). This shows that a clear correlation between extinction and mass concentration is not yet given. If solely PM from diesel engines is considered investigations show that the correlation between mass concentration (μ) and extinction is as follows:

Concentrated exhaust gas (exhaust pipe)

$$K = 6\ \mu$$

Diluted exhaust gas (tunnel)

$$K = 4.64\ \mu$$

The factor 6 was already defined in 1964 (Dodd 1964). The factor of 4,64 has been derived for diluted exhaust. Recent investigations show that the correlation between PM mass and light extinction of modern cars is in the range of 1:9 instead 1:6 (Leeb 2003). This means that PM emitted from modern cars has a higher absorption ratio than in former years. On the other hand exhaust PM has been reduced in tunnels in relation to the non-exhaust PM. As non-exhaust PM has a much smaller correlation factor (as it is bigger and hence the light scattering is not so effective) the correlation factor for tunnel air has to lie between the factors for soot and dust. Figure 3 shows the range of mass and extinction correlations found in the various tunnel measurements. It seems that the factor 4.6 is still a figure which can be used for an estimation of the light extinction caused by the mixture of exhaust AND non-exhaust particle matter.

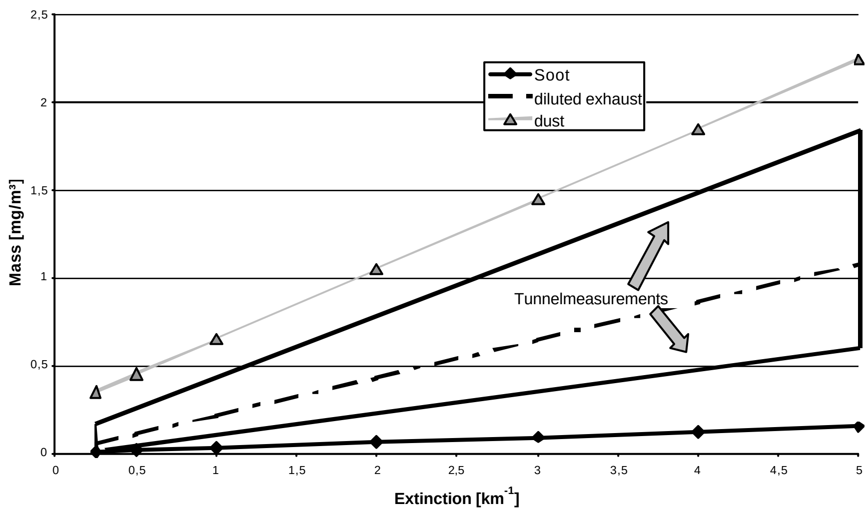

Figure 3: Correlation between PM mass concentration [mg/m³] and extinction [1/m]

2.2.3. Proposed emission factors for non-exhaust PM

Based on the investigations described above a vehicle type dependent emission factor covering the non-exhaust PM emissions is proposed. It has to be remarked that on bases of the available data only a rough differentiation between passenger cars (PC) and heavy duty vehicles (HDV) can be made.

Table 4: PM mass and turbidity emission factors for non exhaust PM 2.5 particles

Source	PC [mg/km]	PC [m²/km]	HDV [mg/km]	HDV [mg/km]
Non-exhaust PM	19± 2.4	0,087	97 ± 12	0,446

The values given in Table 4 are rough estimates based on the currently available knowledge. They refelct the principle difference between passenger car and heavy duty vehicle. As already mentioned it is currently not possible extract dependence on vehicle speed. It is likely that vehicle speed has a non linear influence on the resuspension of dust. It is also very likely that there is a non linear relation between the amount of vehicles and the resuspended dust. I.e. if a bulk of vehicles pass the tunnel all the dust may alredy be resuspended, regardless if other vehicle follow or not. At the moment a linear combination is foreseen. As most of the tunnelmeasurements were performed at speeds between 60 km/h and 80 km/h they are valid for this speed range. A different speed may result in different emission quantities.

2.2.4. Calculation methodology

The emission rate for extinction is now based on two emision factors. One is the exhaust part which is applicable for diesel powered vehicles only. The second one covers the non-exhaust PM emissions. It has to be considered that this part is aplicable to all typ of vehicles in the tunnel.

The emission due to PM (e_{ext})is:

$$e_{ext} = e_o + q_{ne} \qquad (4)$$

where e_o is the tail pipe emission contribution as a function of vehicle type, speed, slope, year, height, mass and

q_{ne} is the emission contribution from abrasion/tyre and break wear/resuspension. f(vehicle type, speed)

2.3. Application of the new emission data to the Austrian standard for ventilation design

2.3.1. Fresh air amount due to visibility

The Austrian standard for the calculation of the fresh air amount is given in the RVS 9.262. The emission factors proposed in te PIARC document have been applied to the Austrian fleet distribution. A peculiarity of the Austrian fleet is the very high share of diesel powered passenger cars. Due to tax incentives for diesel oil the passenger car fleet for 2003 consists already of more than 50% diesel cars. The share of diesel cars within the new vehicles section is more than 75%. This accounts for a relatively high fresh air amount for visibility from the passenger car section. In addition to that the non-exhaust PM have to be considered too. This results in a relatively high fresh air amount. This results in the fact that even in tunnels with a very low HDV share (city tunnels) CO doesn't play a role anymore.

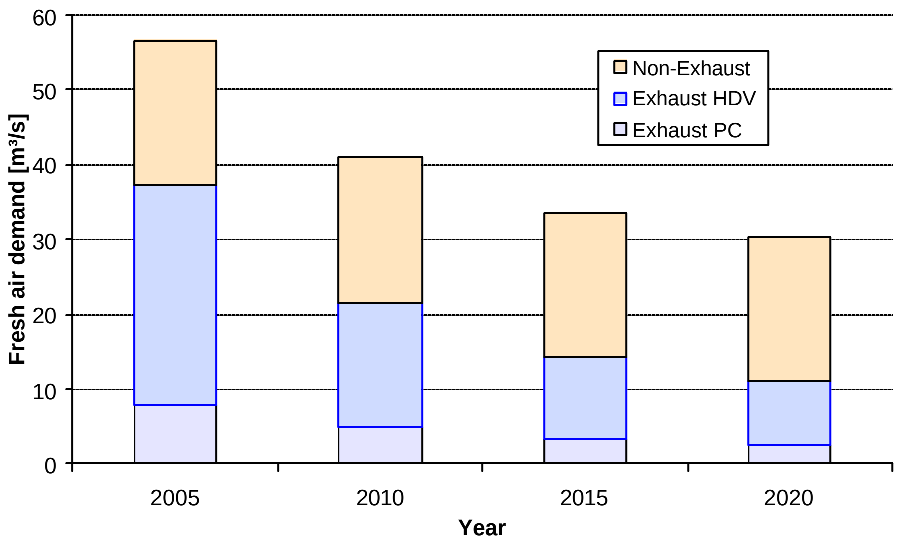

Figure 4: Fresh air demand due to visibility as a function of time

Figure 4 shows the evolution of the fresh air demand due to visibility for a certain traffic volume and different years. The calculation is based on a constant traffic volume of 1100 vehicle per hour with a HDV share of 20%. As the emission factors for exhaust PM take into account the technical developments until EURO 5 (2008) the biggesr reduction in exhaust PM is between 2005 and 2010. As non exhaust PM emission is a function of number of vehicles (no technical measure can reduce this part) the absolute emission quantity stays the same, the relative share increases with the years.

2.3.2. Ventilation due to NOx

Tunnels which are located in close vicinity to residential areas it meight be possible to design the ventilation on bases of criteria defined by the outside air quality rather than the in-tunnel air quality. Such situations may happen if blocks of flats are located close to tunnel portals and the air can not be exchanged via stacks. For such situations emission factors are given either in the PIARC publication or in emission factor databases for road traffic. However, the ventilation control has in such cases to follow other strategies like pre-dilution of tunnel air or increased momentum of the exhaust air jet, etc. The thershold levels meigth either be the in-tunnel NOx or NO2 concentration or the ambient NO2 air quality or a combination of both.

The following example shows a tunnel whose east portal is very close to a couple of blocks. The tunnel is relativly short (600 m), uni-directional with two tubes, and carries some 12 to 14,000 vehicles per day. In the framework of en environmental study the pollution dispersion was checked in the surrounding of the portals. Due to the existing high NO2 level, there is only little space for additional pollution. Hence, it proofed to be necessary that at times with an already bad NO2 air quality a special ventilation scheme would be necesary to pre-dilute the exhaust air before it leaves the tunnel. This will of course not reduce the emissions but would help to keep the concentrations under the AQ threshold level for NO2. Figure 5 shows the east portal. A 7 m high noise protection wall serves in addition as a wind shield and prevents a direct ground level transport of pollutants to the flats.

Figure 5: East portal of the “Unterflurtrasse Kalvariengürtel”

The ventilation control is based on the following parameters:

- in-tunnel air quality: visibility and CO
- ambient air quality: NO2 concentration outside and inside

The ventilation due to the ambient air quality is activated in case of a poor NO2 air quality monitored at the “fence line” of the block of flats and a certain NO2 concentration insisde the tunnel. The crosscheck with the in-tunnel concentration is necesarry in order to prevent ventilation in case of high ambient values (NO2 > 150 µg/m³ as half hour mean value) but only little traffic inside the tunnel. An additional monitoring system checks the air quality at the tunnel entrance. As both portals ar located within the city very often the ambient NO2 concentration at both portals is at the same level. If such situations happen it would not make any sense to transport polluted air from one side of the tunnel to the other.

The effectiveness of the system has been checked with numerical simulations as well as with field tests with tracer gas. The numerical simulations have been done in the framework of the environmental assessment study, the field tests with tracer gas (SF6) during the first winterperiod after the opening of the tunnel. Figure 6 shows the result of a field test with activated ventilation. The meteorological situation was in a way that a direct transport of the exhaust air to the flats could be expected. However, due to the measures (noise protection wall and ventilation) the maximum concentration of the tracer gas in the grounds of the flats was some 2 % of the concentration inside the tunnel. The combination of both measures (construction and ventilation) helped to reduce the direct impact of the exhaust gases from the tunnel portal considerably.

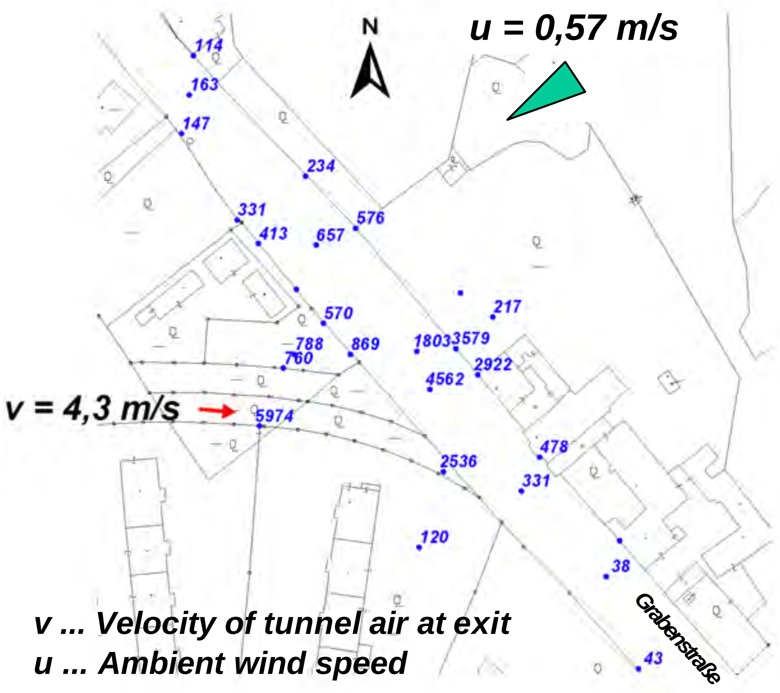

Figure 6: Tracer gas concentration at the east portal with activated ventilation

3. CONCLUSION

The technical development in engine emissions forced an update of the emission data bases for fresh air requirement for ventilation. For many tunnels visibility is now the dominating parameter. As turbidity is caused by exhaust particles as well as by non-exhaust ones, the new calculation sheme has to take this into account. The importance of the non exhaust PM increses as the technical measures reduce the PM emissions from the engine exhaust. However, there is a problem in correlating the PM mass emissions to turbidity. Exhaust and non – exhaust emissions are different in the aerodynamic size of the particles. As the absorbance of light is most effective if the PM size is in the wavelenght of the light, exhaust PM is more effective in light extinction than non-exhaust. However, the data available up to now suggest that the correlation factor between PM mass and light extinction is in the range between 4,7 and 5,5. The more non-exhaust is in the atmospher the lower tha factor is.

It will be task of the next future to perform investigations in the field of light extinction due to tunnel air, taking the different PM sources into account. A further need is to get data about the dependency of non-exhaust PM emissions from vehicle speed and number of vehicles. Available data sugegst a non-linear relation, but the quantity of data is to little to proove this assumption.

Acknowledgements:

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VIRTUALFIRES A Virtual Reality Simulator for Tunnel Fires

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ABSTRACT

The VIRTUALFIRES (Virtual fire emergency) simulator is presented, that allows to train fire fighters in the efficient mitigation of fires in a tunnel, using a computer generated virtual environment. This is a cheap and environmentally friendly alternative to real fire fighting exercises that are currently carried out and that involve burning fuel in a disused tunnel. The simulator can also be used to test the fire safety of a tunnel and to ascertain the influence of mitigating measures (ventilation, fire suppression etc.) on the fire safety level. The simulator is developed with financial support from the European community under the IST (Information society technology) program and combines the simulation of fires using advanced CFD software and the visualization of smoke, toxicity levels and temperature. Two versions are being developed: One using a head mounted display and a laptop, the other using a CAVE virtual environment together with a supercomputer. Both display systems have some advantages and disadvantages. The presented HMD version requires moderate computing power and can show realistic fire and smoke distribution, but the user is not fully immersed in the scene due to the limited field of view. The CAVE version gives a realistic impression of emergency situations in tunnels, because of its room-sized high resolution 3D video and audio environment. The VIRTUALFIRES simulator can be tested by the participants during the conference.
Key words: tunnels, virtual reality, CFD simulation

1. INTRODUCTION

A Virtual Real Time Fire Emergency Simulator (VIRTUALFIRES) has been developed using techniques of virtual reality. In the simulator, the observer is able to visualise the fire and smoke development and the transport of heat and toxic combustion products inside a tunnel and walk or run through the virtual structure in the same way as through a real tunnel. The simulator uses and accesses a database, which contains the results of three-dimensional transient combustion (Computational Fluid Dynamics - CFD) simulations for particular tunnel geometries with associated safety installations, particular fire hazard scenarios, etc.
CFD-results can be displayed as a fixed installation in a CAVE virtual environment and as a portable installation using a PC and a head-mounted display (HMD). Two systems are developed: one where the CFD simulation is pre-calculated, stored into a database and then displayed and another where it is carried out in parallel to the visualisation. In the first system the user will be able to move through the data but will not be able to change the characteristics of the simulation, for example the ventilation characteristics. In the second system the user may change the properties of the simulation while the data are displayed.
The VIRTUALFIRES system will be a unique system that can be used for assessing the fire safety of tunnels, for training of rescue personnel and for planning rescue scenarios and will be able to replace or supplement real fire tests. The end users of this system will be rescue organisations such as the fire brigade and police, tunnel operators and government organisations concerned about tunnel safety. The system can be used for making an objective assessment of the fire safety of existing European tunnels. It can also be used for training drivers on how to behave in the case of a fire emergency in a tunnel.

2. DESCRIPTION

The layout of the software is depicted in Figure 1. At the heart of the system is the CFD simulation software ICE, which uses the Lattice Boltzmann method [1] to compute the air velocity, temperature, pressure and smoke density at a cell point due to a fire.

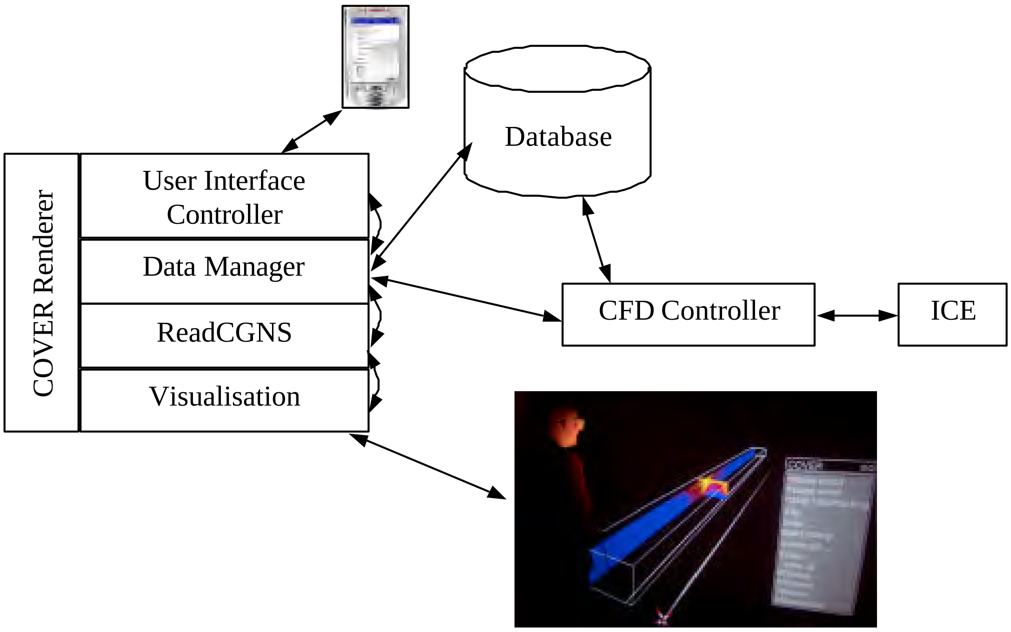

Figure 1: Layout of the VIRTUALFIRES software

The “smoke density” is an artificial quantity, which varies between 0 and 1. The smoke production is taken to be proportional to the CO and CO2 standardized production curves provided as input. It must be pointed out that smoke is a result of fuel rich combustion and the modelling via standardized curves is only an approximation. However, a real combustion model requires input data, which are normally not available and the calculation is very time consuming.

The storage and retrieval of the calculated CFD-data and the states of all objects that are involved in a simulation-run is handled by the Database Manager module. This component serves as the communication layer between the simulation front end and the database server back end. Currently it transparently supports the MySQL 4.0.15 open source SQL server, but is adaptable to any other SQL server.

The communication between the CFD solver and the storage layer is done by the data manager Controller module. This module has been integrated into the Covise VR-environment [2] and also handles all requests from the user interface. As there are normally limited interaction capabilities inside a CAVE environment, a new PDA-based graphical user interface has been developed. This GUI allows the user to specify the mission he/she wants to examine, change simulation parameters and restart a simulation. The major advantage of this solution is that this navigation tool can also be used outside the CAVE with the PC-based VR environment without any changes to the simulator, because it is integrated into the network communication layer inside the simulator.

Within the project also some new visualization techniques have been developed. This was necessary as currently available ones where not sufficient for the system, mainly for 2 reasons:

1. They were to slow to handle the amount of the data produced by the CFD to update the rendering in real time
2. They were not capable of rendering photo realistic fire and smoke

These visualization methods where integrated as plugins for the Cover renderer and can be managed from the user interface. The photo realistic rendering of smoke is done by a fast volume rendering approach which takes advantage of the availability of programmable shader functions on modern graphics boards. This way frame rates around 25fps for the volume rendering of the CFD-results are possible on normal PC hardware. To achieve a photo realistic rendering of fire a fractal 3D texture is applied to the regions of the flames. As CFD results are to coarsely spaced compared to the fast visual fluctuations of a flame front, this behaviour is interpolated by the fractal texturing process until the availability of the next CFD result.

3. CAPABILITIES

3.1. Visualisation

At the current development stage the simulator is able to perform simulation runs for predefined missions. The results can be visualized in 3D on the HMD or the CAVE environment. Navigation in space is supported by a space mouse device and also navigation in time is possible by a simple "VCR-like" graphical user interface. Within this user interface the user can create and define new missions, edit existing ones and start new calculations. The visualization system shows these new results as soon as they are available on the database server.

The following visualization methods are already available on most platforms:

1. Line integral convolution (Figure 2)
2. Streamlines (Figure 3)
3. Isosurfaces (Figure 4)
4. Bill boarding method for realistic smoke visualization (Figure 5)

Figure 2: Line Integral Convolution

Figure 3: Streamlines

Figure 4: Isosurfaces

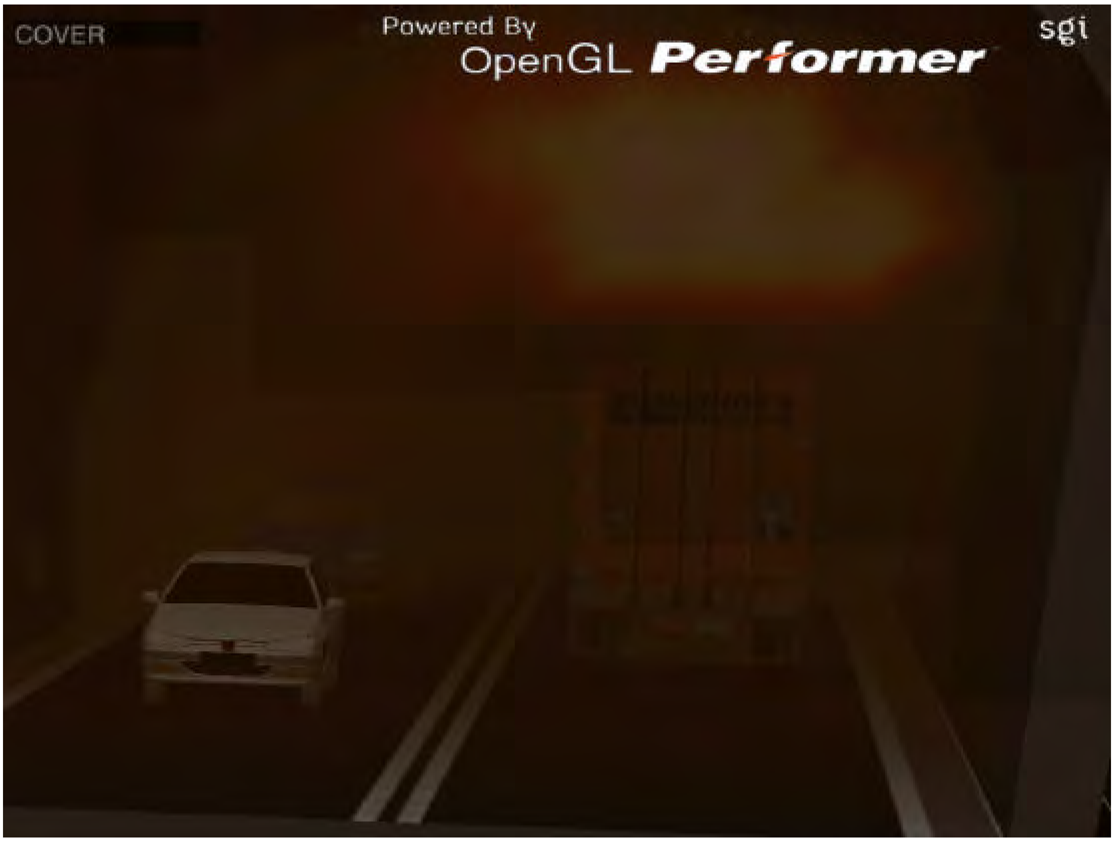

Figure 5: Bill Boarding

3.2. Real time CFD Simulation

Computer programs are usually sequential meaning that their execution is done by only one processor. The computational time varies extremely from a few seconds up to several weeks. Especially in the second case speeding up the computation is of particular interest. One can rely on the steady increasing performance of processor technology or try to parallelise computer codes. The idea of parallelisation is to spread the workload to several processors and therefore speed up computation. The ultimate objective of the Virtual Fires system is to perform real time simulations of tunnel fires in a concurrent VR environment. Since in general CFD calculations are very CPU demanding, it is not possible to perform this on today's single processor systems. Therefore, the parallelisation of the Lattice Boltzmann code ICE is a must to achieve the aforementioned objective.

There mainly exist two classes of parallel programming paradigms:

- The shared memory paradigm consists of sharing data through a common memory by using compilation directives. This paradigm allows using parallel machines without major changes to the sequential code, but becomes inefficient for larger numbers of involved processors due to memory bandwidth limitations or in inhomogeneous environments.
- The distributed memory paradigm consists in distributing the data to the processors to share the work load. Processors requiring information located in another processor have to communicate through messages. As the messages are sent over a network connecting the processors the amount of communication should be minimal. The distributed memory model requires much more programming effort but leads to more efficient codes and can be even used for cluster solutions.

In view of the available hardware and the requirements to the program it was decided to use a distributed memory parallelisation. Distributed memory systems are characterised by a high scalability and the large physical memory available normally. The performance is influenced by the balance between CPU speed and network speed and depends heavily on the programmer. In the MPMD (multiple program - multiple data) programming model each processor executes its own program. The communication between the processors is performed by sending and receiving messages. A subroutine library which contains functions for sending and receiving messages. The data distribution and communication must be explicitly defined by the programmer. Although it is probably the most difficult approach to parallel programming it is selected due to the following reasons:

- It promises the highest performance on distributed memory systems with a large number of processors.
- It is the most portable approach .
- The programmer has all freedom to optimise communication.

There are a few message passing libraries available, but for VirtualFires the Message-Passing-Interface (MPI), the de facto standard, is used for portability. A full description of the MPI standard is given in[3]and [4]. Up-to-date information can be found on the web site of the MPI forum [5]. The VirtualFires project uses a Linux Cluster located at KTH in Sweden. The performance of the code is tested with two different configurations:

1. Test case A consists of 60.000 computational cells and is the most representative for the current use of ICE within the Virtual Fires project
2. Test case B consists of 250.000 cells

Figure 6 shows the speedup factor for the different configurations. For large problems (Test case B) the speedup factor increases linear to the number of processors. For small problems (Test case A) the performance breaks down if more than 8 processors are involved due to the relative increase of communication compared to calculation. Investigations are being performed to optimise the communication so that a real time simulation can be achieved.

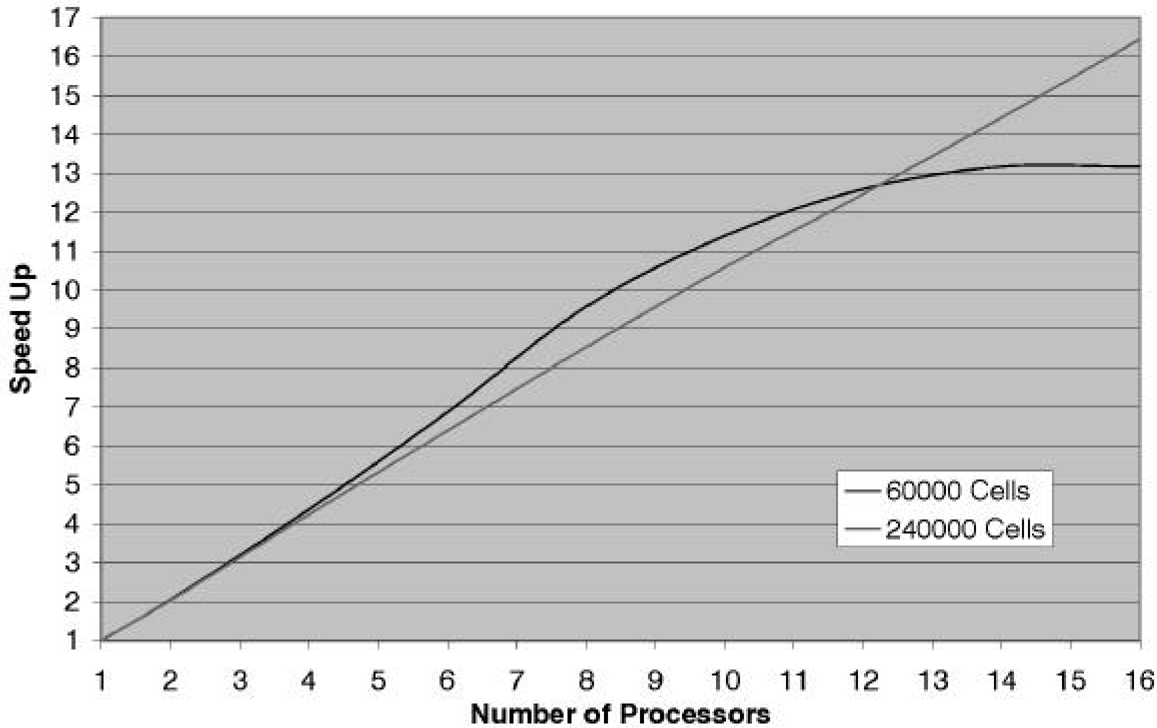

Figure 6: MPIce on Lucidor

4. EXAMPLES

For demonstration purposes some popular fire incidents have been calculated with the simulator. These datasets also serve as a base for the verification of the system. The calculated dataset consists of different ventilation scenarios for the Mt. Blanc tunnel in France and the Gleinalm tunnel in Austria. Both tunnels where examined with their former ventilation system and also with the improved ones after the reopening. Example of fire simulations is given in Figure 7. Also a typical subway station in Dortmund has been analysed. In Figure 8 the temperature distribution inside the station during a fire incident on a subway train is shown. Together with the calculation of smoke spread this kind of simulation is important for the fire fighters to plan their missions inside these stations and to verify that their strategies are efficient.

Figure 7: Mt. Blanc Tunnel

Figure 8: Subway Station Dortmund

5. CONCLUSIONS

A simulator was presented which allows fire men to perform virtual training exercises with a head mounted display or in a CAVE environment. The simulator also allows to assess the fire safety of existing tunnels and can be used as a tool for designing new tunnels. A prototype of the system will be available in May 2004 and it is expected that the system will be marketed world wide.

6. ACKNOWLEDGEMENTS

The work reported here was supported by the European Community under the 5th framework (IST) program.

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SIMULATION OF VENTILATION AND SMOKE MOVEMENT

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ABSTRACT

Long road tunnels still constitute an inherent risk on safety in case of fire. Smoke propagation is the most frequent reason to be killed in such accidents. Therefore special attention has to be paid on the smoke movement which mainly depends on the mean flow velocity. The ventilation system of long road tunnels should be capable to control the smoke propagation in an efficient way. Transversal ventilated road tunnels equipped with adjustable exhaust air dampers provide the necessary prerequisites. In addition, the velocity in the road tunnel has to be adjusted. The paper shows an example of the control mechanism for smoke propagation for a 10 km long road tunnel in Austria. The concept has been elaborated using a simulation model. Finally, the results from fire tests in the tunnel confirm the validity of the concept.

Key words: tunnel ventilation, fire, simulation, automatic control

1. INTRODUCTION

A series of at least 10 major fires in road and rail tunnels have occurred in Europe over the past decade, causing serious loss of life and significant structural damage. It was in particular the human casualties in Mont Blanc, Tauern, Kaprun and Gotthard tunnel fires (221 lives lost in four fires over a period of just two years) that have provided the impetus to intensify the studies on tunnel safety. Results show that the majority of victims in the big disasters in long tunnels have first been captured by smoke and later on they died from suffocation or direct impact from the fire. Only few people could escape through the smoke into rescue zones. The priority therefore must be to enable selfrescue of tunnel users, which is only possible with sufficient visibility in the tunnel. Even fire brigades are severely endangered when they enter a zone full of smoke. Therefore, the most important of all measures in the case of fire is to control the smoke propagation. The possibilities to influence the smoke movement depends on the technical equipment of tunnels. The new European Directive entitled "Safety in European Road Tunnels" proposes that all tunnels longer than 500 m belonging to the Trans European Road Network should have harmonized safety requirements. One of the technical requirements concerns ventilation: Single tunnels with bi-directional traffic shall have transverse and/or semi-transverse ventilation with exhaust possibilities. Longitudinal ventilation pushing smoke in one direction shall be used in these tunnels only when traffic conditions allow uncongested vehicles to drive out of the tunnel. For twin tube tunnels the propagation of smoke of gases from one tube into the other shall be prevented and stricter ventilation standards should be applied to unidirectional congested tunnels.

The paper will show that the smoke propagation from one fire in long transversal ventilated road tunnels can be controlled up to a defined heat load and restricted meteorological boundary conditions. For that purpose they have to be equipped with a exhaust air system which is able to suck off the smoke on any place using adjustable exhaust air dampers. In addition a mechanism to control longitudinal wind velocity in the tunnel must be available.

Simulation is an important tool to investigate the capabilities of the ventilation system to control smoke. Due to the costs of real life tests it is not possible to investigate many cases. Therefore, the majority of situations have to be assessed using a simulation model capable of predicting the physical behavior of the flow and smoke propagation.

2. THERMODYNAMIC ANALYSIS OF A FIRE

Thermodynamic analysis of a fire shows that the chemical reactions, which lead to heat release are: $C + O_2 \rightarrow CO_2$ and $H_2 + ½ O_2 \rightarrow H_2O$. (C …. Carbon, H2 …. Hydrogen, O2 …. Oxygen, H2O …. Water, CO2 …. Carbondioxid). Generally the oxygen is coming from the air. Of minor importance is the reaction of sulfur: $S + O_2 \rightarrow SO_2$, as sulfur does not occur in such big amounts. For materials like plastics or fuel the necessary air for a complete burning is some 15 times more in mass than the mass of carbon and hydrogen. All the other shares of the material do not burn. Assuming a calorific value of 40000 kJ/kg for pure hydrocarbon, 2,5 kg/s have to be burned in order to get a heat release of 100 MW. This results in a primary (pure) smoke mass of approximately 40 kg/s. The volume of this undiluted smoke depends on its temperature. The smoke gas volume can be higher due to evaporated medium. Mostly it is water vapor. So the smoke gas extraction of a tunnel must be able to suck off at minimum the mass of the gaseous fractions of the pure smoke. If the smoke is cold it has a comparable density to air and a volume flow of 34 m³/s. For a smoke temperature of 1200 °C the volume is five times higher (170 m³/s). If the pure smoke gas is diluted with the same mass of air (40 kg/s) the temperature is reduced to 640°C and the density is increased, leading to a volume flow of 210 m³/s. A reasonable part of the heat is transferred to surfaces due to radiation and convective heat transfer, so the effective heat load, which goes to the smoke gas is reduced. This decreases the smoke gas volume flow further. The German guidelines for road tunnels RABT [1] give the following values for the smoke gas volume flow of fires: 100 MW…. 200 m³/s at 300°C. This would mean that approximately 50% of the heat is not contained in the gaseous fraction of the smoke gas. All of the above assessed values are not exact, but should give a good approximation of the smoke gas mass flow and volume flow, which can be expected. The more complex assessment is how the smoke is diluted and dispersed.

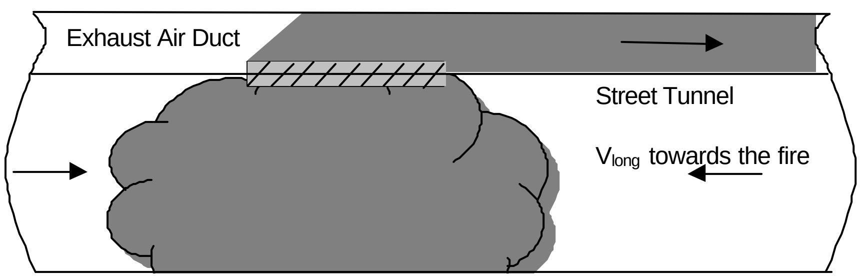

Fig. 1: Ideal Smoke Extraction

Considering the transport mechanism of smoke, namely diffusion (laminar and turbulent) and convection, the convective part is much more important. Even a mean velocity of 0.5 m/s restricts any transport of cold smoke in the upstream direction. So the necessary condition for a complete smoke extraction from the tunnel is to suck off as much as to produce a converging flow in the tunnel towards the open exhaust air damper from both sides of at least 0.5 m/s (for cold air).

For a cross-sectional area of 50 m² this results in a minimum mass flow of cold air from both sides of each 30 kg/s (60 kg/s in total). From the above given assessment this is more oxygen than the fire needs to burn 2,5 kg/s of hydrocarbons. Concluding the assessment the exhaust air ventilator has to suck off some 60 kg/s. As the ventilator transports a certain volume flow, the mass flow depends on the temperature of the smoke at the ventilator. The 60 kg/s at the maximum allowable temperature at the ventilator of 400 °C results in a volume flow of some 120 m³/s. For a lower temperature the necessary volume flow is accordingly lower.

2.1. Influencing the air velocity in the tunnel

In order to meet the described criterion the longitudinal air velocity in the whole tunnel must be influenced by forces. The relevant Austrian guideline RVS 9.262 [2] proposes activating or deactivating the fresh air injection and the exhaust air extraction in certain ventilation sections of a tunnel. This is a possible way, but the influence on the longitudinal air velocity is restricted. Another possibility to affect the longitudinal flow is the installation of jet fans, as it has been done in the Montblanc tunnel. The injection of fresh air through a jet nozzle which perfectly transfers the pressure difference into flow velocity in the longitudinal direction (comparable to Saccardo nozzles), has been proposed by the authors [3], [4]. In order to control the longitudinal air velocity the forces have to be adjustable. Application of a control system with predefined power settings for the ventilators in order to influence the flow in the tunnel can only be made for a small range of boundary conditions. Such a predefined system can not react on changing meteorological conditions or on a malfunction of any ventilator etc. Closed loop control systems are able to react on varying boundary conditions. But they need a clear concept which provides a control variable. A PID controller unit adjusts the forces in the way that the target value is reached as soon as possible. The controlled variable for the flow in the tunnel is the longitudinal velocity which represents the volume flow and the mass flow, when the velocity profile and the density is known. Therefore the velocity measurement must have a high quality, that requires a high accuracy of the sensor and a permanent availability of the controlled variable in the controller unit.

2.2. Backlayering

The temperatures of the smoke gas of fires have been investigated in several investigations. Temperature values of 1200 to 1300 °C can be expected around the fire. Due to mixing with fresh air, the evaporation of water or the imperfect burning smoke gas temperatures can be lower. Depending on the temperature of the smoke gas the buoyancy effects are important and the hot smoke rises up to the tunnel ceiling. There the 3-dimensional effect of the movement of smoke into the opposite direction of the mean flow (backlayering) happens. It is an important effect, which has to be taken into account in the risk assessment. Investigations show that backlayering is a strongly stratified flow. The size of the smoke penetration depends on the smoke gas temperature and the mean flow velocity. It is a fact that for a steady state situation the mass in a tunnel section does not change. Due to continuity the sum of all mass flows over such a section must be zero. In a backlayering zone the hot smoke moves against the oncoming fresh air in the uppermost layer. Below this zone the smoke is colder and moves in the direction of the oncoming fresh air. Still it is much warmer and represents a stable stratification. The oncoming fresh air has to go underneath this hot wedge of smoke gas and is therefore accelerated. In the contact zone between smoke gas and fresh air the smoke is diluted and transported to the fire. As long as the mean flow is directed to the fire there exists a fresh air below the smoke gas. If the temperature difference between the smoke gas and the fresh air is small turbulence is able to mix both gases. Values of mechanical turbulence can be high, if there exist 3-dimensional effects like the flow around cars or trucks. In all the cases where there exists no backlayering any more, the smoke is not able to move against the oncoming fresh air.

The description of the 3d-effects around the fire can be concluded as follows: If there exists a backlayering, the flow is stable stratified and is therefore not mixed down to the ground. So a fresh air layer exists below the smoke. If the stratification is less stable and/or the mechanical turbulence is larger, the smoke is mixed and transported with the oncoming fresh air towards the fire. In both cases the area upstream of the fire, which is affected by the smoke, remains small as long as the fresh air moves towards the fire [5]. 3d-effects are only of interest in the nearfield of the fire. In the rest of the tunnel a 1-dimensional behaviour of the flow combined with the smoke propagation occurs.

3. SIMULATION MODEL

Applying a 1d-simulation model the distributions of velocity, temperature, pressure, smoke etc. can be predicted in an adequate way in the whole tunnel system. This was the reason for developing a 1-dimensional flow simulation model called (**Gra**z **T**unnel **I**nvestigation **S**ystem **GRATIS**) which solves the 1-dimensional conservation equations for mass, momentum, energy and passive scalars. The equations are solved transiently using an explicit time integration scheme and a Finite Volume method. This numerical method is a so-called pressure linked method, where the predicted mass flows over the volume surfaces are corrected by the pressure field. The pressure correction produces a flow which fulfills the continuity equation. The pressure can be interpreted as the static pressure. The model considers the equation of state for ideal gases and is therefore able to treat varying density according to temperature and pressure changes.

Wall friction, flow resistance due to obstacles or deflection and other momentum sources are treated as sources in the momentum equation. Sources in the energy equation are heat transfer to the walls, heat release due to the fire, etc. The model runs on a standard PC and is written in FORTRAN 77, combined with a pre- and postprocessor in VISUAL BASIC.

The model handles all geometrical and equipment data of a real tunnel. This includes ventilator characteristics, friction factors, drag coefficients, heat transfer coefficients etc. It is able to deal with the flow rates through dampers and the recovery of momentum due to the directed flow in the exhaust air channels. There are the equations available to treat humidity with evaporation and condensation of water. There exists also a subroutine, where a PID controller can be simulated applying any constants. Finally a fire can be simulated, where the thermodynamic interrelation of smoke gas production, temperature, density and flow characteristics are handled.

Applying GRATIS the automatic control mechanism for the smoke extraction can be calculated. The influence of unfavourable boundary conditions, varying fire loads, different initial conditions and other effects can be studied. So the cases in which the tunnel equipment fails to suck off the smoke gas can be elaborated.

Figure 2 shows the postprocessor of the 1d-model where the distribution of the variables are rendered. In the case shown the smoke extraction of the new bore of the Plabutschtunnel has been investigated. The results leaded to innovative solutions concerning the control mechanisms, which are described in the following section.

4. SIMULATION OF THE SMOKE EXTRACTION IN THE NEW PLABUTSCHTUNNEL

The Plabutschtunnel is a 10 km long tunnel directed from north to south in the west of Graz, Austria. The old east bore was opened in the year 1986. Due to a continuous increase of traffic the second bore has been built over a time span of 4 years and was opened end of January 2004. For the year 2004 the new tunnel bore will be operated with two way traffic, as the old bore will be refurbished. Afterwards both bores will be operated with one-way traffic.

In both bores a transversal ventilation system is installed. The new bore is equipped with remote controlled exhaust air dampers of a size of approx. 9 m² positioned every 100 m over the whole length of the tunnel. The ventilation system consists of five sections of 2 km each. Four of the five sections are connected to the surrounding via two vertical shafts. One section is ventilated via the north portal.

In the case of fire the detection system starts the emergency ventilation system. There are two systems implemented (a) a closed loop control system which adjusts the volume flow on both sides of the fire according to figure 1 and (b) a pre-adjusted control mechanism, which gives fixed answers for a fire in every tunnel ventilation section. In the following the closed loop control system is described. In case of fire the fresh air supply in the affected ventilation section is switched of. The exhaust air damper closest to the fire is opened, all the other dampers of the ventilation section are closed, and the exhaust air ventilator is switched to the maximum volume flow. The target value for the controlled variable, namely the longitudinal velocity in the tunnel, is deducted from the measurement values of the temperature and the volume flow at the exhaust air ventilator. The target value of the longitudinal velocity in the tunnel is calculated in the way to produce half of the mass flow at the ventilator. The closed loop control system adjusts the longitudinal velocity to the above described target value.

The postprocessor of GRATIS (fig. 2) shows the simulation results for velocity (left upper diagram), temperature (right upper diagram), pressure (left middle diagram) and the smoke (right middle diagram). In the lower diagram the whole tunnel and the ventilation sections (divided by dotted lines) are shown. The vertical bars embrace the zooming area

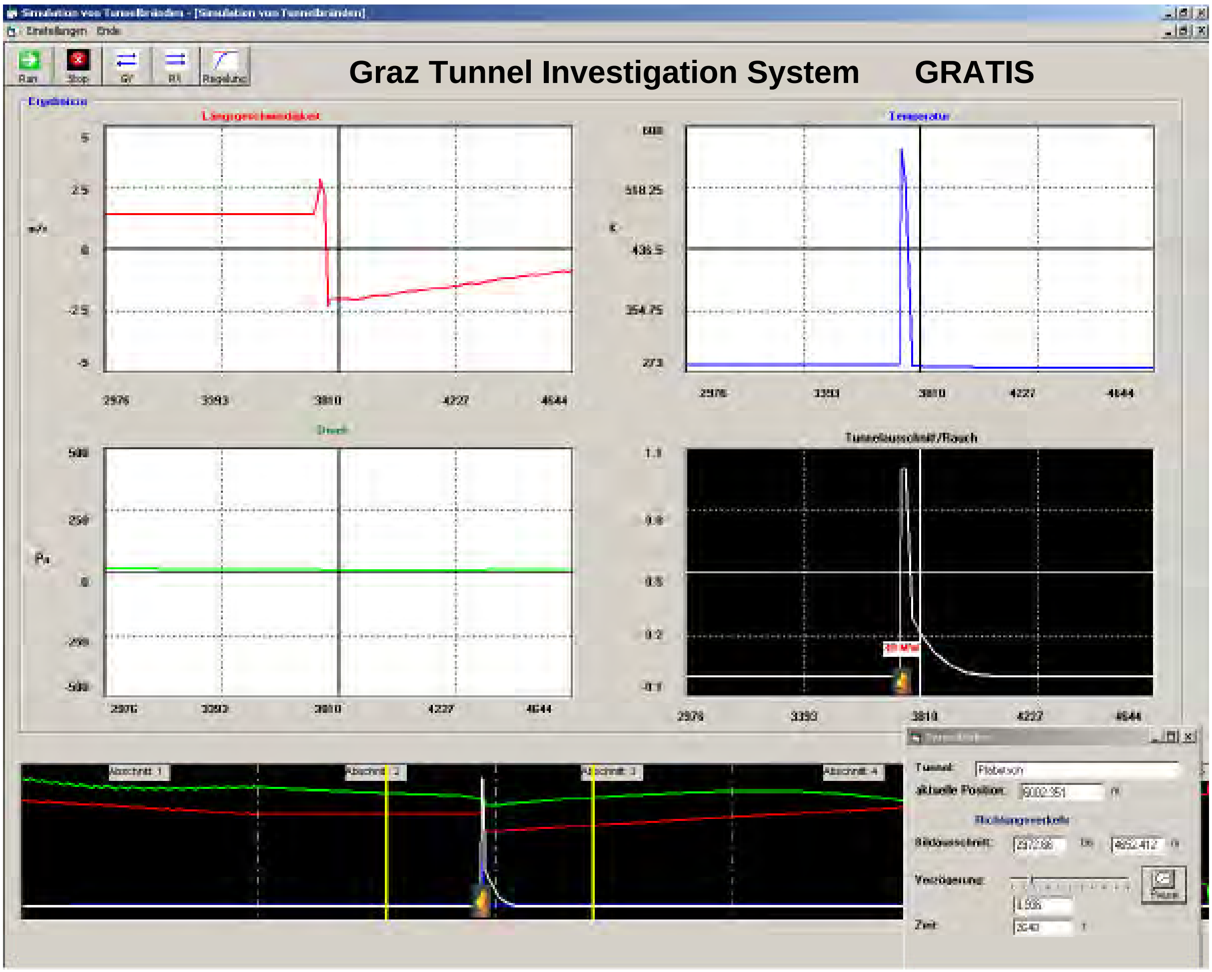

Figure 2: Simulation results for a smoke gas extraction in case of fire for the Plabutschtunnel

which is rendered in the four upper diagrams. The fire starts with a linear increase of its strength over five minutes. Then the strength is kept constant at a value of 30 MW. The results shown for the distributions 12 minutes after the beginning of the fire. The PID controller has already managed the velocities to be directed towards the fire with a speed of approx. 1.9 m/s. The smoke temperature reaches approx. 570 K (300 °C) at the position of the damper. The smoke which was initially transported downwind the tunnel (from left to right) has almost been sucked of by the ventilation system. The exhaust air ventilator provides a volume flow of 193 m³/s in normal operation. In case of fire the volume flow depends on the position of the exhaust air damper and the temperature of the smoke gas at the damper and at the ventilator. The volume flow at the damper is highly increased when the smoke gas temperature at the ventilator is much smaller than the temperature at the damper.

The variable forces for influencing the longitudinal flow in the tunnel are produced by the changing mass flows in the exhaust air and the fresh air system. In order to accelerate the longitudinal air flow in a tunnel section from north to south, the following measures have to be taken: (1) the fresh air flow in the north has to be increased (2) the exhaust air flow in the south has to be increased, (3) the exhaust air flow in the north has to be reduced, and (4) the fresh air flow in the south has to be reduced. For the acceleration into the opposite direction the measures have to be the other way round. In order to make the system more reliable the revolutions per minute of the ventilator are restricted between 100% and 35%. In addition there are four jet fans installed in the south of the tunnel, which support the longitudinal flow. The change from the maximum force in one direction to the other direction needs approx. 2 minutes.

5. VALIDATION OF SIMULATION RESULTS IN THE PLABUTSCHTUNNEL

In order to check the smoke extraction of the real tunnel, several tests have been carried out. Two fire tests on the 22nd of January showed reasonable results. The smoke gas has been completely sucked of during the two fire tests with a heat load of approx. 6 MW. Further improvements of the constants of the PID controller have been made for the final tests

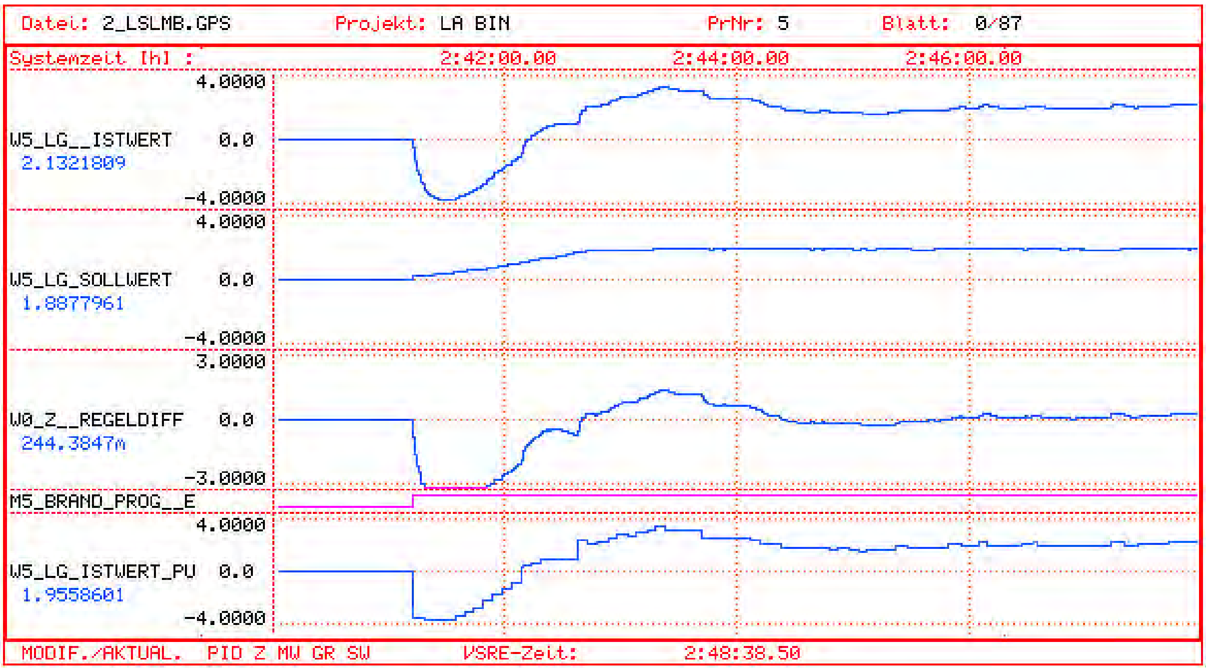

Figure 3: Results for the smoke gas extraction test in the Plabutschtunnel

on the 28th. Figure 3 shows the temporal evolution of the longitudinal velocity for a test without fire in the 5th ventilation section in the south. The diagrams show (a) the measured longitudinal velocity (smoothed), (b) the target value, (c) the difference between (a) and (b), and (d) the measured longitudinal velocity (without smoothing). The recording of the variables started when the fire alarm was triggered. Hence, all variables before that time had the value zero. The target value evolves according to the volume flow of the exhaust air ventilator, which starts from zero and needs approx. 90 seconds to reach its maximum. During the same time span the damper next to the fire is fully opened, all the other dampers of the ventilation section are closed, and the fresh air supply is switched of. The third diagram shows the changes for the control deviation. At the beginning the control deviation is more than 3 m/s. After approx. 60 seconds the control deviation is reduced to zero, but overshoots the target value. After approx. 3 minutes after the start of the fire the ventilation system has arrived at its target value.

6. CONCLUSIONS

In case of a fire in a road tunnel the smoke extraction is of major importance for the prevention of casualties. Smoke reduces the visibility in the tunnel to a level where selfrescue and even rescue by fire brigades is impossible. The smoke dispersion in a tunnel is mainly dependent on the longitudinal velocity. 3d-effects like backlayering are of minor importance. Therefore, the simulation of the time dependent distribution of velocity, temperature and smoke using a 1d-model is the proposed method to investigate the smoke gas extraction performance of a tunnel ventilation system. The 1d simulation model GRATIS (GRAz Tunnel Investigation System) is able to predict these values by solving the conservation equations of mass, momentum, energy, water vapor, smoke, and the thermodynamic interrelations respectively.

Long transversal ventilated road tunnels in Austria are nowadays equipped with remote controlled exhaust air dampers, where the total volume flow of one ventilator can be sucked off over one to three dampers. A prerequisite for a functioning operation is that the longitudinal velocity in the tunnel is adjusted in a way that the flow is directed to the fire from both sides. For the adjustment of the velocity the forces in the tunnel have to be controlled. In order to be able to deal with unfavorable boundary conditions the control mechanism should be automatic. The comparison of results from simulations and experiments show that the smoke extraction performance of a tunnel can be predicted and optimized using a 1d-simulation tool like GRATIS.

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THE AUTOMATION OF THE VENTILATION RESPONSE IN THE CASE OF A FIRE IN A TUNNEL

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ABSTRACT

In 1999, the working group n°6 " Fire and Smoke Control " of the PIARC Committee on Road Tunnels (C5) produced a document entitled "Fire and smoke control in road tunnels". The recommendations on the ventilation control mention an evacuation phase followed by a fire-fighting phase.

During the refurbishment of the Mont Blanc tunnel, these recommendations are at the base of the regulation rules used for controlling the ventilation system in the case of a fire.

For the evacuation phase, the bi-directional character of the traffic imposes to control the conditions of development of the natural stratification of the hot smoke. This objective is achieved by associating the operation of jet fans with the activation of a capacity of extraction centred on the fire, as soon as the operator validates the location of fire.

This system, entirely automatic, was tested during full-scale tests in January 2002. The results are exceptional since, during the most powerful fires (8 MW), the maximum extension of the smoke (perfectly stratified) was 300 m. These tests played an essential role in the decision of re-opening the tunnel.

The publication summarily describes the Mont Blanc tunnel and its ventilation system. It presents the scientific bases of the development of the stratification. It gives finally a description of the full-scale tests and synthesises interpretations of the mechanisms that were observed on this occasion.

The last part of the paper deals with the phenomena linked to the development of the hot smoke stratification. An overview of the question is presented. This represents the basis of a French national research program, initiated at the beginning of 2003.

Key Words : Tunnel / Fire / Ventilation / Automation / Stratification / RGC&U project

1. THE MONT BLANC TUNNEL PRESENTATION

1.1. The conclusions drawn from the catastrophic fire of march 24, 1999

The Mont Blanc tunnel is a 11.6 km long tunnel. It links France and Italy between the Chamonix and Courmayeur valleys. The vehicle traffic is bi-directional, composed of a significant part of HGV.

On march 24, 1999, a HGV fire in the Mont Blanc tunnel caused the death of 39 people, as well as great destruction. The fire propagated to other vehicles. It lasted more than two days.

The media attention focused on this event because the Mont Blanc tunnel is a major road communication between France and Italy and because its seriousness highlights particular processes of dangerous atmosphere transfers. These processes were observed in the fires that occurred later in the Tauern tunnel in Austria and in the Gotthard tunnel in Switzerland.

These events have shown that a fire occurring on a HGV, involving goods not classified as a dangerous may cause considerable heat and toxic release rates.
Additionally, the confinement of the internal volume of the tunnel helps the propagation of the opacity and toxic conditions over significant distances, without reducing their dangerousness.

Finally, these events have highlighted the fact that an inappropriate operation of the ventilation system increases the consequences of the fire, especially, during the first minutes of the fire.

1.2. The tunnel renovation

As a consequence of this catastrophic fire, it appeared that the refurbishment works had to include a deep renovation of the safety systems, and particularly of the ventilation system.

The tunnel companies ATMB (France) and SITMB (Italy) entrusted the association Scetauroute-Spea with the renovations studies and works. An international Safety Committee was in charge of providing the specific recommendations and supervised the renovation works.

The most complex phases of the works required more than one thousand people in the tunnel. The works went on two years. The tunnel re-opening to the traffic happened in March 2002.

A European Association for developing commercial interests (Mont Blanc Tunnel GEIE) performs the operation of the renovated tunnel. This association was involved in the renovation studies and works.

2. THE RENOVATED VENTILATION SYSTEM

2.1. The recommendations and some practical consequences

The Safety Committee published recommendations based on the French Circulaire Ministérielle 2000-63.

New dispositions are mentioned by this text:

- The creation of pressurised shelters each 300 m;
- The creation of a pressurised evacuation route, connected to the shelters;
- The increase of the smoke extraction capacity;
- The installation of remote controlled dampers connecting the tunnel with the extraction duct, each 100 m. Existing similar devices were located each 300 m.

Actually, integrating these recommendations led to innovations because it was impossible to increase the existing structure while the ventilation capacities had to increase (Guigas et al., 2001).

2.2. The fresh ventilation system

This system is composed of eight specific ducts connected to as many centrifugal fans (4 at the French portal and 4 at the Italian portal). Each duct includes a transit part exiting in a diffusion part.

In order to take the new pollution threshold values into account, the capacity of each fan is increased to 83 m^3/s. The former capacity was 75 m^3/s.

At the same time, this system is also used in order to provide fresh air and pressurisation to the shelters during a fire. It is also used as an escape route aiming at evacuating the people out of the tunnel. To satisfy these new functions, it is necessary to open doors between the ducts, in the safety ventilation configuration. This results in a significant imbalance of the pressures and the flow rates between the ducts. The main risk resulting from this imbalance if the excessive pressure loss at the end of a duct where a shelter may be found. These effects were studied and the ventilation levels were adapted to these constraints.

These studies have also highlighted that the efforts that the people have to produce on the doors located between adjacent ducts remain acceptable, especially in the fire ventilation configuration.

2.3. The extraction duct

In the initial configuration, the French and Italian extraction ducts were not connected at the centre of the tunnel. Each duct used to be depressurised by centrifugal fans located at each portal.

The Safety Committee has recommended connecting the two ducts at the centre of the tunnel so that the fans located at one portal can provide assistance to the opposite ones in the case of a failure. The initial extraction capacity used to be about 70 m³/s at each portal. The global effective extraction capacity is increased to 150 m³/s.

The activation of the global capacity at the two portals should normally lead to this result with a significant increase of the fan capacity. Actually, preliminary measurements performed in the ducts have pointed out important leakage between the extraction duct and the tunnel on one hand and the extractions duct and the fresh air ducts on the other hand. The renovation works had to reduce this leakage, but it was clear that they could not be totally reduced.

In order to take this situation into account, it was decided to install four intermediate fans along the extraction duct. They aim at reducing the variation of the pressure. Thus, the leakage is also reduced, resulting in a global effectiveness of the extraction installation.

The extraction dampers are located each 100 m. They are installed in a small duct connecting the tunnel crown to the extraction duct located under the pavement. These dampers are remote controlled. A few of them are opened in the fire area in order to focus the extraction capacity in this zone.

2.4. The tunnel

The Mont Blanc tunnel is subject to important natural pressure differences. Measurements performed in the 60ies have shown that they can reach 600 Pa in one direction or the other. The induced natural longitudinal velocity is then 4 to 5 m/s.

This effect happened during the catastrophic fire. It deeply influenced the recommendations of the Safety Committee.

Since the control of the longitudinal velocity is a major stake of the renovated ventilation system, the tunnel is equipped with 76 jet fans. The unit thrust is 600 N. They are located under the vault of the tunnel.

Activating a jet fan modifies the internal pressure of the tunnel. At the end of the fresh air ducts, the residual pressure level may be of the same magnitude, resulting in the inversion of the ventilation direction through some fresh air louvers. The risk is to promote the penetration of smoke in the fresh air ducts. This effect must be avoided because the fresh air ducts are used for the evacuation of the people. As a consequence, the jet fans are installed in the tunnel far form the fresh air ducts ends.

3. THE PRINCIPLE OF THE AUTOMATION OF THE VENTILATION SYSTEM

3.1. The recommendations

The recommendations imposed by the Safety Committee are the main reference of the renovation studies.

The safety stakes are important. As a consequence, the PIARC 1999 recommendations are also widely used, especially in the conception of the automation of the ventilation system.

This reference mentions two phases to control during a fire:

- The evacuation phase: During this phase, the people must find acceptable conditions in order to join the shelters. Since the Mont Blanc tunnel is a bi-directional traffic tunnel, the people may be trapped on both sides of the fire. The PIARC recommendation is the control of the ventilation so that the natural stratification of the hot smoke may develop;
- The fire fighting phase: This phase must allow the fire brigade to join the fire area and fight the fire in acceptable visibility conditions. The recommendation consists in blowing the smoke on one side of the fire.

In a practical point of view, in order to let the stratification developing, it is necessary to maintain a longitudinal velocity as close to 0 m/s as possible in the fire area. At the opposite, in order to blow the smoke on one side of the fire, it is necessary to control a longitudinal velocity greater than a threshold called “critical velocity”. This value is about 2 m/s for small fires (several MW) and about 4 m/s for great fires (several tens of MW).

3.2. The scientific bases

The study of the critical velocity was the object of numerous research works. Even if all the author do not fully agree, the formulation proposed by Kennedy provides a satisfactory synthesis of the various findings (Kennedy, 1996). The mechanical means aiming at controlling this result inside the tunnel are correctly estimated with the help of numerical simulations.

At the opposite, the stratification of the combustion products in a tunnel has been the object of very few studies.

Controlling a low longitudinal velocity in the vicinity of the fire is recognised as a simple and reliable rule to let the stratification developing. Actually, this should not hide a very complex reality.

The principle of the control of the stratification conditions adopted in the Mont Blanc tunnel was the subject of a public presentation in 1999 (Casalé, 1999). This principle is based on various research results aiming at describing the characteristics of the backlayering. This is the hot smoke layer that develops in the opposite direction of the general longitudinal velocity, as soon as the longitudinal velocity remains lower than the critical velocity (Figure 1).

Some simulations involving the reduced scale model in the Valenciennes University (France) have highlighted remarkable singularities developing in the longitudinal velocity profile, in the backlayering zone» (Mégret & Vauquelin, 2000, Mégret, 1999). These singularities, combined with an important vertical gradient reveal a significant stability of the backlayering. At the opposite, these characteristics do not appear in the stratified layer that flows away, downstream of the fire. The major reason is probably the fact that this layer is submitted to intensive exchanges, especially in the zone of the fire drag effects, resulting of the turbulence developing there (Figure 1).

At the same time, numerical simulations performed in the Marseilles University (France) about the representation of the stratification have shown that the turbulence model has to include additional terms aiming at integrating the characteristics of the flows developing in the backlayering (Cordier, 2001, Auguin et al., 2003). The analysis of the signification of these terms led to the same conclusions as those drawn in the Valenciennes University.

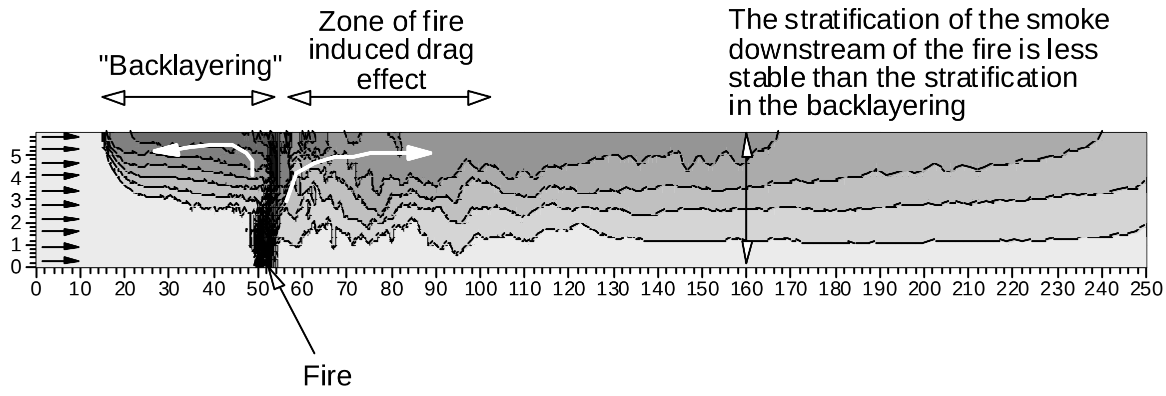

Figure 1 – Numerical simulation of a 1.5 MW fire with a 1 m/s longitudinal velocity. Opacity field after 6 min

Since it cannot be admitted that a stratified layer propagates along the tunnel in an uncontrolled manner, it appeared necessary to look for a method to stop this development. Here also, the longitudinal velocity appears to play a major role. The first results of the research works engaged on the topic (confinement velocity) point out a relationship quite similar to the critical velocity (Casalé & Biollay, 2001).

3.3. Application to the Mont Blanc tunnel

The practical conclusion of the previous findings is that, in order to preserve the visibility conditions during the evacuation phase, it is necessary to develop a stratification which characteristics are similar to those of the backlayering. Since the direction of the longitudinal velocity determines these characteristics, it appears that the ventilation system should induce a converging motion of the air in the direction of the fire. Thus, the stratified layers develop on both sides of the fire in the opposite direction of the local fresh air velocity (Casalé, 1999).

This converging motion is the result of the activation of the extraction capacity and the focusing of this capacity in the fire area. This control does not necessarily result in a symmetrical converging motion.

The symmetry is controlled by the appropriate activation of the jet fans in the tunnel. Since the activation of the jet fans produces a high turbulence level, the stratification cannot be maintained. This is the reason why the jet fans located inside a zone centred on the fire are kept shut (exclusion zone).

The activation of the jet fans is part of a complex regulation loop. The longitudinal velocity is measured with the help of 20 anemometers located along the tunnel. The information provided by the sensors located inside the exclusion zone is not taken into consideration, because it is suspected to be deeply influenced by the local motions induced by the fire.

The regulation loop is installed in the computed located in the control centre. The operator role is limited at the manual validation of the fire location and the activation of the first ventilation phase.

4. THE FIRE TESTS

4.1. The tests conception

The full-scale fire tests appeared as a fundamental requirement for the tunnel re-opening to the traffic. The Safety Committee has asked for fire tests involving significant heat release rates. The chosen value was 8.4 MW.

Preliminary fire tests were decided by the tunnel companies, on the basis of Scetauroute advises. They involve lower heat release rates, 1.4 MW. These tests aim at preparing the Safety Committee tests and at characterising the mechanisms resulting of the interaction of the fire with the motions induced by the ventilation control. The chosen procedures allow the confirmation of the scientific information at the origin of the ventilation control concept.

The full-scale fire tests conclude a series of other tests involving the various ventilation systems.

4.2. The fire source

The fire is located at 8780 m from the French portal, i. e. approximately at the centre of the Italian half tunnel.

The fires involve gasoline pools of 1.2 m diameter. The unit heat release rate is 1.4 MW (about one passenger car). One tub is used for the low heat release rate fires. Six of them are located over ten meters in order to simulate the 8.4 MW fire (about one van fire).

Figure 2 – View of a 1.4 MW fire, at the end of the transient ventilation phase. The stratification and the longitudinal confinement of the smoke are controlled

4.3. The measurement means

About 120 sensors are positioned according to a 3D grid in the fire area. These are mainly thermocouples. Some anemometers are positioned on vertical poles in order to provide the evolution of the velocity profile.
The sensors are connected to data loggers. The information is recorded each 3 s.

4.4. The scenarios

The tests have been performed in January 2002:
- On January 19th: Two tests involving 1.4 MW fires;
- On January 30th: Two tests involving 8.4 MW fires;

The scenarios are reproduced according to the same sequence. Each of the tests is performed twice in order to compare the performances of the automatic system with those of the operator.

During the first test, the control of the ventilation procedure was performed manually. The engineer in charge of the automatism integration replaced the operator. The second test was performed several hours later, with the fully automatic control of the ventilation system. The scenario is performed as follows:

At t = 0min: Fire ignition. The longitudinal velocity s about 4 m/s in the fire area, in the direction of the Italian portal (Figure 3);

At t = 1 min: Pre-alert activation (Jet fans shut down, extraction fans activation, etc.). The pre-alert was activated at t = 0 min during the tests performed on January 19th (1.4 MW fires);

At t = 2 min: Activation of the alert (the dampers located close to the fire are open, the regulation of the longitudinal velocity is activated, etc.).

The fire duration is about 25 min. After the extinction, the ventilation system is modified to a smoke removal configuration, in order to evacuate the residual smoke present in the tunnel.

5. MEASUREMENT ANALYSIS

5.1. The measurement

The measurement analysis is performed with the help of a specific software developed for several years in Scetauroute for the needs of previous fire tests. This tool provides the evolution of the temperature and velocity fields on the basis of the measurement results.

Since the sensors density is important, the evolution of the thermal fields can be related to the longitudinal velocity controlled by the ventilation system, especially in the fire area. The velocity is calculated from the measurements performed on both sides of the fire. The relevant location of the anemometers is between open dampers (Figure 3). The analysis of the velocity signal derived from the measurement shows that this value decreases down to the range - 1 m/s - + 1 m/s in less than 4 min following the activation of the pre-alert phase. This effectiveness is due to the regulation of the longitudinal velocity with the jet fans.

In this context, the thermal field behaviour reveals the stratification of the hot gases mechanisms (Figure 4):

- During the first minutes of the fire, the smoke is transported by the initial flow, towards Italy. The smoke stratification is lost downstream of the fire and a thermal stratification exists (Figure 4, t = 120 s);
- Two minutes later, the smoke remains located on the Italian side of the fire. At that time, the longitudinal velocity is low and the smoke motion toward the fire is initiated as a result of the activation of the extraction (Figure 4, t = 240 s);
- About six minutes after the beginning of the test, the smoke stratification conditions are obtained. The temperature increases slowly at the ceiling, in the fire area. The smoke stratification develops slowly on this basis (Figure 4, t = 360 s).

The comparison of the system performance with the operator one highlights the great effectiveness of the algorithm implemented in the centralised system. The longitudinal velocity control is obtained in twice less time with the use of the automatic system (Figure 5).

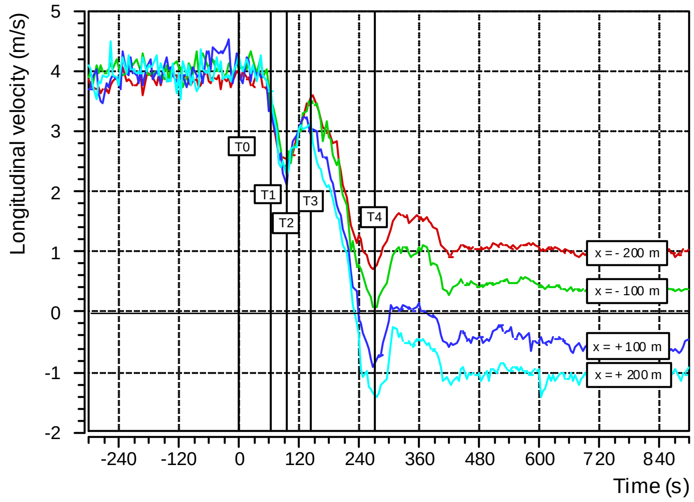

Figure 3 – Mean longitudinal velocity evolution at the measurement sections located on both sides of the fire, calculated from the measurement

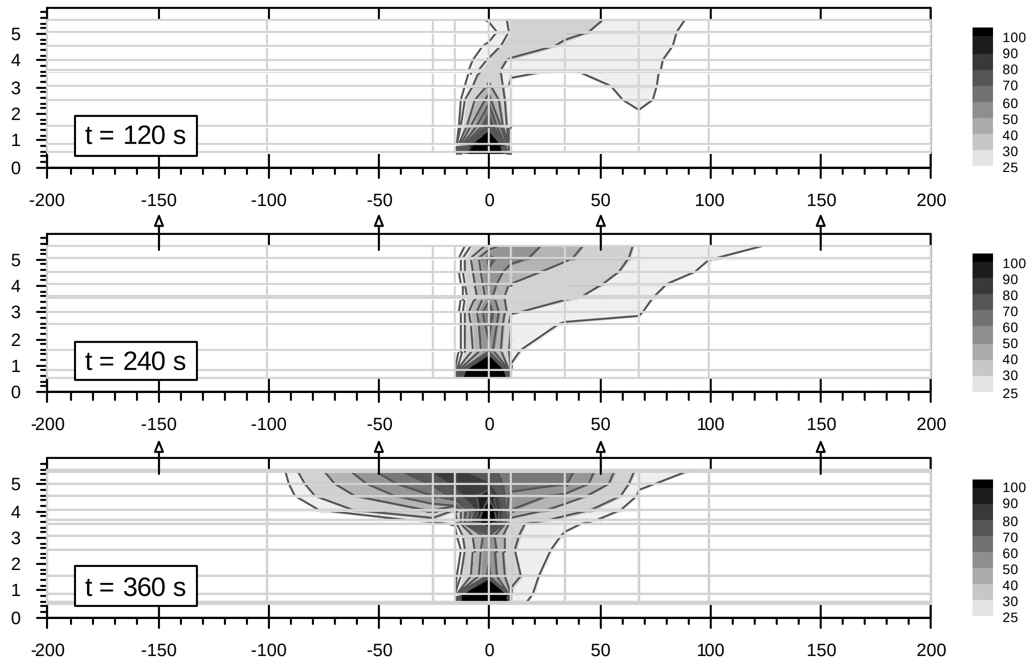

Figure 4 – Thermal field evolution for the 1.4 MW fire, under the automatic ventilation control (the temperature is given in °C). The represented grid gives an idea of the location of the sensors

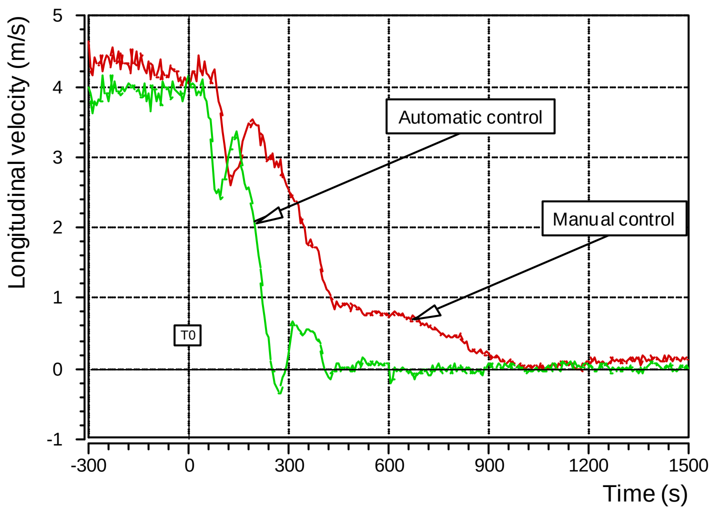

Figure 5 – Comparison of the performance of the automatic system with those of the operator, according to the longitudinal velocity control in the fire area

5.2. The numerical simulations

The fire tests were subject to numerical simulations (CFD). The aim is the comprehension of the phenomena resulting in the stratification development in the fire area. Initially, the smoke affected the complete section.

The simulation of the 1.4 MW fire including the automatic ventilation control provides the following results (Figure 6).

It is shown that the thermal fields are in agreement with the results of the measurement analysis. In other words, the opacity appears to be more invading than the temperature. It affects potentially great distances meanwhile the temperature, subject to the exchanges with the walls or fresh air layers, remains confined close to the fire. The thermal stratification is observed at t= 360 s (Figure 4). The opacity stratification is fully developed significantly later since it appears at about t = 600 s (Figure 6).

The calculation points out also that the opacity found close to the pavement, which requires additional time to be removed, actually corresponds to the smoke initially produced by the fire, transported and destratified by the initial velocity and finally drawn back to the fire area by the controlled velocity resulting from the extraction and the jet fans control. This phenomenon highlights the necessity of efficient and rapid ventilation procedures. It could not be identified by the analysis of the measurements.

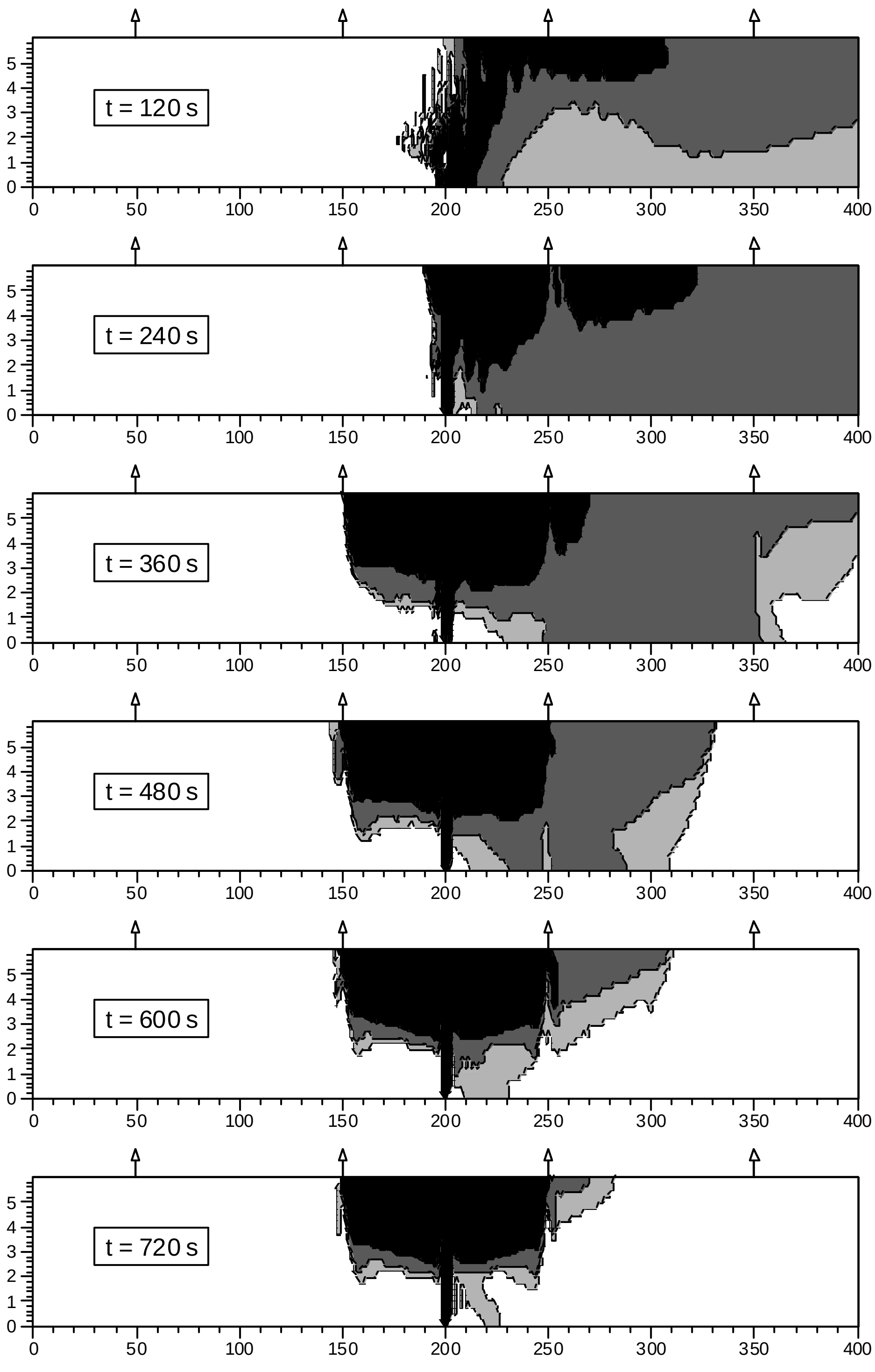

Figure 6 – Calculation of the evolution of the opacity field for the test involving the 1.4 MW fire, with the automatic control of the ventilation

6. FINDINGS AND CONCLUSIONS

6.1. Conclusions of the Mont Blanc tunnel ventilation complete automation

The integration of the automatic procedures in the central system of the Mont Blanc tunnel is an important innovation related to the safety. It aims at performing the operation of a complex ventilation system, including the effectiveness and the rapidity. This operation aims at providing an active control of the physical conditions of the evacuation of the people in the tunnel, in the case of a fire. The objective is the control of the conditions allowing the natural stratification of the hot smoke to develop.

The tests performed at the end of the works, preliminary to the opening of the tunnel to the traffic, have shown that the objectives are matched by the ventilation control procedures. They also highlight the effectiveness of the automatic systems, that requires twice less time to control the longitudinal velocity objective than a trained operator. In real fire conditions, it is admitted, and shown that any operator may commit mistakes in the application of the procedures.

The integration of the automatic procedures in the central control system of the Mont Blanc tunnel relates to marginal costs in the renovation works. Most of the costs are actually due to the application of the recommendations.

The automation of the ventilation system, aiming at controlling the safety conditions in the case of a fire, used to appear as utopia several years ago. The technical success of the Mont Blanc tunnel is now a fundamental reference for new tunnels or renovation works. A similar fully automated system is under study for the Chamoise tunnel enhancement works.

6.2. Unanswered questions relative to the stratification – The RGC&U project

The knowledge developed about the hot smoke stratification in tunnel appears quite uncompleted. It appears limited to a unique principle: the longitudinal air velocity must be as limited as possible, especially in the fire area.

This principle was applied in the case of the Mont Blanc tunnel refurbishment. Additional precautions were taken. But this approach is not based on a satisfactory knowledge of the phenomena participating to the hot smoke stratification in the case of a fire in a tunnel.

For this reason, Scetauroute proposed a national research program, partly funded by the French Research Ministry. This project gathers the main French actors of the research in fires in tunnels:

- Scetauroute, leader of the project;
- Laboratoire Unimeca, Marseilles University (which replaces the Valenciennes University);
- Laboratoire de Modélisation et Simulation Numérique en Mécanique (CNRS, Marseille) ;
- Laboratoire de Combustion et de Détonique (CNRS, Poitiers);
- Company Agefluid;
- Centre d’Etudes des Tunnels (Cetu) recently joined the project.

The main topics dealt with by the project are:

- The inventory of the flow structures resulting from the interaction of the longitudinal flow with the transverse jet of the fire (reduced scale model);
- The study of the thin fluid structures developing in the vicinity of the fire, influenced by a longitudinal flow (reduced scale model);
- The CFD modelling of the turbulence associated to the stratification;
- The compared development of the stratification in a 3D model and a 2D model.

The program began early 2003. It should provide its conclusions end of 2005.

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OPTIMISATION OF VENTILATION IN THE CASE OF A FIRE IN ROAD TUNNELS

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ABSTRACT

The control of the tunnel ventilation in a 2.7 km long dual bore tunnel in the event of a fire has been optimised. In particular, the conditions for the evacuation phase of self-rescue are addressed. Besides the requirement for smoke control in the affected tunnel with the fire, a fixed plan is normally defined for the ventilation of the unaffected tunnel during an emergency. However, as shown in this paper, the optimal ventilation depends on the detailed aerodynamic aspects prior to the incident. The objective is to ensure that the unaffected tunnel is at a higher pressure than the affected tunnel and to prevent a short circuit of smoke at the portal.

On the basis of extensive calculations of the non-stationary scenarios, the optimal jet fan settings were determined by analysing the distributions of velocities and pressures in the two adjacent tunnels. The present ventilation settings were examined and optimal setting derived. Optimal conditions in the unaffected tunnel can be obtained rapidly adopting a two-step procedure. It is shown that traffic conditions in the unaffected tunnel immediately prior to the outbreak of the fire also have an effect on the optimum jet fan setting.

1. INTRODUCTION

There are several philosophies on how a longitudinal ventilation system shall operate in the case of a tunnel fire. In tunnels with unidirectional traffic the common strategy is to maintain the direction of the traffic induced airflow. Upstream of the fire the incoming vehicles come to a halt due to heat and the spread of smoke. In order to keep the stationary vehicles in a smoke free zone, a minimal air flow velocity (e.g. the critical velocity) should be established and maintained.

Devising models of ventilation control for dual bore road tunnels with unidirectional traffic demonstrates the difficulty in achieving and maintaining the three fundamental requirements for tunnel ventilation during the initial evacuation phase of self-rescue. Usually a fixed and relatively simple control setting is opted for. In order to satisfy all requirements it may be necessary to adapt the initial ventilation settings. The design of control concepts should consider both free flowing and slow moving traffic. However, most studies are restricted to the free flowing traffic in the unaffected tunnel. As shown in this paper, slow moving traffic in the unaffected tunnel should also be considered. Moreover, results of the present (original) and optimised control settings are presented for a 2.7 km long tunnel with unidirectional traffic and longitudinal ventilation using jet fans.

2. VENTILATION STRATEGY FOR FIRE IN UNI-DIRECTIONAL TUNNELS

During a fire the tunnel ventilation strategy must take into account two distinct phases: evacuation and fire-fighting. During the evacuation phase of self-rescue the tunnel users are escaping from the fire zone. The tunnel ventilation must ensure optimal conditions in order to protect the people fleeing from smoke and heat.

To achieve this three fundamental conditions should be satisfied:

- controlling smoke in the affected tunnel
- building up higher pressure in the unaffected tunnel than in the affected tunnel in order to keep the escape routes free of smoke

- avoiding a short circuit of air flow at the portals and thereby preventing that smoke exiting the affected tunnel enters the unaffected tunnel

During the fire-fighting phase the ventilation is used to aid the fire brigade.
Figure 1 shows the recommended ventilation setting during the evacuation phase in a dual bore tunnel with longitudinal ventilation and unidirectional free flowing traffic. The smoke is pushed through the tunnel to the exit portal in the same direction as the traffic flow with sufficient longitudinal air velocity, as recommended in various national and international guidelines [1],[3],[2],[4]. To avoid a back-flow of smoke, which is often termed "back-layering", a minimum velocity (i.e. the critical velocity) must be achieved. The computation of this velocity is given in [7]. It is typically in the range of 2.3 m/s to 3.6 m/s [3]. However, the airflow velocity required causes turbulence and affects the smoke stratification downstream of the fire. This phenomenon becomes more evident at higher air velocities. The smoke stratification is also influenced by the longitudinal slope of the tunnel and in particular by the vehicles. By comparison, the Austrian guideline RVS requires an air velocity of 1.0 m/s to 1.5 m/s [2], but does not aim at avoiding back-layering but maintaining stratification.
With slow moving or congested traffic, it is important to keep the smoke stratification intact during the evacuation phase as people may be on both sides of the fire. This means that the longitudinal air flow velocity should be kept relatively low and no jet fans should operate in the smoke zone. This is the recommended ventilation setting for the affected tunnel during the evacuation phase of a fire.
To keep the escape and rescue routes free of smoke, higher pressure is built up in the unaffected tunnel. The pressure difference between the affected and unaffected tunnel should not exceed a certain level so that it is still possible to open cross passage doors enabling the tunnel users to escape [3].
Finally the third condition requires the air flow in the unaffected tunnel to be reversed as quickly as possible in order to avoid a short circuit at the portals [3].
In order to work out a suitable control strategy first of all the priority of two of the conditions, avoiding an air flow short circuit and building up higher pressure, has to be determined on the basis of the specific tunnel conditions. Initial examination of this example has shown that it is not possible to fulfil both conditions concurrently. Hence a two step control strategy is adopted. At first avoiding an air flow short circuit takes priority in this particular case. In the first few minutes after the fire is detected the ventilation control is set to avoid an air flow short circuit. The effects of ventilation on events and pressure distribution are not very pronounced in this period. Afterwards the ventilation control is set to fulfil the required build up of higher pressure to reach the optimum pressure drop over the cross passages.

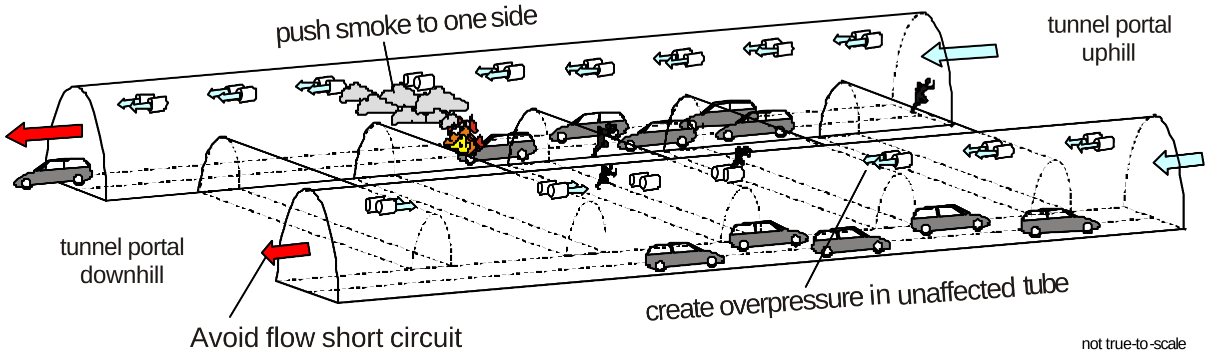

Figure 1: Longitudinal ventilation system in the case of fire in the downhill tunnel

3. DESCRIPTION OF THE TUNNEL

The tunnel consists of two 2.7 km long bores each with unidirectional traffic in two lanes. The longitudinal incline is a constant 1.1 %. The principal geometric and traffic data are as follows:

- 57 m^2 cross sectional area
- 7.8 m hydraulic diameter
- 520 m height above sea level
- 43400 veh/24h number of vehicles passing through both tunnel bores
- 14 % proportion of heavy goods vehicles
- 80 km/h recommended travel speed
- 9 cross passage connections leading to the adjacent tunnel, fitted with fire doors
- 18 jet fans (35 kW electric power) in the downhill tunnel and 14 jet fans in the uphill tunnel

4. METHOD USED

4.1. Influences on smoke propagation

The spread of smoke in a road tunnel depends on a series of parameters. Most of these remain constant during a fire, for instance tunnel geometry, location of the fire, position of the jet fans. Other parameters are not constant, such as the heat release rate, number of vehicles, fire detection time.

Some of the parameters, which have a strong influence over smoke propagation, are considered in the following section.

Fire detection time

The fire detection time should be as short as possible in order to allow quick intervention. A period of three minutes from the start of fire to its detection is usual and realistic. This potential time delay is considered in the ventilation control strategy.

Traffic conditions (free flowing or slow moving traffic)

The traffic conditions immediately before and after the fire starts affects the flow velocity due to the piston effect. Therefore the airflow is affected by the direction of traffic, the volume of traffic, the velocity of vehicles, the proportion of heavy goods traffic and the behaviour of drivers after the fire starts. It is assumed that vehicles moving ahead, away from the fire are not affected and leave the tunnel with a constant travel speed. Vehicles moving towards the fire cannot pass its location due to stationary vehicles, heat and smoke. Before the portals are closed to incoming traffic, the number of vehicles moving in the direction of the fire falls only relatively slowly until stationary vehicles fill the tunnel between its entrance and the fire. Moving vehicles continue to push tunnel air forward.

Location of the fire and tunnel length

Depending on the location of the fire, the evolution of flow velocity with time may be completely different. If the fire is close to the entrance portal, the piston effect of vehicles entering its portal is reduced. If the fire is close to the exit portal, the piston effect of vehicles is greater because of the longer distance covered.

Meteorological pressure differences

Two meteorological effects can influence airflow in a tunnel. One is wind pressure at the portal and the other is the atmospheric pressure difference between the tunnel portals (“barometric barrier”). Both wind and atmospheric pressure can lead to a considerable airflow inside a tunnel. Atmospheric pressure differences are more relevant to longer mountain tunnels.

Tunnel gradient and fire heat release rate
A fire may lead to high temperature differences and thus cause an airflow towards the upper portal due to the stack effect. The importance of this airflow depends on the size of the fire and the slope of the tunnel.

4.2. Scenarios investigated

A fire causes the following sequence of events in the affected tunnel as illustrated in Figure 2.

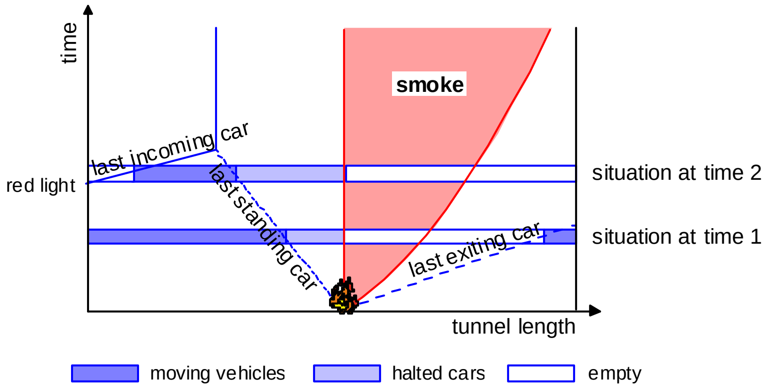

Figure 2: Time dependent traffic distribution and smoke propagation from the start of the fire

The vehicles moving forward, away from the fire are not affected and leave the tunnel with a constant travel velocity. The vehicles moving towards the fire cannot pass it due to the stationary vehicles. They are also hindered by the smoke and heat. If the traffic lights at the portal do not prevent traffic from entering the tunnel, vehicles only stop once they reach the stationary ones inside the tunnel or if they get alarmed by the smoke. Figure 2 shows curves of the position of the vehicles and the extent of smoke propagation with respect to the length of the tunnel. The vertical axis represents the elapsed time since the start of the fire. The broken line to the right of the fire represents the position of the last vehicle leaving the tunnel. The thin broken line to the left of the fire shows the extent of the congested traffic inside the tunnel. A few minutes after the start of the fire, the entrance portals are closed. This is indicated by the thin line running to the right showing the position of the last incoming vehicle, which stops and then forms the rear end of the congested traffic. After this point, all vehicles in the tunnel are stationary. The vehicle distribution at two different times is illustrated. Before the fire detection and hence the portal closure, the number of vehicles moving towards the fire falls only relatively slowly until stationary vehicles fill the tunnel from the entrance to the fire. These vehicles continue to push the tunnel air forward.

4.3. General introduction to the simulation program used

The simulation program “SPRINT – Smoke PRopagation IN Tunnels“ has been used to simulate fire scenarios. This program is a tool for design and review work used to examine the dimensioning and the control of the tunnel ventilation. It is described in articles [5] and [6]. The following parameters are taken into account in the program “SPRINT”: tunnel geometry, traffic piston effects, the build up of congestion in front of the fire, the stack effect due to heat release rate, the spread of smoke due to the basic air flow in the tunnel and the front velocity of smoke. The time dependent distributions of pressures, velocities, smoke concentrations and temperatures over the length of the tunnel are computed.
The effects taken into account are the piston and drag effect of the vehicles, the thrust from the jet fans, the friction losses, the inlet and outlet losses and meteorological influences.

Moreover, the fire is modelled as a heat and smoke source with either constant intensity or a prescribed evolution with time.

5. RESULTS

5.1. Present concept of a ventilation control

The present concept for ventilation control for free flowing traffic has been to operate all the jet fans in the same direction as the traffic flow in affected tunnel. In the unaffected tunnel one group of jet fans was set in the same direction as the traffic flow and the other groups set to reverse mode against the direction of traffic. This setting is appropriate if there is free flowing traffic in both the affected and unaffected tunnel. It is also appropriate for slow moving traffic in the unaffected tunnel.
In the unaffected tunnel the air direction is reversed and the air exits the lower situated entrance portal. Fresh air flows into the tunnel via the upper portal.

5.2. Optimised concept of a ventilation control

For the unaffected tunnel a two-step control strategy is implemented in order to firstly reverse the air flow and secondly to build up an adequate higher pressure with respect to the affected tunnel. In the scenarios examined, a pressure difference between the two tunnels of 100 Pa maximum is envisaged.
Compared to the present concept the settings in the affected tunnel are also revised. The jet fans close to the fire are not switched on as they merely causes turbulence. A different setting is selected if there is slow moving traffic in the affected tunnel.

5.3. Two examples of fire scenarios

The results of the study are illustrated by two representative cases for a fire in the downhill tunnel. In the first scenario the fire is located 300 m from the entrance portal. The traffic is free flowing traffic and a wind pressure of 25 Pa acts on the lower portal, see results in Figure 3. In the second scenario the fire is located 2000 m from the entrance portal. The traffic is slow moving and a wind pressure of 10 Pa acts on the upper portal, see results in Figure 4.
The course of events is as follows: t = 0 min is when the fire starts at the specified location. Three minutes later (t = 3 min) the fire is detected, both entrance portals are closed to traffic and the fire ventilation plan is initiated. A further two minutes later (t = 5 min) the ventilation settings in the unaffected tunnel are changed to achieve the best possible conditions. The end of the simulation is at t = 20 min.
The co-ordinate at X = 0 m represents the position of the uphill portal in all graphs. The co-ordinate at X = 2700 m represents the downhill portal.
The positions of the cross passages between the tunnels are added to the graphs as an orientation aid when determining the pressure differences between the two tunnels.
In the affected tunnel the smoke is driven downstream towards the exit portal using ventilation control. By quickly adjusting the control setting air flow is initially reversed in the unaffected tunnel. Two minutes after the fire is detected (five minutes after fire started) the setting is adapted to also create a higher pressure in the affected tunnel in order to achieve the optimum pressure drop between the tunnels at the cross passages.
In the case of free flowing traffic Figure 3 shows the results of the non-stationary calculations for the present and optimised settings. The variations of the pressure with time to the ambient pressure (Δp) are shown for two representative times (4 min and 6 min after fire started). The pressure distributions are shown for both ventilation settings (present and optimised) and for both tunnels. In the first few minutes applying the present scheme, the pressure distribution is

not ideal as the pressure in the affected tunnel is higher than in the unaffected tunnel (at t = 4 min). Using the optimised settings the situation improves. The pressure in the unaffected tunnel is higher than in the affected tunnel at the position of the cross passages. Therefore the requirement to keep the escape routes free of smoke is fulfilled and the conditions are improved for those fleeing.
The variation of the tunnel air velocities with time is shown in separate graphs. The air flow velocity is drawn on the abscissa and the vertical axis represents the elapsed time since the start of the fire.

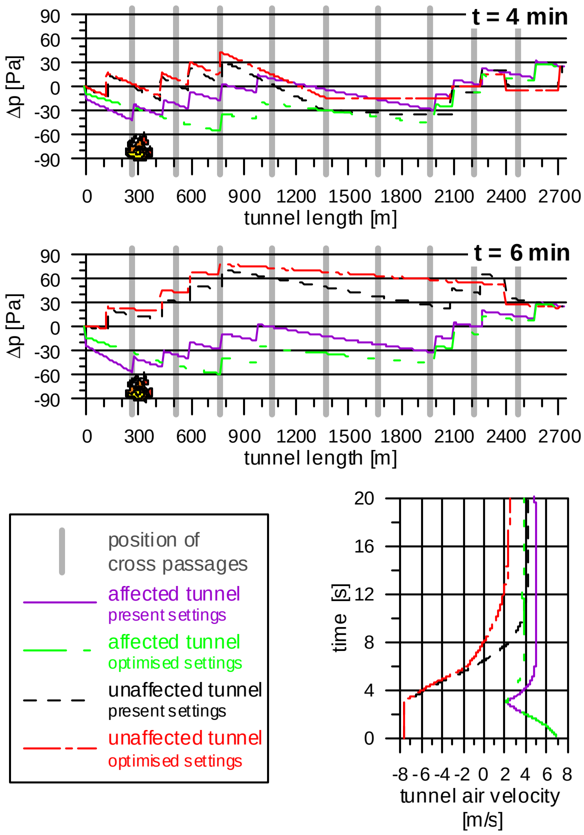

Figure 3: pressure distributions (Dp) for both settings with a fire 300 m from the entrance portal, free flowing traffic and a wind pressure of 25 Pa

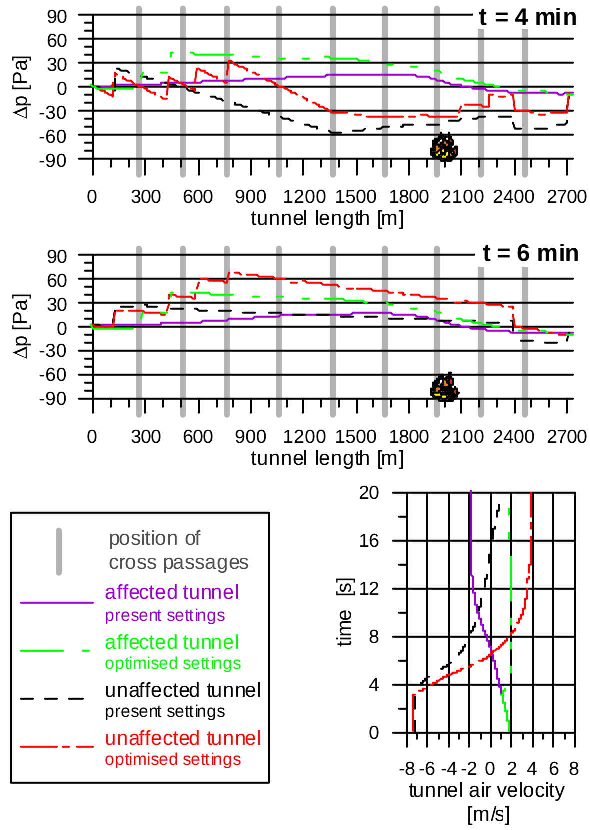

Figure 4: pressure distributions (Dp) for both settings with a fire 2000 m from the entrance portal, slow moving traffic in the affected tunnel and a wind pressure of 10 Pa

For slow moving traffic in the affected tunnel Figure 4 shows the corresponding results applying the present and the optimised settings. The velocity in the affected tunnel is disadvantageous with the present setting as the air flow velocity is reversed at t = 7 min. The situation is improved considerably when applying the optimised settings. The air flow velocity remains in the direction of the traffic flow at a low velocity as desired.

In order to fulfil the three fundamental requirements listed in section 2, an optimised control strategy has been implemented. This distinguishes between free flowing and slow moving traffic in the affected tunnel as well as in the unaffected tunnel.

With respect to the potential occurrence of a flow short circuit at the portal, the air flow velocities are unfavourable at the time of the onset of the fire. This is due to the piston effect of the vehicles and cannot be influenced within the first few minutes of the fire.

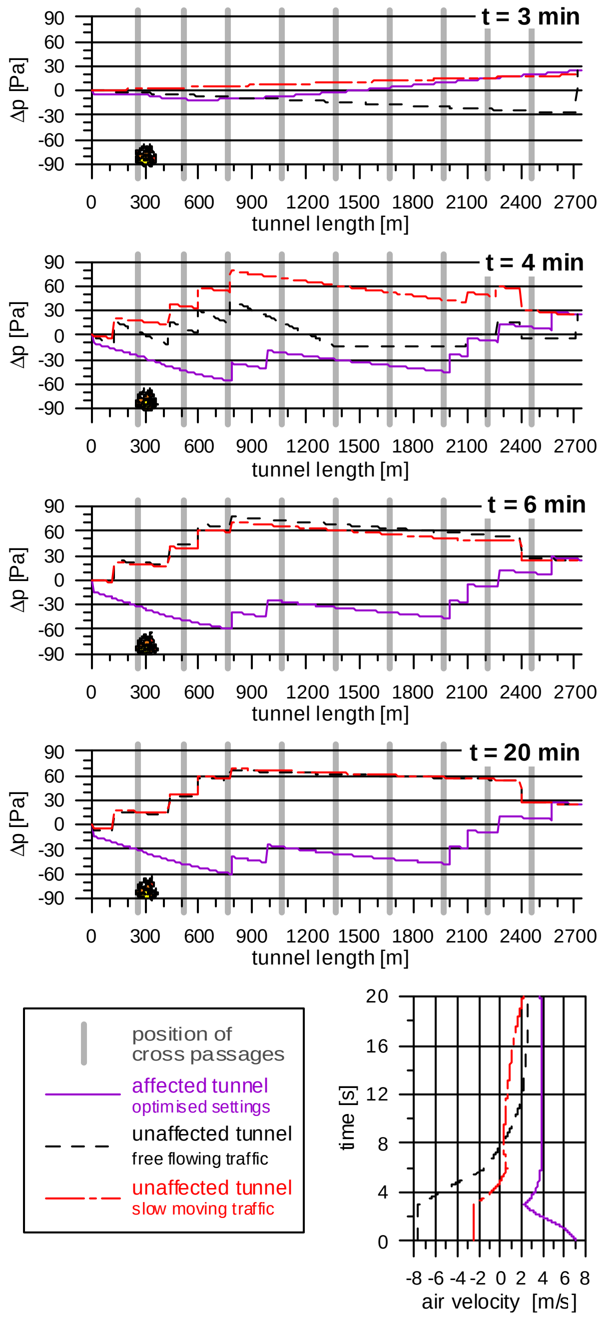

Figure 5: Pressure ratio and air velocity with free flowing traffic in the affected tunnel with free flowing and slow moving traffic in unaffected tunnel

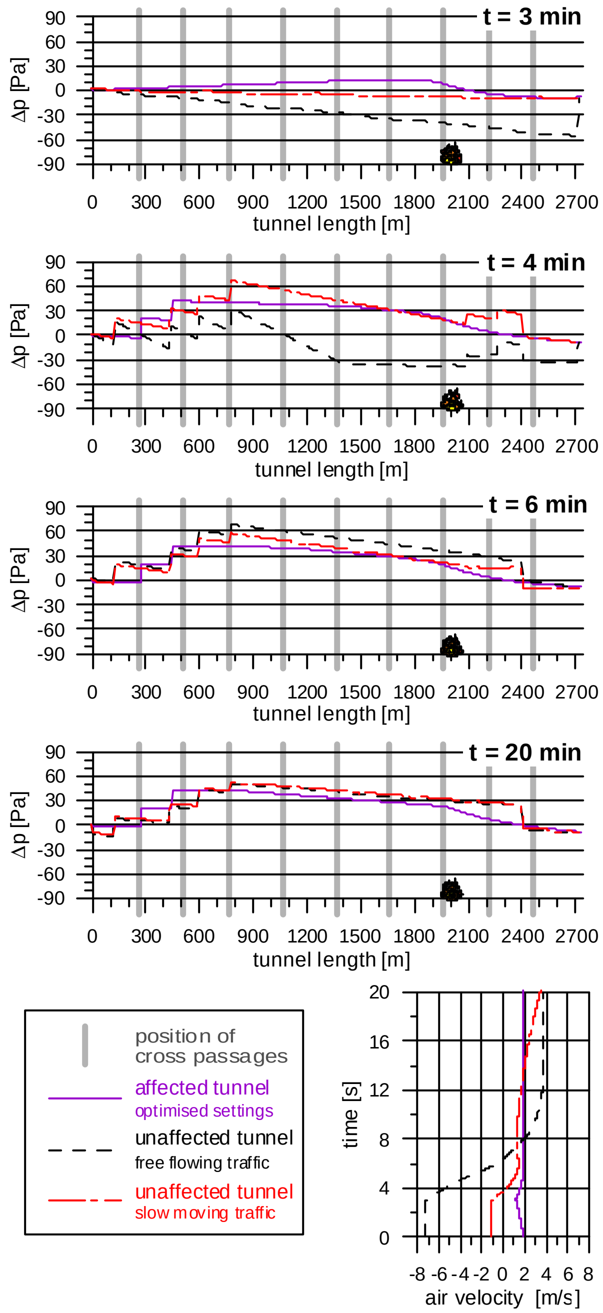

Figure 6: Pressure ratio and air velocity with slow moving traffic in the affected tunnel with free flowing and slow moving traffic in unaffected tunnel

The tunnel ventilation and the closure of the entrance portals to traffic is initiated at the time of the fire detection e.g. three minutes after the onset of the fire. During this period the pressure difference between the two tunnels is rather unfavourable. The pressure in the affected tunnel is higher than in the unaffected tunnel, allowing smoke to spread into the unaffected tunnel via the opened doors in the cross passages.
Congestion in front of the fire in the affected tunnel and the resulting decrease in vehicle velocity reduces the air velocity. The rate of decrease in velocity depends on the location of the fire. Prior to the fire detection the traffic flows undisturbed in the unaffected tunnel.
The pressure difference between the tunnels changes once the tunnel ventilation starts. A considerable improvement is achieved by using the two-step adjustment to optimise ventilation control of the unaffected tunnel.

A comparison of the consequences of the traffic conditions in the unaffected tunnel is shown in Figure 5. The effect of free flowing and slow moving traffic in the unaffected tunnel is very distinct when the same settings are used in both cases for the tunnel ventilation. Having free flowing traffic in the unaffected tunnel, the pressure difference between the tunnels is satisfactory. However if slow moving traffic prevails in the unaffected tunnel, the pressure difference increases and may exceed the acceptable limits with limited zones, as shown in Figure 5 at t = 4 min.

A completely different picture results from the comparison between free flowing and slow moving traffic in the unaffected tunnel when having slow moving traffic in the affected tunnel, as shown in Figure 6. In this case the pressure difference between the tunnels is limited and not optimal in all areas. In this scenario the pressure difference is much less favourable at t= 4 min. The conditions then change with time to reach almost the ideal conditions later on.

6. CONCLUSIONS

By means of simulation models it is possible to derive the optimum settings for the tunnel ventilation in the case of a fire. When designing the ventilation control strategies, all traffic scenarios prior to the onset of the fire including slow moving and free flowing traffic for the affected tunnel and the unaffected tunnel should be considered. This enhances the complexity of the control system and requires an input from the traffic management system. Nevertheless, it is the only viable procedure in order to ensure optimal conditions for the evacuation phase of self rescue.

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SELF RESCUE IN RAILWAY TUNNELS - EVACUATION SIMULATION RESULTS

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ABSTRACT

Evacuation simulations were performed to analyse the sequence of events of organised self-rescue campaigns and to identify the relevant influencing factors. Two different tunnel systems – a twin-bore tunnel with cross-passages and a twin-track tunnel with emergency exits – were used as examples to determine and compare evacuation times for pre-selected scenarios. These investigations helped to bring the strong points and the weak points of the tunnel systems, the procedures adopted, and the behaviour of the persons involved to light.

1. RELEVANCE OF SELF-RESCUE IN RAILWAY TUNNELS

In the past, it was long unclear, which targets should be prioritised and which topics should be focused on with respect to the safety design of railway tunnels. On the one hand, designers were confronted with a lack of experience, as accidents in railway tunnels would only occur very infrequently, and on the other hand there was a lack of practice in performing systematic safety analyses. All this changed drastically in the 1990ies. At this point in time, several accidents involving fire in railway tunnels (e.g. the Zurich Hirschengraben Tunnel in 1991, the Channel Tunnel in 1996) as well as in road tunnels (the Mount Blanc Tunnel in 1999, the Tauern Tunnel in 1999, and the Gotthard Tunnel in 2001) occurred which dramatically illustrated the potential hazards and subsequently prompted a dynamic development in the field of tunnel safety. The planning of numerous new tunnels furthermore forced designers to intensively discuss safety questions prior to any construction works.

Today Austria, like many other European countries, has a clear and largely undisputed ranking of priorities with respect to safety targets:

- Prevent accidents
- Minimize the extent of damage of accidents
- Ensure a fair chance for self rescue
- Provide good conditions for assisted rescue

If a comparison is made between the efficiency of self rescue and assisted rescue, both the practical experience gained with fire accidents and the results obtained from risk analyses clearly tip the scales in favour of self rescue. With fires, it's the first few minutes, which decide about the actual rescue chances. Outside help normally tends to come too late. It is for this reason that the focus of attention is on self rescue.

With self rescue, it is the prime objective of the persons affected by a fire accident to reach a so-called "safe area" as fast as possible. Such a "safe area" may either be an emergency exit leading to the open air, or a cross-passage leading to a second tunnel tube, which is unaffected by the accident including possibly resulting consequences (fire).

With respect to this prime objective, there is a general agreement both in Austria as well as in other European countries. Yet there is no agreement when it comes to details, e.g. the maximum admissible distance to be observed between emergency exits or cross-passages. In this context it is often overlooked that the decisive criterion is not the distance to be covered, but the time needed until a safe area is reached.

If one now looks into the special case of "railway tunnels", where a great number of people try to escape to a safe area at the same time, even a rough analysis reveals that the distance between the emergency exits is only one out of many influencing factors, determining the time required for passengers and train staff to reach a safe area. It is the aim of this paper to identify and analyse these influencing factors. For this aim to be achieved, a comparison between the following two scenarios was made:

- two single-track tunnels featuring two separate running tunnels and cross-passages (twin-bore tunnel)
- a conventional railway tunnel featuring only one tube with two tracks and emergency exits (twin-track tunnel)

This paper is based on the results of a computerized evacuation simulation, which – on behalf of HL-AG - was performed for the Wienerwald Tunnel as well as for two other tunnels in the Perschling valley.

2. BASIS FOR EVACUATION SIMULATION MODEL

2.1. Procedures to be Adopted for Self Rescue

The rescue concept starts from the following basic assumptions, which are identical with the standards, which in recent years have been developed by the Austrian Federal Railways for self-rescue procedures to be adopted in tunnels. At present, train attendants receive regular training for self-rescue campaigns in tunnels.

- If a fire is detected while a passenger train is travelling through a tunnel, the affected train will first try to leave the tunnel.
- However, if the train comes to a halt inside the tunnel, the train attendant will have to make a decision after investigating the situation on site and after communicating with the traffic control centre
  - whether to evacuate the train
  - how to evacuate the train

  The train attendant will subsequently have to inform the passengers over the train's loudspeaker system and the traffic control centre over the train radio.
- The traffic control centre will have to inform the fire brigade and will have to issue the necessary instructions for any subsequent or oncoming trains (stopping all train traffic and vacating the tunnel). After clearance has been given for the second track, the train attendant will have to initiate the evacuation of the passengers. They will have to leave the train and walk towards the nearest accessible cross-passage (in the twin-bore tunnel) or the nearest emergency exit (in the twin-track tunnel).
- The passengers will have to leave the affected tunnel bore through cross-passages or emergency exits to reach a safe area.

These steps are independent of whether the train is in a twin-track tunnel or in a twin-bore tunnel. In both cases there are emergency exits, which lead to a safe area, and the evacuation can only be initiated after all train traffic has been stopped.

2.2. Evacuation Simulation Model

For the simulation, the BuildingEXODUS 3.0 software was used. BuildingEXODUS is an evacuation model for the built environment that can be used for evaluating the emergency and non-emergency movement and behaviour of people. BuildingEXODUS enables the analysis of complex people-people, people-structures and people-environment interactions.

The three submodels of the software are:

- Movement:
  Controls the physical movement of individual occupants from their current position to the most suitable neighbouring location, or supervises the waiting period if such a location does not exist. The movement may involve such behaviour as overtaking, side-stepping or other evasive actions.
- Behaviour:
  Determines an individual's response to the current prevailing situation on the basis of personal attributes.
- Occupant:
  Describes an individual as a collection of defining attributes and variables such as gender, age, max. running speed, max. walking speed, response time, agility, etc.

2.3. Infrastructure

2.3.1 Twin-Bore Tunnel

Tunnel system: two parallel running tunnels with one track and cross-passages

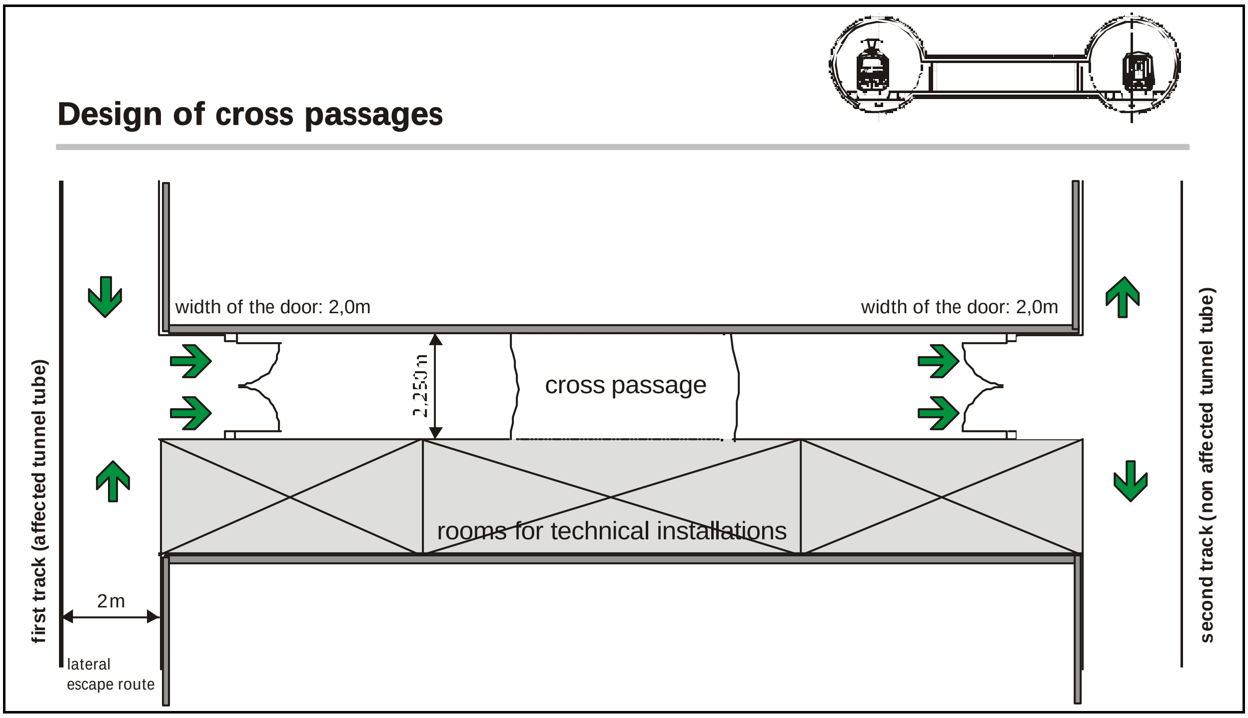

Figure 1: Twin-bore tunnel - design of tunnel system and cross-passages

Width of lateral escape route in running tunnel:	approx. 2 m
Distance between cross-passages:	500 m
Width of cross-passage doors:	2.0 m
Length / width of cross-passages:	approx. 20 m / 2.25 m

2.3.2 Twin-Track-Tunnel

Tunnel system: single-bore, twin-track tunnel with emergency exits with short stairway to the open air

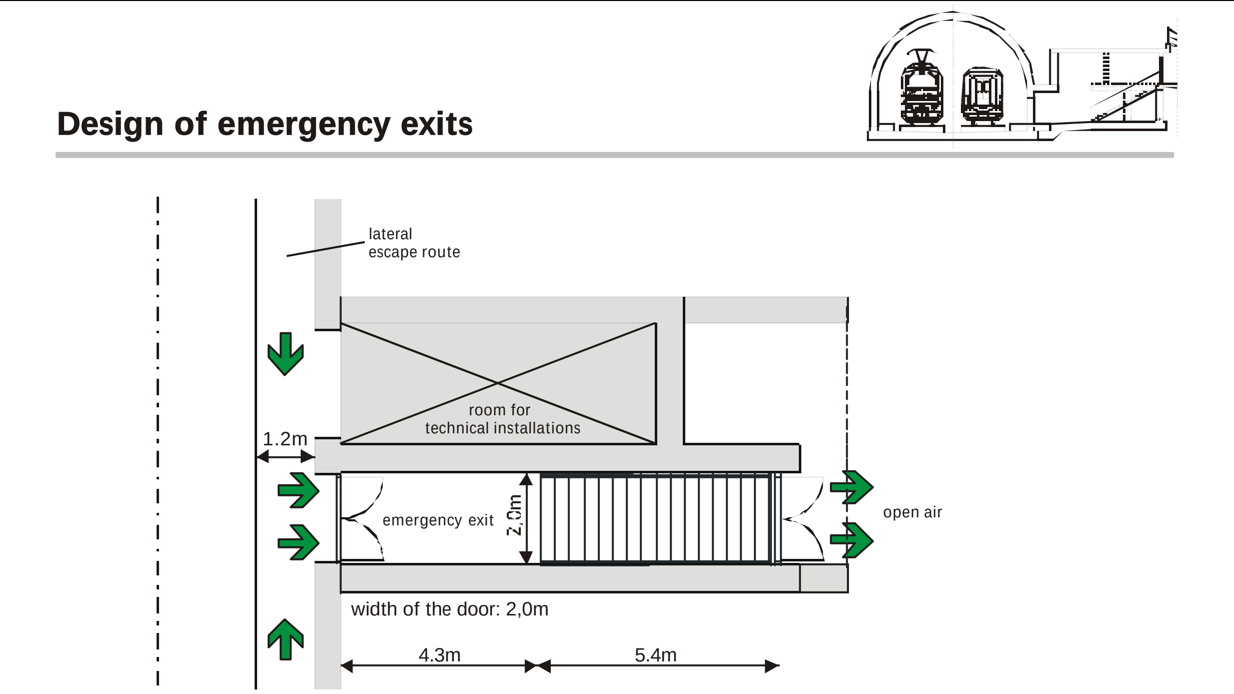

Figure 2: Twin-track tunnel – design of tunnel system and emergency exits

Width of lateral escape routes in running tunnel:	1.2
Distance between emergency exits:	500 m
Width of emergency exit doors:	2.0 m
Length / width of stairway:	5,4 m / 2.0 m
Length / width of queuing space in front of stairway:	4.0 m / 2.0 m

For a comparison of the two tunnel systems, an approx. 1000 m long section of each tunnel system with 3 emergency exits was selected. With both tunnel systems it was assumed that in case of a fire, suitable ventilation measures will be adopted for the safe areas to be protected against the ingress of smoke.

2.4. Number of Passengers / Position of Train in Tunnel / Location of Fire in Train

With all scenarios, the investigation focused on a rather busy, standard-length train. This train consists of 10 passenger carriages without compartments (26 m in length) and carries 500 passengers. In the course of a sensitivity analysis, studies were also conducted for higher passenger numbers.

For both tunnel systems, the following two train positions were scrutinized:

- Train stops between two cross-passages
- Train stops so that the cross-passage is halfway between the front end and the rear end of the train

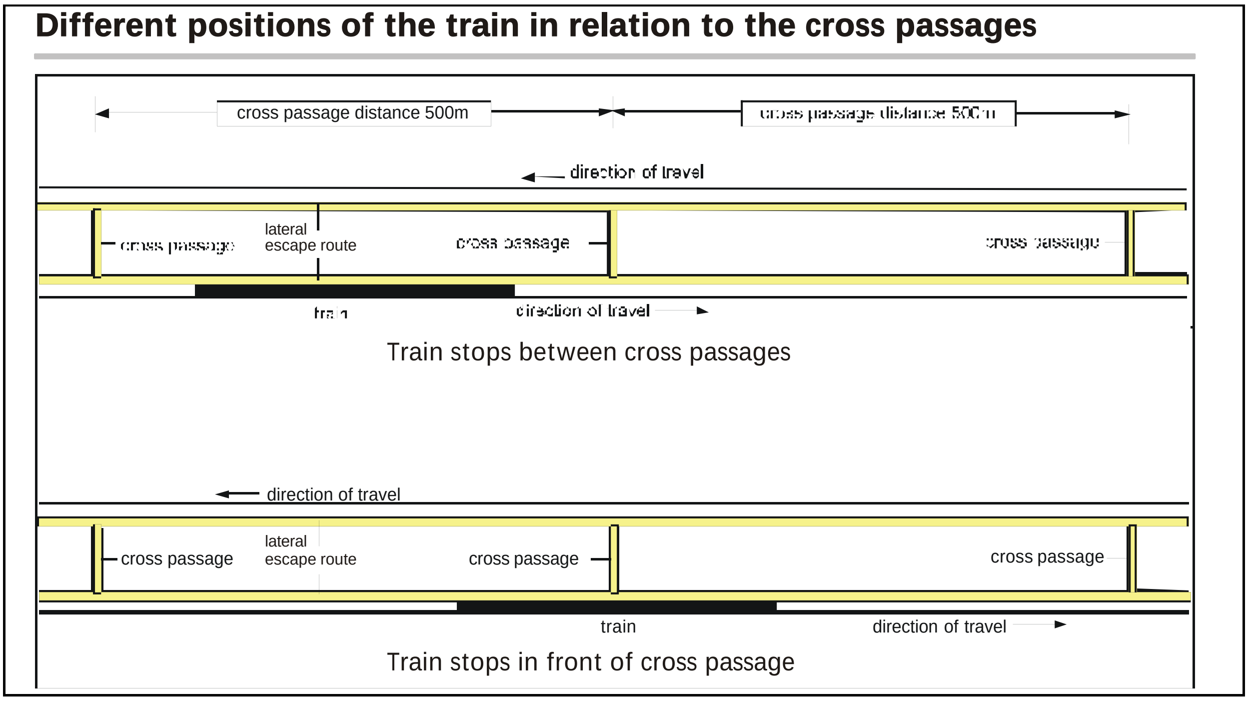

Figure 3: Position of Train in the Twin Bore Tunnel

With the twin-track tunnel, the following differentiation was furthermore made for the "train stops in front of emergency exit" scenario:

- Train stops immediately in front of emergency exit
- Train stops right next to emergency exit (on the opposite track)

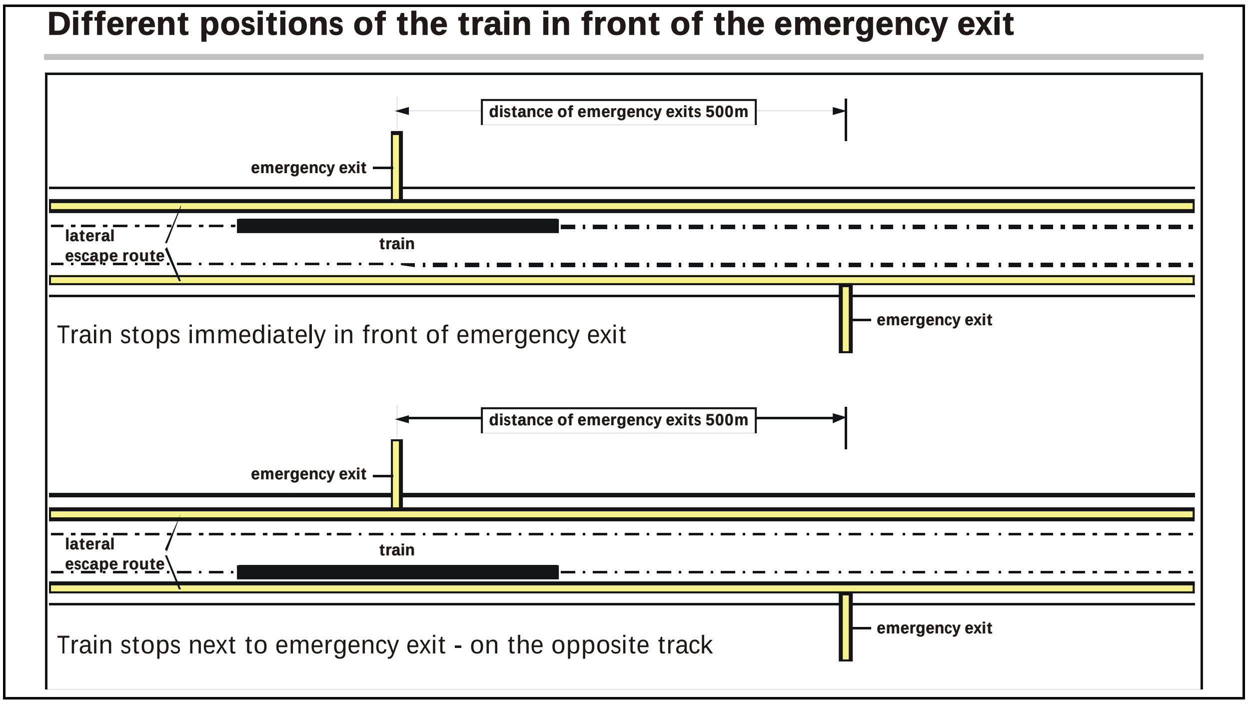

Figure 4: Position of Train in the Twin Track Tunnel

With respect to the location of the fire, investigations were made for positions at the front end, in the middle section, and at the rear end of the train.

2.5. Tunnel Environment and Behaviour of Passengers

For the evacuation, the following boundary conditions were assumed:

- Evacuation without restrictions
- Evacuation with limited visibility on account of incipient smoke build-up in the tunnel

The limited visibility was simulated by progressively reducing the walking speed to 50 % of the initial speed.

Assumed behaviour of people:

- In case of an evacuation without restrictions, it was assumed in the simulation that the people walk to the nearest emergency exit, following the emergency escape signs.
- In case of an evacuation with smoke build-up, it was assumed in accordance with the results of the air flow calculations, that even after the train has come to a halt, an air flow in the direction of travel persists for several minutes inducing the smoke to first spread in the direction of travel. It was furthermore assumed that the fire cannot be passed neither inside nor outside the train. People therefore have to escape on both sides of the fire, away from the fire. Those in front of the source of fire thus have to escape in the smoke-filled tunnel in the direction of air flow.

2.6. Calculation of Total Evacuation Time

The total evacuation time is composed of the following elements:

- Decision time (recognition of danger – coordination with traffic control centre – decision to evacuate the train – instruction to effect self rescue);
  For all scenarios a constant value of 2 minutes was assumed – this value is realistic if the communication sequences are well organised.
- Evacuation time (leaving the carriage – moving away from the danger zone – walking to a safe area, possibly congestion in front of the emergency exit – exit to a safe area) This value was calculated by means of the simulation programme. The results tabled below also contain a decision time of 2 minutes.

3. EVACUATION SEQUENCE – DIFFERENCES BETWEEN TUNNEL SYSTEMS

Prior to any determination of the evacuation times for the individual scenarios, a detailed analysis of the evacuation sequence is required for the different assumptions. This analysis already provides valuable information for the preparation and implementation of a self-rescue campaign and reveals distinct differences between these two tunnel systems:

Twin-bore tunnel:

- The situation at the time of passengers leaving the train is clear and obvious, as is the escape direction (only one sideway; egress only possible on one side of the train; escape to the nearest emergency exit following the escape route signs).
- In the initial self-rescue phase, there is no danger by trains on the neighbouring track.
- The danger of an emergency exit being overlooked due to limited visibility is negligible (all emergency exits are located on one side; clear marking and guidance by handrails possible).
- There is generally a risk of tunnel occupants being endangered by trains on the second track (e.g. in case of communication problems or shortcomings in the preparation of the self-rescue effort), yet only once they enter the 2. tube
- Passengers who have already reached the sideway of the safe tube may literally stand in the way of passengers subsequently seeking to escape through the cross-passages.

Twin-track tunnel:

- The situation at the time of passengers leaving the train is not clear (sideways on both sides; egress on both sides possible; nearest emergency exit may be on either side). Thus there are several options for train occupants to leave the train and to seek refuge, and the optimum option may not be visible at first glance.
- The risk of passengers being endangered by trains on the neighbouring track (e.g. in case of communication problems or shortcomings in the preparation of the self-rescue effort) is imminent immediately upon disembarkation.
- The emergency exits may be located on different sides. Tunnel occupants may - as a result - be obliged to cross tracks or may run the risk of missing an emergency exit on the opposite side due to limited visibility.

4. EVACUATION SIMULATION RESULTS

4.1. Potentials and Limitations of Evacuation Simulations

Evacuation simulations, in principle, start from the assumption of an organised self-rescue campaign, i.e. the evacuation is co-ordinated by the train crew in compliance with existing railway regulations with passengers following their instructions. Yet, in reality this may not always be true, i.e. passengers – or at least some passengers – might behave differently. Evacuation simulations may also be utilized to investigate differences in behaviour; yet this was not the case in this investigation.

Evacuation simulations may be used to study various plausible, yet previously determined behaviour patterns and to reveal possible consequences. This way, weak points in the system, in the organisational procedure, or in the individual behaviour can be identified and suggestions for improvement can be made and evaluated. The experience thus gained may then be used to

- optimise the system and/or the procedure, respectively
- favourably influence the travellers' behaviour by adopting suitable measures.

Evacuation simulations are, however, not suited to predict the travellers' behaviour in a concrete accident situation. The present investigation is definitely not suited to provide a final answer to the myriad of complex questions that circulate around the self-rescue procedure issue, but is intended to raise the sensibility for the multitude of conceivable correlations and to analyse the relevant influencing factors including their mechanisms of action.

The investigation covers scenarios with and without smoke; without smoke to first analyse the relevant influencing variables of the system without hampering environmental effects, and with smoke to determine which additional effects are created by the impact of smoke.

4.2. Results Twin-bore Tunnel

The total evacuation time for the investigated scenarios has been listed in the Table below:

Scenarios	Train between cross-passages	Train in front of cross-passage
without fire	8 min 55 sec	6 min 07 sec
with fire at rear end of train	14 min 57 sec	6 min 43 sec
with fire in middle section of train	10 min 31 sec	21 min 27 sec
with fire at front end of train	12 min 37 sec	6 min 23 sec

On the basis of these results, the following essential conclusions can be drawn.

Scenario without fire:

- Train between cross-passages:
  The decisive influencing factor is the distance between the cross-passages.
- Train immediately in front of cross-passage:
  The decisive influencing factor is the capacity of the cross-passage door.
- The sideway width in the running tunnel is no decisive factor.
- The evacuation time of 500 passengers is shorter with the “train in front of cross-passage” scenario than with the “train between cross-passages” scenario. Yet with growing passenger numbers, the evacuation time for the “train in front of cross-passage” scenario increases considerably, since in contrast to the “train between cross-passages” scenario, there is only one emergency exit.

Scenario with fire:

- The build-up of smoke in the tunnel and the need to take a different escape route due to an unfavourable location of the fire (people will escape away from the fire and will not try to get past the fire) inevitably lead to considerably longer evacuation times.
- Train between cross-passages
  In some scenarios, the emergency exist cannot be reached due to an unfavourable location of the fire and the passengers are forced to head in a different escape direction (longer escape routes and the influence of smoke cause considerable delays)
- Train in front of cross-passage
  Only minor delays are experienced if the fire is situated at the front or the rear end of the train. The most unfavourable situation occurs when the source of the fire is located in the middle section of the train and in the immediate vicinity of a cross-passage preventing people from using this cross-passage and forcing them to proceed to the next cross-passage.

4.3. Results Twin-track Tunnel

Scenarios without fire

Scenarios	Train between emergency exits	Train in front of emergency exit
Standard design emergency exit	9 min 38 sec	9 min 37 sec
Improved design emergency exit		
- wider stairway (2.40 m instead of 2.00 m)	9 min 20 sec	7 min 41 sec
- sufficient queuing space in front of stairway (25 m²)	9 min 23 sec	8 min 22 sec

- Train between emergency exits:
  The decisive influencing factors are the distance between the cross-passages and the stairway capacity
- Train immediately in front of emergency exit:
  The decisive factor is the stairway capacity; there are considerable capacity problems at the emergency exit.

Therefore the following improvements have been investigated:

- Increase of stairway width by 40 cm (an additional walking lane)
  20 % improvement achievable
- Increase of queuing space in front of stairway from 7 m² to 25 m²
  10 % improvement achievable

Both these measures show only little effect if the train comes to a halt between emergency exits (only minor capacity problems, because two emergency exits can be used)

- The sideway width is no decisive factor (although width in twin-track tunnel only 1.2 m compared to 2.0 m in twin-bore tunnel).

Scenarios Train stops next to emergency exit on neighbouring track	Train next to emergency exit
Alternatives of disembarkation: - Egress to neighbouring track - Egress to opposite sideway, Crossing of tracks before / behind train - Egress to opposite sideway, Evacuation to neighbouring emergency exit	 9 min 59 sec 11 min 20 sec 13 min 44 sec

This scenario, which forces passengers to cross the tracks to reach the emergency exit on the opposite side (see figure 4), causes delays independent of the disembarkation alternative ultimately chosen.

- Both alternatives which involve crossing the tracks and using the opposite emergency exit were found to be more favourable than the option of using the neighbouring emergency exit without crossing the tracks
- Yet this effect is reduced in case of rising passenger numbers, due to capacity problems which are experienced if only one emergency exit is used.

<u>Scenarios with fire:</u>

Scenarios	Train between emergency exits	Train in front of emergency exit
without fire (for comparison)	9 min 38 sec	9 min 37 sec
with fire at rear end of train	14 min 46 sec	-
with fire at middle section of train	10 min 36 sec	18 min 45 sec
with fire at front end of train	14 min 59 sec	9 min 37 sec

- Train between emergency exits
  The main influencing factors and the simulation results are very similar to those of the twin-bore tunnel. The longer evacuation times in the "fire at front end of the train" scenario can be explained by the necessity of having to cross the tracks to reach the emergency exit
- Train in front of emergency exit
  The most unfavourable situation occurs when the source of the fire is located in the immediate vicinity of a cross-passage (i.e. cross-passage can not be used and tunnel occupants will have to proceed to the next emergency exit)
- The impact of an insufficient stairway capacity continues to persist even in case of a delayed evacuation as a result of limited visibility due to smoke build-up, which explains the considerably longer evacuation times (as compared to the twin-bore tunnel).

5. CONCLUSIONS

- The investigation results reveal that in a modern railway tunnel with emergency exits at intervals of 500 m, a self-rescue of approx. 500 passengers is possible in a period of approx. 6-15 minutes. This is even true in case of limited visibility due to smoke build-up. Only under very adverse conditions, may self-rescue efforts require up to 20 minutes.
- The main influencing factors and the simulation results tend to be very similar with twin-bore tunnels with cross-passages and with twin-track tunnels with emergency exits.
- Yet, decisive differences are discernable in the following domains:
  – The decision-making process before and during an evacuation procedure as well as the evacuation sequence, tend to be more complex in a twin-track tunnel than in a twin-bore tunnel.
  – With emergency exits featuring stairways in a twin-track tunnel, the stairway capacity decisively influences the evacuation time.
- In case of a fire, the worst-case scenarios are those in which the location of a fire blocks the access to a favourably sited emergency exit forcing passengers and train staff to take a detour.
- The results clearly show that the evacuation time is substantially influenced by the position of the train and/or the position of the fire inside the train. It should thus be checked whether in case of an emergency stop, the position of the train in relation to the emergency exit can be influenced in a favourable way and if so which pre-conditions and which information would then be required.

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TUNNEL DESIGN WITH SPECIAL VIEW TO THE PORTALS

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After the disasters which in 1999 occurred in several European tunnels it has been realized that the behaviour of drivers has a great influence on tunnel safety. Therefore an appropriate method to analyse the behaviour of drivers in tunnels has been searched for.

In spring 2001 the ÖSAG has charged the KfV (Austrian Board of Trustees for road safety) with a study on the behaviour of drivers in motorway tunnels. The research has been finished in autumn 2001 and its results were presented on the 1st symposium in April 2002.

The results of this research have been considered in the planning of the ÖSAG-projects "Semmering pass" consisting of a tunnel chain with a total tunnel length of 16 km and "Tunnel chain Klaus" on the A9 Pyhrn Motorway which consists of 6 tunnels constructed by mining method and 4 short tunnels constructed by cut-and-cover method. Most part of the long tunnels constructed by mining method are divided only by valley crossings.

Additionally, these results have been considered in the guidelines for the design of portal areas and in the revised guidelines for operating and safety equipment in tunnels.

1. GUIDELINE FOR THE DESIGN OF PORTAL AREAS:

In summer 2002 within the ASFINAG group there has been established a working group charged with the working out of guidelines which in autumn 2003 have been finished. In collaboration with a traffic psychologist (author of the above mentioned study) the members of this working group have tried to find strategic principles for designing the portal area and to draw up model plans for the portal area.

In detail the following regulations have been worked out:

A) Main principles of these guidelines

- The design of the portal area has to keep the drivers free of optic impressions, so that he can concentrate on the driving into the tunnel. The driver shall have as few disturbing impressions and information as possible approaching and entering the tunnel. The definition of the portal area is a distance, which you can pass in 5 seconds using the allowed speed. Driving with 80 or 100 km/h this is a distance of about 110 to 140 m before the portal.

- If a driver error occurs in the portal area and there is a collision, the consequences of the collision have to be minimized; primarily the design has to protect other road users but also the driver himself.

- An architectural design of the portal also has to fulfil these principles.

- If topographical situations do not allow to obey the specific regulation, as a minimum the mentioned principles have to be fulfilled.

B) Special regulations

- Definition of the placement of traffic lights (directly at the portal and 250 m before the portal), it is preferred that they are overhead and they shall be in LED-technique.

- The markings before the portal in a length of about 250 m shall be made with a short distance of the lines.

- Rumble strips have to be made at the edge line and at the continuous traffic line at bi-directional tunnels for about 100 m before the tunnel portal to give an acoustic sign when a car looses its way (s.pic 1).

pic.1

pic.2

- Dampers have to be installed on the right side of tunnel portals of bi-directional tunnels (s.pic.2).

- The situation of the signalization of the speed limits and the speed limits themselves before the tunnel portal are defined in the draft of the new regulation as follows (s.tab.1):

Kind of traffic	Speed on open road [km/h]	State of operation	Speed limit [km/h]	Distance [m]	Speed limit [km/h]	Distance [m]	Speed limit [km/h]	Distance [m]	Speed limit [km/h]
bi-directional	130	Normal	100	300 - 500	80	300 - 500	--	100	80
		Works in the tunnel	100	300 - 500	80	300 - 500	50	100	30
		Jam - closure	100	300 - 500	80	300 - 500	Stau	100	General prohibition of driving
	≤ 100	Normal			80	300 - 500	--	100	80
		Works in the tunnel			80	300 - 500	50	100	30
		Jam - closure			80	300 - 500	Stau	100	General prohibition of driving
uni-directional	130	Normal			100	500 - 800	100	500 - 800	100
		Works in the tunnel			100	500 - 800	80	500 - 800	30
		Jam - closure			100	500 - 800	Stau	500 - 800	General prohibition of driving

tab.1

- The signalisation of the name and the length of the tunnel together with the tunnel symbol will be situated not in the mentioned portal area, but some hundred meters before the tunnel. The board with radio frequencies will also be situated not in the portal area. (s.pic.3)

pic.3

- There will be installed information boards about 1,5 km before the tunnel entrance and directly at the entrance of the tunnel, to make it possible to inform drivers in case of emergency or road works inside the tunnel (s.pic.4).

pic.4

2. TUNNEL CHAIN AT KLAUS:

The fact that the motorway section between Schön and Lainberg Nord runs through a deep valley required the building of many tunnels.

As a result about 10 km or 70 per cent of this 16 km long motorway section run underground in tunnels.

The planning of this project was very challenging especially because of the direct succession of so many tunnels which partly are divided only by valley crossings.

2.1. Operating and safety equipment

The arrangement of construction elements such as lay-by niches, cross passages for pedestrians and cross passages for vehicles as well as the installation of operating and safety equipment have been carried out according to the RVS 9.281 and RVS 9.282 and according to the latest technical standards.

On the motorway section between Schön and Lainberg Nord among others the following safety facilities have been installed

- Emergency phones
- Fire alarm devices
- Video monitoring system with digital recording of video images
- Surveillance of air quality in the tunnel
- Ventilation during operation and in case of fire
- Fire extinguishing facilities
- Tunnel radio system
- Height control facility
- Tunnel lighting
- Information boards for additional traffic information

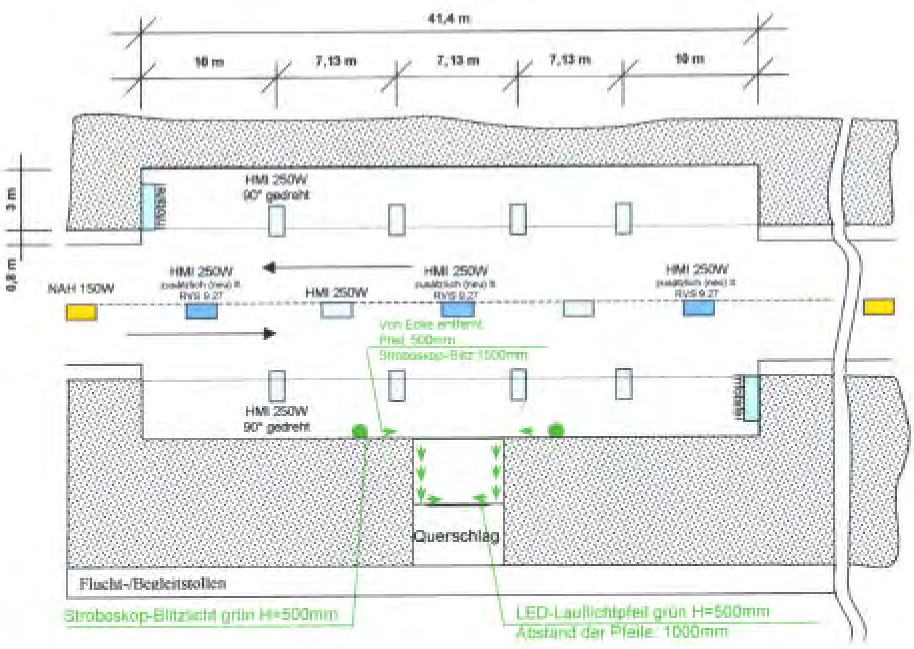
All facilities are controlled by the control centre situated in Ardning (s.pic.6).

pic.6

Considerable emphasis has been laid on the quality of the lighting system in the tunnel.

In the interior zone of the tunnel 150W Sodium high pressure lamps have been installed in distances of 17,85 m which leads to an average luminance of 5 cd/m2 during operation. At the lay-by niches in the interior zone there are installed 250W HMI-lamps in order to reach halation-effects. Additionally, the emergency phone niches are lighted up by 250W HMI-lamps installed in the lighting axis and rotated through an angle of 90°.

LED-arrows indicating escape routes in case of emergency and stroboscopic flashes represent important safety criteria (s.pic.7).



pic.7

The working out of a traffic control plan was a very challenging task.

The main problem consists in the fact that before the tunnels traffic cannot be diverted and there is not enough space in case of jams because the open road sections between the tunnels forming the tunnel chain are very short (often with bridge constructions)

Considering these facts traffic control plans for two cases have been defined:

- Short term obstructions
- Long term obstructions

Normally, short term obstructions have no impact on neighbouring tunnels so that traffic control measures have to be taken only for the tunnel concerned. For example: emergency information in unidirectional tunnels

Long term obstructions inevitably impact on neighbouring tunnels (on tunnels lying before the tunnel concerned). Depending on the kind of obstruction general danger alarms (eg. yellow flashing traffic lights) or traffic diversion at the junction lying before the tunnel chain are put into effect.

For example: fire alarm

3. PSYCHOLOGICAL INVESTIGATIONS

On 26 September 2003 the tunnel chain has been opened to traffic. In order to check over the efficiency of the measures which have been taken the KfV (Austrian Board of Trustees for road safety) has been charged with a new psychological research.

Like the research carried out in 2001 in this new research varied data have been collected from 67 test subjects. In both researches the test subjects had to drive with cars provided with instruments through several tunnels of the Pyhrn Motorway. Then they were interviewed in a detailed way about their impressions and about other aspects. In the latest research the test subjects had additionally to undergo high-frequency ECGs which allow to collect objective data about the stress the test subject is under.

The test section of the recent research was about 90 km long and ran on the A9 between Ardning and Schön. On this section older tunnels such as the Bosrucktunnel and the Lainbergtunnel had to be passed as well as the tunnels of the tunnel chain at Klaus which - as mentioned above - have been constructed according to the latest standards. But also the older tunnels meet the latest standards under many aspects because they have been renovated in the last years. Comparisons with former standards could be made on the basis of the data collected in 2001 partly on the same motorway sections.

The latest analysis has been carried out under the aspect of traffic signs, tunnel entrances, tunnel lighting, design of the tunnel walls, road markings, safety equipment and design of transition areas (transition from one or more lanes to one lane, rapid succession of tunnels and open road sections). The results of the study carried out in 2001 have already shown that differences in the above mentioned designs have impact on the behaviour and the subjective feeling of the driver.

The results of the recent research show that the new tunnel designs have been accepted positively by the drivers. In the area before the tunnel information have been structured in a new way and have been reduced to the essential. As a result drivers now record more easily the important traffic signs which call for actual action. The new designs of tunnel portals show also elements of art. The comparison between portals of different designs shows that every design is accepted. In 2001 as well as in 2003 the test subjects were asked about suggestions for improvement under all aspects. The study of 2003 virtually brought no actual new idea which has not been realised in the meantime. The test subjects are very satisfied with tunnel lighting, the design of tunnel walls, marking signs and reflectors. The drivers also know more about safety equipment and the right behaviour in case of emergency.

Nevertheless the latest research show that there are also some points - specific of this section - which potentially could be improved. Several test subjects felt uncomfortable about the rapid succession of tunnels and open road sections. Some drivers felt also irritated by traffic signs and guidance systems lit by LED-technique which generally have been accepted positively but at night-time make a sharp contrast with the background. To solve this problem it has been suggested to dim the lights.

Like the former research also the recent study compares the statements of the test subjects with their behaviour in order to compare the subjective feeling about safety with objective safety indicators. As higher levels of planning standards should lead to a reduction of driving errors and this indicator sometimes may be not exact enough, variability of heart beat frequency has been analysed, too. On the basis of this physiological indicator the stress of the test subject can be measured objectively and details which did not come out during the interview can be found out. Using this method above all the stress of anxious people can be measured more exactly. The latest research is now being analysed and evaluated, the results will be available in time when the symposium takes place.

ADVANCED DETECTION SOLUTION – SIADS EVENT DETECTION IN TUNNELS

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ABSTRACT

In 99.9% of all cases, fires in tunnels are caused by motor vehicles. In this environment, fire is not only concern; rather, smoke gasses and their uncontrolled spread pose a considerable risk. Increasing traffic, length of tunnels, opposing traffic in single tube tunnels, the higher load capacity of trucks and trucks with lower quality standards from Eastern European countries all serve to increase the potential dangers.
A vehicle fire is generally preceded by events that, to date, have not been evaluated by traditional fire alarm technologies. SiADS, the video based sensor system presented in this document, offers comprehensive detection of traffic related events not been detected by earlier sensor systems, e.g. collisions, accidents and wrong way drivers. Using SiADS to *complement heat sensor systems* from the fire detection industry enables a significant reduction in detection times. As such, organizational and corrective measures can be taken earlier, to potentially save the lives of primary victims and avoid endangerment of secondary victims altogether.

Key words: tunnels, smoke detection, traffic monitoring, event detection

1. BACKGROUND

1.1. Risk Management in Tunnels

Due to the special thermal conditions in tunnels, conventional fire alarm technologies with point sensors are pushed to the limits of their detection ability. Newer systems such as the linear heat alarm system Fibrolaser II (differential alarm) require roughly 180 seconds prior to reporting a standard vehicle fire with a heat production level of 5MW; however, one should note that a vehicle fire can not be detected more quickly than the specific development of the individual fire allows (see figure 1):

- A motor fire spreads to the car’s interior within five to ten minutes, where toxic gasses quickly develop
- According to ECE-R34, a fuel tank withstands open flames for 3 minutes
- If fuel is released from a physically damaged tank (puddle creation), a fire can fully develop within 30 – 60 seconds
- Depending on the tunnel’s geometry and features, natural convection can cause winds of up to 12 meters per second, allowing smoke to spread up to over 700 meters before being detected by a fire alarm system

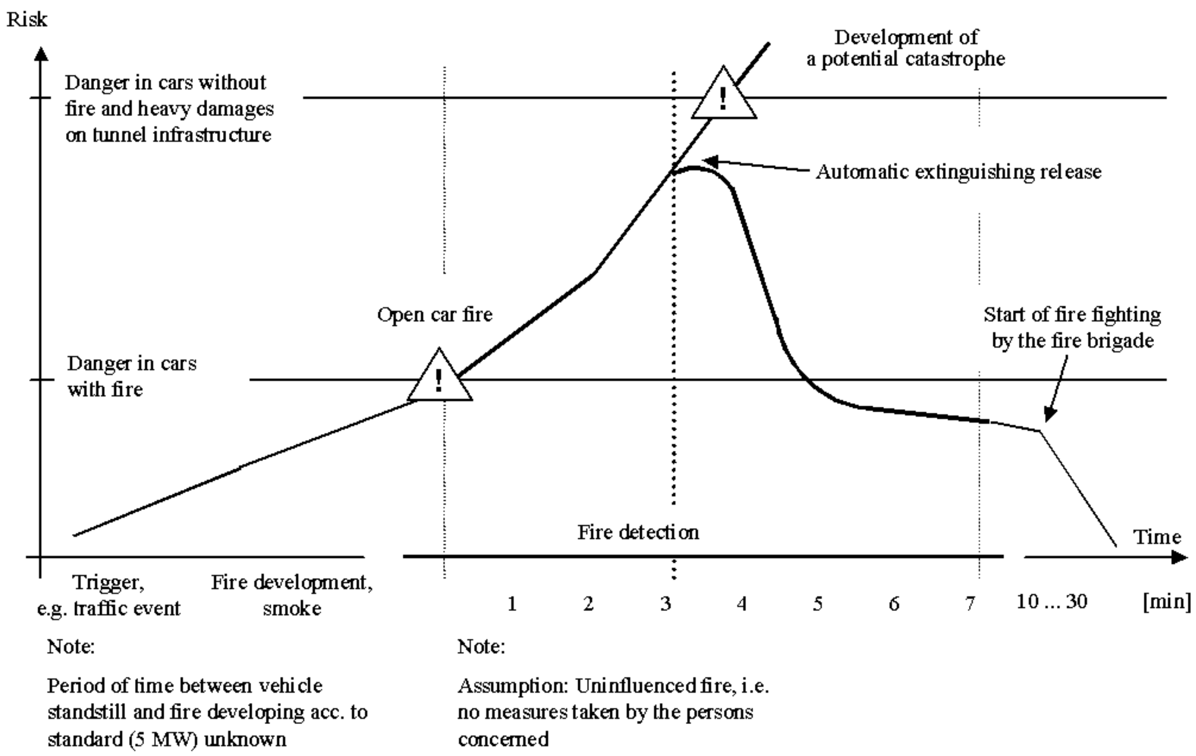

Figure 1: Risk Development in Tunnel Fires

With this in mind, the following particular dangers are common in tunnel fires:

- Generally, only a long escape route is available
- Smoke often spreads as quickly as a person on foot can distance himself from the endangered area
- Extreme temperatures are achieved quickly (chimney effect)
- Within a narrow tunnel, turning around is nearly impossible and there is little room to maneuver
- Rescuer workers are hindered (poor visibility, exceptionally narrow)
- Motors and pumps can fail due to the lack of oxygen

1.2. Chain of Events

Normally tunnel fires do not ignite spontaneously; rather, they are of the result of a chain of preceding events that to date have not been detected by traditional fire alarm technologies. Further, fire alarm systems only helped protect secondary victims rather than primary victims.

Accidents and slow moving or stopped vehicles cause two thirds of all damages to vehicles entering the tunnel. Generally, a vehicle will slow down prior to coming to a stop. Once stopped, the fire develops initially from a small, smoky fire without open flames (e.g. fire in the motor compartment) to an open fire (see figure 2).

Additional indications for potentially dangerous situations for the ensuing traffic include:

- Vehicles occupy the emergency parking spaces
- People at the mouth of the tunnel and in the driving lanes
- Poorly secured vehicle cargo and objects falling from a vehicle

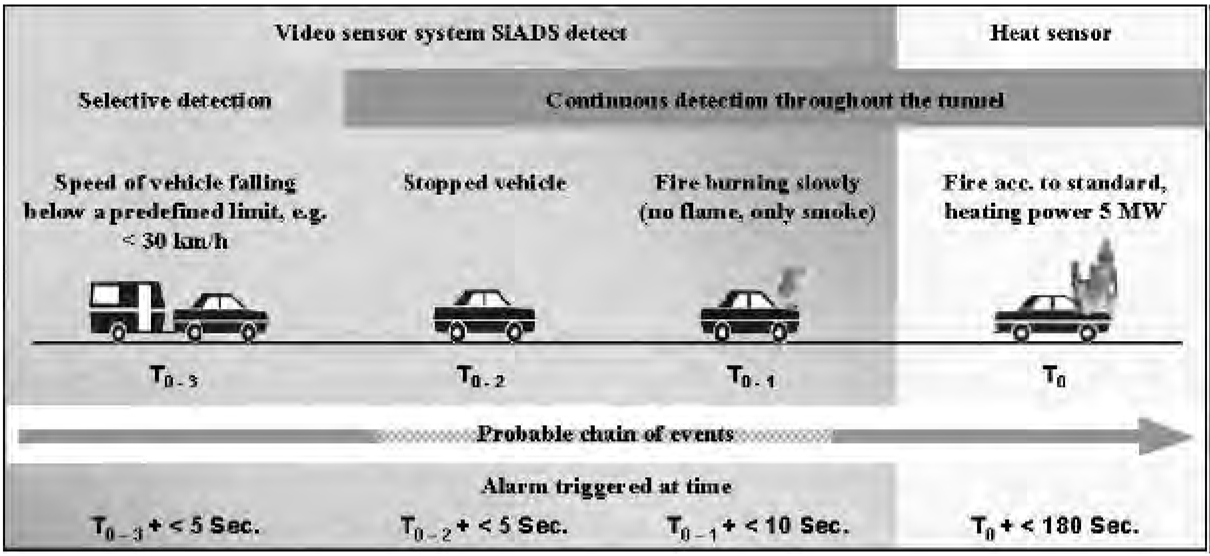

Figure 2: Chain of Events

2. SYSTEM CONCEPT

The background described above has resulted in the increasing demand for comprehensive, uninterrupted event detection over the entire length of a tunnel as a complement to traditional fire detection systems Since most tunnels over 500 meters in length generally have installed video systems to allow operators to monitor conditions in the tunnel and take corrective measures if needed, it makes sense to further use such existing video systems for automatic event detection.

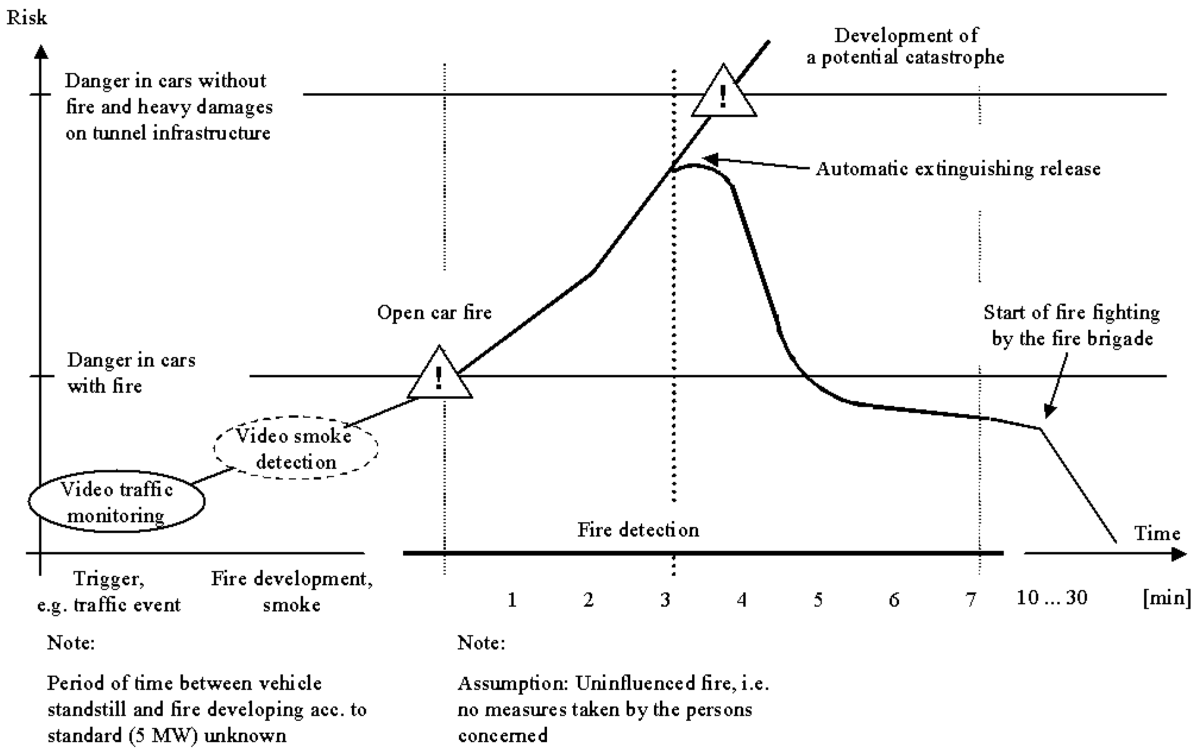

Figure 3: Risk Reduction Using Complementary Event Detection

This method of event detection uses the technological advantages of image sensors such as:

- Shortest detection times (target: realtime)
- Multi-functionality (detection, reporting, transmission, recording)
- Largest possible detector zone offered by the camera's viewing field
- Multi-functionality of the detection itself (multiple event types)
- Improved selection of the measures through visualization of the event

3. SIADS SCOPE OF PERFORMANCE

3.1. Event Detection :

Slow Moving Vehicle Detection SLVD:

- Lane specific, uninterrupted detection
- Operators can temporarily deactivate detection for individual lanes (e.g. for road maintenance work)

Stopped Vehicle Detection STVD (Figure 4):

- Lane specific, uninterrupted detection of individual stopped vehicles
- Operators can temporarily deactivate detection for individual lanes (e.g. for road maintenance work)

Traffic Jam Detection TJD (Figure5):

- Lane specific, uninterrupted detection of traffic jams
- Operators can temporarily deactivate detection for individual lanes (e.g. for road maintenance work)

Smoke Detection VSD (Figure 6):

- Smoke detection using contrast analysis of the upper third section of the video image

Wrong Way Driver Detection WDD:

- Lane specific detection of vehicles travelling in opposition to the direction defined for the lane. Detection is always in the foreground of the video image
- Operators can switch lane directions without complicated system reconfiguration (e.g. for construction work)

All detection modules have a reaction time of less than five seconds and accuracy of greater than 95%. Cameras centered at a mount height of 4.80 meters on the tunnel ceiling at 80 meter intervals is sufficient for comprehensive, uninterrupted detection in the tunnel (see figure 7).

The system also reports the resolution of an event, including the specific event, the lane, the segment and the object itself.

Figure 4: Stopped Vehicle

Figure 5: Traffic Jam

Figure 6: Smoke Detection

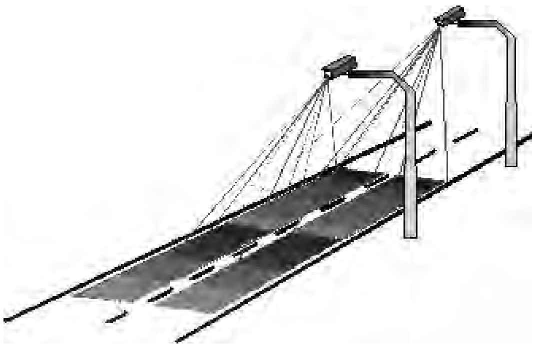

Figure 7: Camera Positioning

3.2. Video Recording VRB

In addition to the actual detection of events, SiADS offers a freely configurable video storage system for each input channel. The recording system features

- Recording in ring operation mode
- Configurable ring length (pre-event recording time) with a configurable recording rate of up to 12,5 fps
- Configurable post recording time with a configurable recording rate of up to 12,5 fps
- Upon event detection or alarm, the ring and post event sequences are stored permanently
- The recording uses a compression technique to retain image changes over the recorded time period (MPEG4 Technology)

The in ring operation mode in the implemented video storage system allows operators to analyze events efficiently and reconstruct the chain of events e.g. to assist in determining culpability or identifying deficiencies in the security precautions taken.

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3.3. System Connectivity

SiADS can be used in a stand alone environment or as a subsystem within an overall security system. Using a generic interface (gateway), SiADS can be connected to a range of other systems with a minimum of integration effort.

As part of an security system (see figure 8), SiADS detects, records, transmits, visualizes and reports events to a controlling fire or danger management system. The control or danger management system can then assume automatic control over subordinate systems. This usage may provide additional feedback to the detection system and further optimize its use for the specific event.

3.4. Traffic Data Capture TDC:

As detailed above, the scope of the SiADS video sensor system was primarily conceived for event detection as a complement to a fire alarm system. Although the system also offers a simple traffic data capture module, this module should by no means be seen as a replacement system for TLS certified data capture systems such as induction sensors or radar devices:

- Lane specific traffic data capture at a freely selectable time interval
- Average velocity per each lane
- Vehicle count per each lane

4. FIELD EXPERIENCE

Conditions	STVD	SLVD	TJD	WDD	VSD
Internal, ceiling mounted cameras Camera height: 5.55m Camera: K505 (1/3", 12mm) Tunnel lighting > 40 Lux No lighting variations Roughly 10,000 vehicles per day	0,03	≈ 0	≈ 0	≈ 0	≈ 0 optimal cond.
Tunnel mouth, ceiling camera Camera height: 4.4m Camera: 1/2", 12mm Lighting variations Slight image noise at night Roughly 40,000 vehicles per day	0,86	0,17	≈ 0	0,14	0,42 weather and slow trucks
Internal, wall mounted cameras Camera height: 4.3m (appx.) Camera: FAC838 (1/2", 16mm) Strong image noise due to poor lighting Roughly 10,000 vehicles per day	0,11	0,07	≈ 0	0,23	Not worth while to evaluate

5. SUMMARY

Based on fire safety concepts, four different types of risk reduction measures should be taken to improve safety in tunnels:

- Construction measures
- Technical measures
- Organizational measures
- Traffic related measures

SiADS targets improving the technical and organizational measures.

SiADS significantly improves technical measures by allowing lane specific, uninterrupted and segmented event detection over the entire length of the tunnel as a complement to heat sensors and fire alarm system.

The organizational measures are improved as the reduced detection times allows a better reaction time. Detecting events that precede a fire allows operators to take organizational measures at an earlier stage, which can help save the lives of primary victims and avoid endangering potential secondary victims altogether.

The visualization of the detection events by the target system in the control center allows an improved selection of appropriate and effective measures.

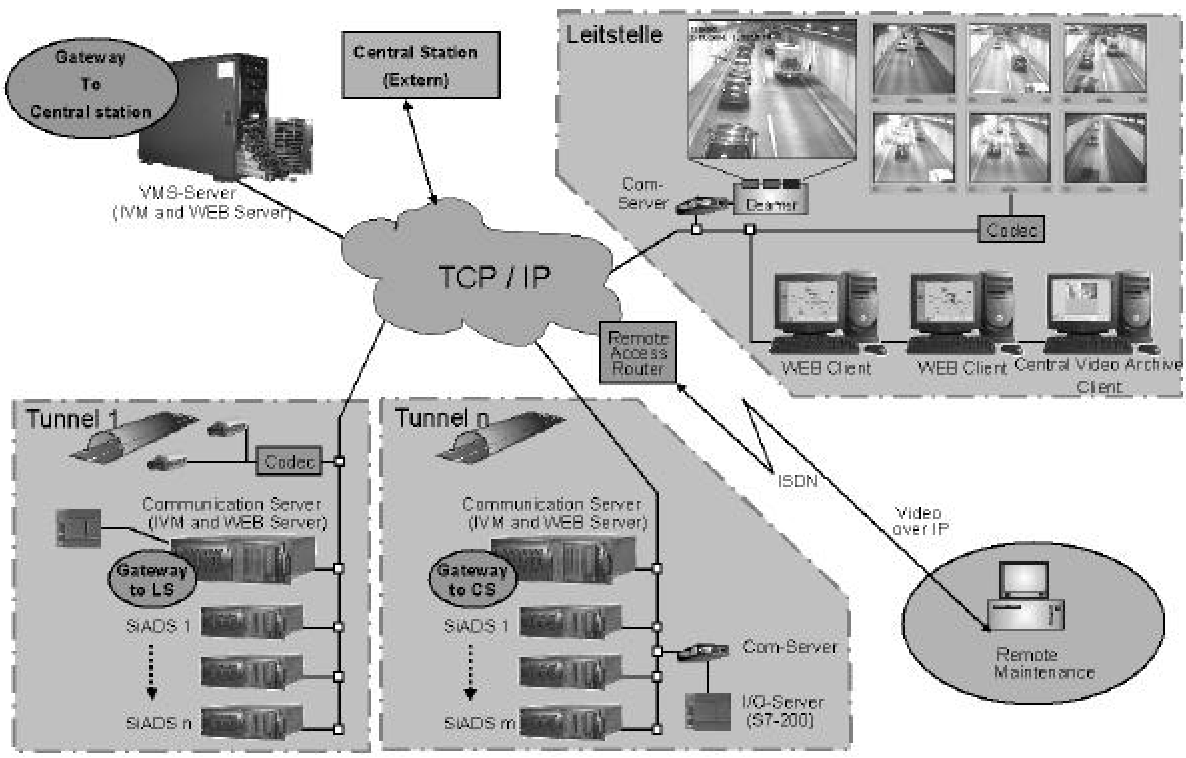

Figure 8: Typical System

FIBRE OPTIC LINEAR HEAT DETECTION APPLIED TO TUNNELS

Chris Conway – Sensa.

INTRODUCTION

This paper describes fiber optic linear heat detection technology and its advantages as an intelligent temperature profiling system for tunnels. Emphasis is placed on the ability of such systems to produce early and reliable alarm annunciations combined with maximum false alarm rejection. Reference is made to currently installed systems as well as fire test data, made available from full scale fire tests carried out in the Benelux tunnel, on behalf of the Dutch Ministry of Transport in Rotterdam (Nov 2001)[i,ii].

The DTS system is integrated into tunnel safety management systems and examples of current system design topologies are discussed. The temperature information is typically used to control the ventilation in the tunnel under normal operating conditions and also during emergency periods.

There is the basic assumption that that any automatic fire detection system should work to provide early and reliable detection of fires. The balance between early detection and maximum rejection of false alarms has most certainly been the focus for tunnel operators and equipment suppliers alike.

1. FIBRE OPTIC LINEAR HEAT DETECTION TECHNOLOGY

Generically this technology has been referred to as Fibre Optic Distributed Temperature Sensor Systems, or DTS Systems for short. It shall be referred to as such hereafter, within this paper. The DTS System comprises two main components:-

1. The Sensor Control Unit
2. The Sensor Cable

Sensor Control Units

Optical fibre based distributed temperature sensing uses a combination of technologies which allows one to produce temperature profiles using a fibre optic cable as a temperature transducer. The optical fibre within the Sensor Cable is therefore analogous to a continuous "addressable" thermocouple up to several kilometres in length. The associated control equipment (Sensor Control Unit) can effectively quantify the temperature at any point along the path of the optical fibre. The Sensor Control Unit can determine temperature and distance data points along the length of the fibre.

The temperature information combined with position data enables the DTS System to produce a real time graph on a monitor, as shown in **Figure 1**. This profile is taken from a utility tunnel carrying high voltage power cables, with the x-axis is distance in meters, y-axis is temperature in centigrade.

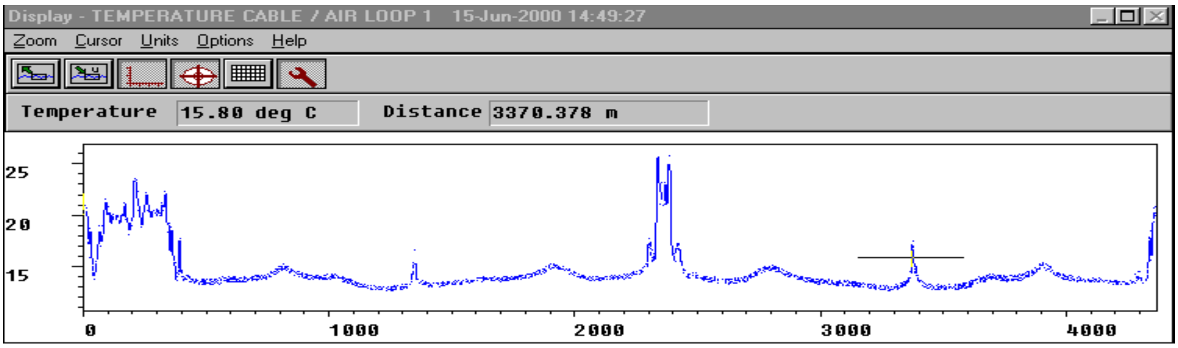

Figure 1 DTS Temperature Profile example

DTS Systems are able to produce complete temperature profile measurements typically, approximately every 10 seconds. Each measurement may contain temperature data for every 1m of fibre optic cable. The maximum length of continuous fibre connected to a Sensor Control Unit, the measurement time, the spatial, positional and temperature resolution tend to vary between system manufacturers. The technology is therefore producing large quantities of data, which allow the control systems to make more effective asset monitoring and alarm decisions. The Sensor Control Unit is programmed with special fire detection algorithms so that the unit can make a verified alarm decision. In doing so, the DTS System can operate as a "stand alone" detector. The DTS Systems can also share the calculated temperature and distance data with other third party systems e.g. SCADA control systems. This data can then in turn be used to influence other decisions made by external systems.

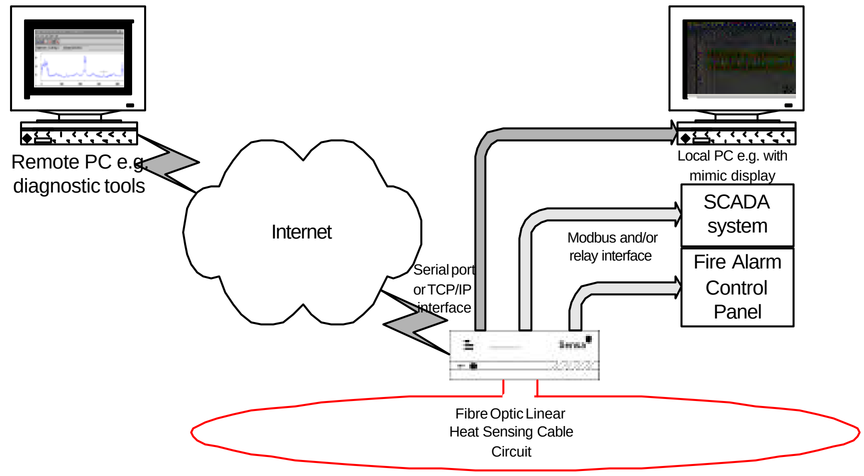

Figure 2 DTS system architecture

A DTS System normally includes a number of different interface options as standard. Alarms decisions may be communicated to the main Fire Alarm Control Panel by monitored relay contacts. This low level interface often provides a very secure alarm communication path. Alternatively, the DTS System may communicate alarms and real time temperature and distance data via a secure Modbus communications path. Modbus is a well established industrial communications protocol and can offer interconnection over RS232 or TCP/IP. Fire Alarm Control Panels (and networks) often have a proprietary graphics command and control workstation which provides a single Graphical User Interface (GUI) to manage the entire fire detection system. There are a large number of accepted gateway solutions available to ensure effective data communication between DTS Systems and Fire Alarm Control Panels/Networks.

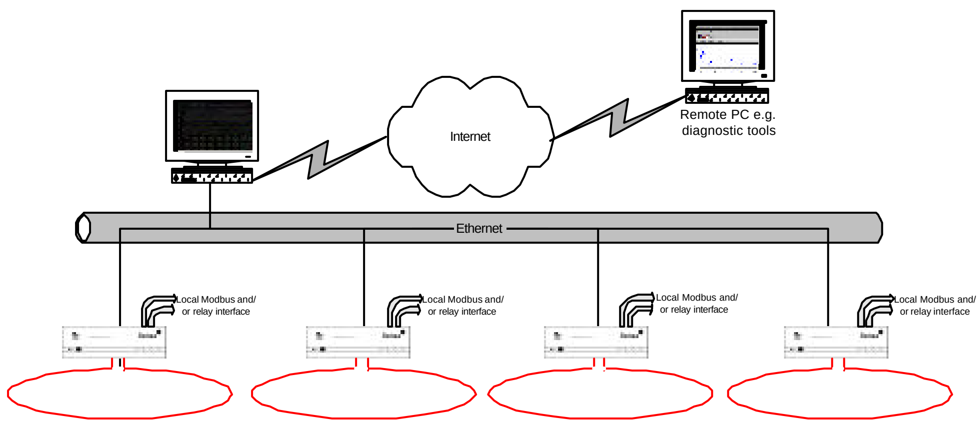

Figure 3 DTS network system architecture

DTS Systems have TCP/IP connectivity and so it is possible to provide Ethernet based network solutions for larger system design requirements. A number of network topologies are available and for systems requiring the highest integrity, redundant topologies are available. A central workstation typically includes a “soft mimic” representing the entire system configuration. This type of package typically includes a programmable site graphic, alarm display and alarm management system. Internet connectivity is also used to provide remote monitoring at a clients site, or indeed to provide remote diagnostic and system maintenance checks from a remote location.

Sensor Cable Temperature Range

The temperature range of optical fibres is a function of the fibre coating and the outer jacket material. Standard acrylate coated fibres can operate between -40ºC to +90ºC continuously and up to +150º for short periods e.g. 48 hours. A wider temperature range can be achieved (-185ºC to +400ºC) using a polyimide coating but this is not considered necessary for normal Fire Detection applications.

Outer Jacket Materials and Installation

The two jacket materials normally utilised are thermoplastic low smoke zero halogen and un-coated metal tubing (e.g. stainless steel 316) for harsh environment applications. In tunnels, the sensing cable will be subject to chemical attack and mechanical damage and therefore the un-coated stainless steel metal tubing is normally recommended. This produces a robust sensor with excellent thermal response characteristics and very long life.

2. MAJOR ADVANTAGES FOR TUNNEL DESIGNERS, OPERATORS AND RESCUE SERVICES[iii].

Immunity to EMI

The optical fibre uniquely acts as both sensing element and transmission medium and is immune to electro-magnetic interference. The quality of the measurement is therefore not affected by the application of the sensor cable close to high voltage power cables or leaky feeder cables. Using a Class 1 laser in the Sensor Control Unit, the system is also safe for use in occupied areas even if the sensor is broken. The sensor cable is also safe for use in hazardous areas.

Programmability

A DTS System is fully programmable. Physical fire zones can be programmed along the Sensor Cable and in each zone multiple fixed alarm thresholds may be specified according to design requirements. A combination of threshold temperature alarm and variable Rate of Rise alarm can be nominated for each fire zone and the number of iterative counts adjusted to increase or decrease system sensitivity. For each detection zone it is possible to configure pre-alarm levels to alert personnel to imminent alarm events. In practice, settings can be adjusted at site to correspond to prevailing conditions and recording tunnel temperatures during commissioning can be advantageous in determining appropriate thresholds.

Loop Design

The DTS System automatically detects and locates any break in the Sensor Cable. If the Sensor Cable is not connected to a Sensor Control unit at both ends, any severed section will not be addressable beyond the break.

Designing the DTS System so that the Sensor Cable forms a continuous loop from and to a Sensor Control Unit produces a high integrity system, which is recognised by some authorities as essential. If “Double Ended Processing” is employed any break in the fibre will not affect the ability of a Sensor Control Unit to continue poling both end sections of the

Sensor Cable. Loop designs using Double Ended Processing therefore ensures that DTS Systems remain fully operational throughout the incident period and beyond, for end sections of fibre not destroyed by fire or explosion.

Assessment of Fire Development

The DTS System operates by analysing the back scattered light and therefore in a fire condition all unaffected fibre will continue to give temperature and positional information providing one end is connected to the Sensor Control Unit. As the fire develops and moves along the tunnel, more of the Sensor Cable will be affected and this real time information can be presented either as a temperature/distance trace or as a graphic mimic display.
The location, affected area and direction of fire spread together with the prevailing temperature conditions elsewhere within the tunnel can therefore be viewed at a safe location on the appropriate user interface. Rescue services will find this level of information extremely valuable, particularly if combined with CCTV.

Dual Function Facilities

Another advantage of a DTS System is the ability to prescribe and identify either peak or average temperatures within a zone. Fire detection applications are normally based on identifying peak temperatures and therefore the average temperature function can be used for other applications such as general tunnel condition monitoring. This is particularly useful in underground rail networks, which use push/pull ventilation based on motion of a train. In times of congestion or power failure, tube trains can remain stationary in a tunnel for considerable periods. Heat given off from the train's condensers can raise the stagnant air temperature above acceptable limits and require forced ventilation to be activated. However an increase in tunnel temperature may also be due to a fire condition and in these circumstances it would be dangerous to automatically switch on the ventilation fans. The DTS System can differentiate between the two conditions by setting up parallel zones to search for peak and average temperatures. The ventilation fans can be switched on and off between limits without concern that the temperature rise has been caused by a fire condition.

3. DESIGN STANDARDS AND SITE TRIAL DATA

Example Recommendation

It is currently widely accepted that linear heat detection technology has a significant role to play in the protection of tunnels. By way of example, RABT (Richtlinien Ausstattung und den Betrieb von Straßen Tunneln) provides a clear indication of the basic requirements of automatic fire detection systems within tunnels.

An English translation of the relevant section of the standard is given is the inset Table1 below. The recommendation represents a not uncommon minimum expectation of automatic fire detection system performance. A fire of 5 MW approximates to a burning passenger car.

Table 1 RABT 2001, rev. 6, Section 2.5.3: Fire detection and alarm systems

1. RABT 2001, REV. 6, SECTION 2.5.3: FIRE DETECTION AND FIRE ALARM SYSTEMS

2.5.3 Fire Detection and Fire Alarm Systems

The fire detection and fire alarm system should be connected without using a main alarm routing equipment through the management system to the tunnel observation.

2.5.3.1 Manual Fire Detection Equipment

Manual fire detection equipment in tunnels with a length of ≥ 400 m should be a manual call point according to DIN 5411 and placed at each emergency call station.

2.5.3.2 Automatic Fire Detection Equipment

In tunnels with a length of ≥ 400 m and in tunnels with a mechanical ventilation system automatic fire detection equipment should be used.

Automatic fire detectors in tunnels should be able to detect a fire with a fire load of 5 MW (that means a 20 litre gasoline fire on a 4 m^2 surface) and longitudinal air speeds with up to 6 m/s within one minute after fire ignition and provide a localisation within 50 m.

There should be installed line type heat detectors, which respond on a rate of rise of temperature as well as on a fixed temperature. The sensor has to be fixed on the tunnel-ceiling above the clear space. Line type heat sensors should be subdivided into several sections. If one section is damaged, all other sections must stay in operation.

Opacity meters may be used for fire detection (pre alarm). (Distances see Section 2.3.6)

The use of temperature cameras or suitable video devices instead of fire detectors can be permitted, if the same requirements are fulfilled.
Such systems should be equipped with an image detection, which allows a judgement of the situation (digital video analysis).

Automatic fire alarm systems should also be installed in operating rooms with equipment worth to be protected, e.g. electrical devices.

At the entrance of the premises or at other suitable places (e.g. portal) fire detection panels should be installed in order to display

Some may argue that the automatic fire detection systems should be able to detect such an incident at a relatively earlier stage. It is also worth noting above that other incident detection systems, e.g. opacity meters and CCTV systems, can be used to assist in producing early “pre-alarm” warnings to imminent alarm incidents. DTS Systems can provide the flexibility, quality of measurement and reliability that enables early incident detection.

Example Product Standard

Reliability can be defined not only in terms of system availability but also by the number of false alarms produced by the system. British Standards definition for false alarms[iv] as applied to fire systems indicates that a false alarm is a fire signal resulting from a cause(s) other than fire.
A false alarm event is further categorised into one of four classes:-

1. Unwanted alarms from a fire-like phenomenon or environmental influence, accidental damage, inappropriate human action.
2. Equipment false alarms: the alarm is raised by a fault in the system,
3. Malicious false alarms;
4. False alarms with good intent

As part of the design process for any fire system, the system designer must design out the possibility of false alarms, especially with regard to classes 1 and 2, as far as reasonably possible. Classes 3 and 4 are often out the system designer’s control.
Likewise, insurers, tunnel operators, owners and the authorities normally require some third party verification of the manufacturers’ stated level of functionality and reliability of

proposed equipment. This is achieved to a large extent by the test and certification schemes adopted throughout Europe and the rest of the world[v]. This practice has proved successful over the last number of decades and has prompted the further development of new standards and refinement of established standards. The approval from the third party provides assurance that product and services conform to a known and “accepted” standard.
Many of the product standards for fire detection devices can trace a history back through the decades. The current European product standard for fire detection devices is the CEN standard BS EN54:2001. EN54 part 5 is the product standard for point heat detectors and can trace its origins back to BS3116-1:1970. The purpose of minimum response times
Referring to Annex C of EN54 part 5 one can see that the lower limit of response time is an established parameter and is included to “minimise the incidence of false alarms due to changes in air temperature which occur under non-fire conditions”.

Table 2 Response time limits for Class A1 heat detectors

4. EN54 PART 5 5. CLAUSE 5.4 AND 5.1.5	Response Lower limit of response time (mins:secs)	Time Upper limit of response time (mins:secs)
ROR 1°C/min	**29:00**	**40:20**
ROR 3°C/min	**7:13**	**13:40**
ROR 5°C/min	**4:09**	**8:20**
ROR 10°C/min	**1:00**	**4:20**
ROR 20°C/min	**0:30**	**2:20**
ROR 30°C/min	**0:20**	**1:40**

The above standard also considers detector behaviour when the ambient temperature is a low as 5°C**.** Devices compliant with this clause 6.2, and the other relevant parts of the standard are defined as class A1R devices. There are DTS systems available that are approved by LPCB as Class A1R detectors.

Example Site Trial Data

During fire tests in the Benelux Tunnel in Rotterdam (Nov 2001), a number of full scale tests were completed with linear fire detection systems. One of the fire detection systems was a DTS System. The fire size, the place of the fire according to the position of the detectors and the longitudinal ventilation speed were varied. The aim of the tests was to determine the time between ignition of the fire and fire detection and to determine the location of the fire accurately.

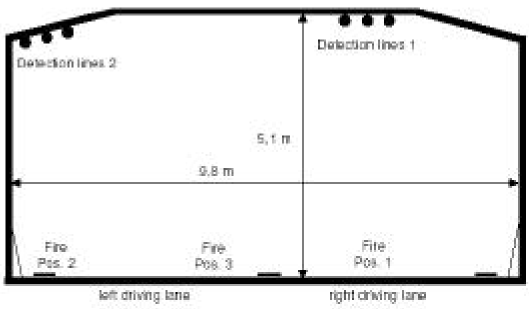

Figure 4 Position of the detection cable and fire location in the test tunnel

The tests began with an initial false alarm test where the control systems to be tested had to differentiate between a 0.5m² pool fire and a 1.1m² pool fire by producing no alarm and producing an alarm condition respectively. Regardless of the detection algorithm employed, one would expect the false alarm criteria of test OC & OD to influence the desired results (*) of the following set of tests, from OE to 4.
A complete set of data from the tests was stored so that the data could be used for retrospective tests. The measurement time for the DTS System under test produced a new tunnel profile every 7.5 seconds, with temperature values plotted for every 1metre of sensing cable on the circuit. One of the tests carried out, was to replay the logged test data using an algorithm, primarily focusing on the response time requirements of EN54 part 5, but specially adapted for tunnels. The results of such a test are indicated in Table 1 column (**).

Table 3 Overview of conducted tests

Test	Fire Size	Position	Wind	Purpose(*)	Tunnel/EN54-5 Algorithm(**)	Location of fire alarm from fire source
OC	**6L pool 0.5m²**	Pos.1	0 m/s	False Alarm Test	Not relevant, alarm in 24 s	0.5 m
OD	**6L pool 0.5m²**	Pos.2	0 m/s	False Alarm Test	Not relevant, alarm in 24 s	0.5 m
OE	**12L pool**	Pos.1	0 m/s	Alarm Required	Alarm in 22 s	0.5 m
OF	**12L pool**	Pos.1	3 m/s	Alarm Required	Alarm in 59 s	2 m
OG	**12L pool**	Pos.1	5 m/s	Alarm Required	Pre-Alarm in 60 s	6 m
OH	**12L pool**	Pos.3	3 m/s	Alarm Required	Alarm in 66 s	4 m
OI	**12L pool**	Pos.1	0 m/s	Alarm Required	Alarm in 23 s	0.5 m
OJ	**Truck Exhaust**	Pos.1	0 m/s	False Alarm Test	No alarms	-
1	**4MW pool**	Pos.1	0 m/s	Alarm Required	Alarm in 22 s	0.5 m
4	**15 MW pool**	Pos.1	2 m/s	Alarm Required	Alarm in 20 s	0.5 m

The most significant factor in achieving the response times indicated in Table 3 is the setting of the rate-of-rise function in the detection algorithm. Predominantly, the alarms are achieved using a rate-of-rise function, rather than temperatures reaching a fixed (maximum temperature) predetermined value. In order to determine alarms in a rapid manner it is imperative that the rate-of-rise function is able to make relatively rapid measurements and so determine the effective temperature gradient experienced at the ceiling, or wherever the sensor cable is located. The nature of the DTS System is such that the sensing cable is a continuous sensor and therefore has complete profile for the tunnel for every meter of sensing cable. The detailed temperature and position data generated by the DTS System permits earlier and more reliable alarm decisions. The air velocity in the tunnel, the tunnel dimensions, location of the fire source as well as the detection cable within the tunnel can also have a significant effect on the length of time it takes for a system to produce an alarm.

Discussion

The reasons for selecting the three examples above are such that each example illustrates a separate point view regarding fire risk and acceptable automatic detection methods to help minimise that risk. The concept of false alarm rejection is inherent to the automatic fire detection products as they are applied to the risk area. So, not only is there the possibility of false alarm from the equipment itself, there is also the possibility of false alarm from the external environment e.g. the tunnel in which it is applied. EN54 part 5 not only defines acceptable response times for heat detectors (for buildings), but it is also the purpose of the standard to help identify and quantify a device's susceptibility to false alarms. For devices that rely heavily upon software algorithms for generating alarms, a detectors compatibility with EN54 part 2 (Control and Indicating Equipment) may also be appropriate when reviewing a device's software integrity. EN54 is a fire products standard, which has been defined for fire products as they are used in buildings. Although the standard does not specifically currently address some of the issues raised by application of detection products in the tunnel environment, the standard currently serves as an effective benchmark for detection systems. As an example one could reason that a detector which meets the requirements of an A1R detector, could meet with the recommendation indicated in the RABT document. At this time, a CEN working group, is developing a new standard for linear heat detectors – EN54 Part 22. This standard plans to develop new test criteria to establish effective benchmark tests for application of line type heat detectors in a tunnels environment, as well as for the current buildings environment.

6. CASE STUDY – BRITOMART QUEEN STREET STATION, AUCKLAND NEW ZEALAND

Britomart's underground railway station has three platforms and five rail lines, which can currently handle up to 40 trains and as many as 17,000 passengers an hour. The station was designed with the future very much mind as there is capacity to extend beyond that.

A DTS System is installed throughout the platform areas and within the tunnel section approaching the station. The DTS System is primarily concerned with the identification of major train fires. A secondary function of the DTS System is to provide the SCADA system with temperature and position data, to provide effective ventilation control during normal system operation. The fibre optic sensor cables are run in the ceiling space above the tracks in both the station box and tunnel areas and provide digital feedback of temperature in each of 32 zones of the platforms and tunnel.

Zone temperatures are monitored by the DTS System on a continuous basis. If the temperature in any of the 32 zones rises above pre-determined levels, the Fire Control Panel will initiate deployment of foam in the corresponding zone(s). The system is also programmed to provide staged alarms (pre-alarm and alarm levels) so that early warning of an impending event can be altered. The actual operating alarm and pre-alarm temperatures were adjusted following initial trials. When the building and tunnel were originally designed an estimate was made of the ambient temperatures within these areas. The predicted ambient temperatures and profiles within the area fluctuated depending upon whether electric or diesel rolling stock were present. Seasonal temperature changes also effected ambient temperatures within the area. The operator wanted the flexibility offered by the DTS System to adjust the alarm levels after the sensor cable was installed and after the trains were running.

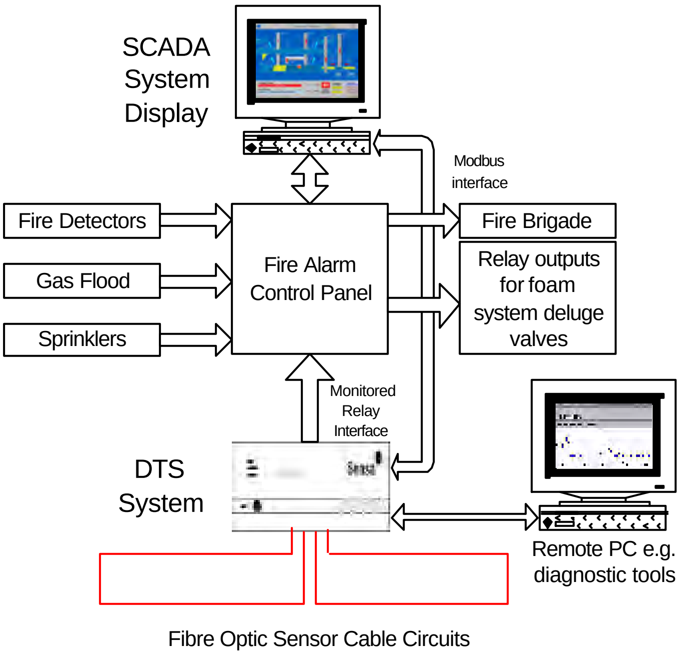

Figure 5 Britomart Fire System Block Diagram

Please refer to Figure 5. The primary alarm path is achieved through a monitored relay interface to the main fire alarm control panel. A more sophisticated level of data is concurrently available from the Modbus port and this data is gather by the tunnel SCADA system and integrated into the main Safety Management System.

By using an additional RS232 communications port from the Sensor control Unit, dedicated PC is also used to display a mimic of the site and may include access to view temperature traces and other important system diagnostic and facilitate remote maintenance.

All three forms of output can operate concurrently, which results in a flexible system design.

One of the main the responsibilities of the SCADA System is control of the implementation and coordination of the station Emergency Response Scenarios. The system components which may be called to respond in the implementation of an Emergency Scenario are as follows:

- Ventilation Systems
- Escalators
- Passenger Information Displays
- Evacuation Announcements
- Fire Systems

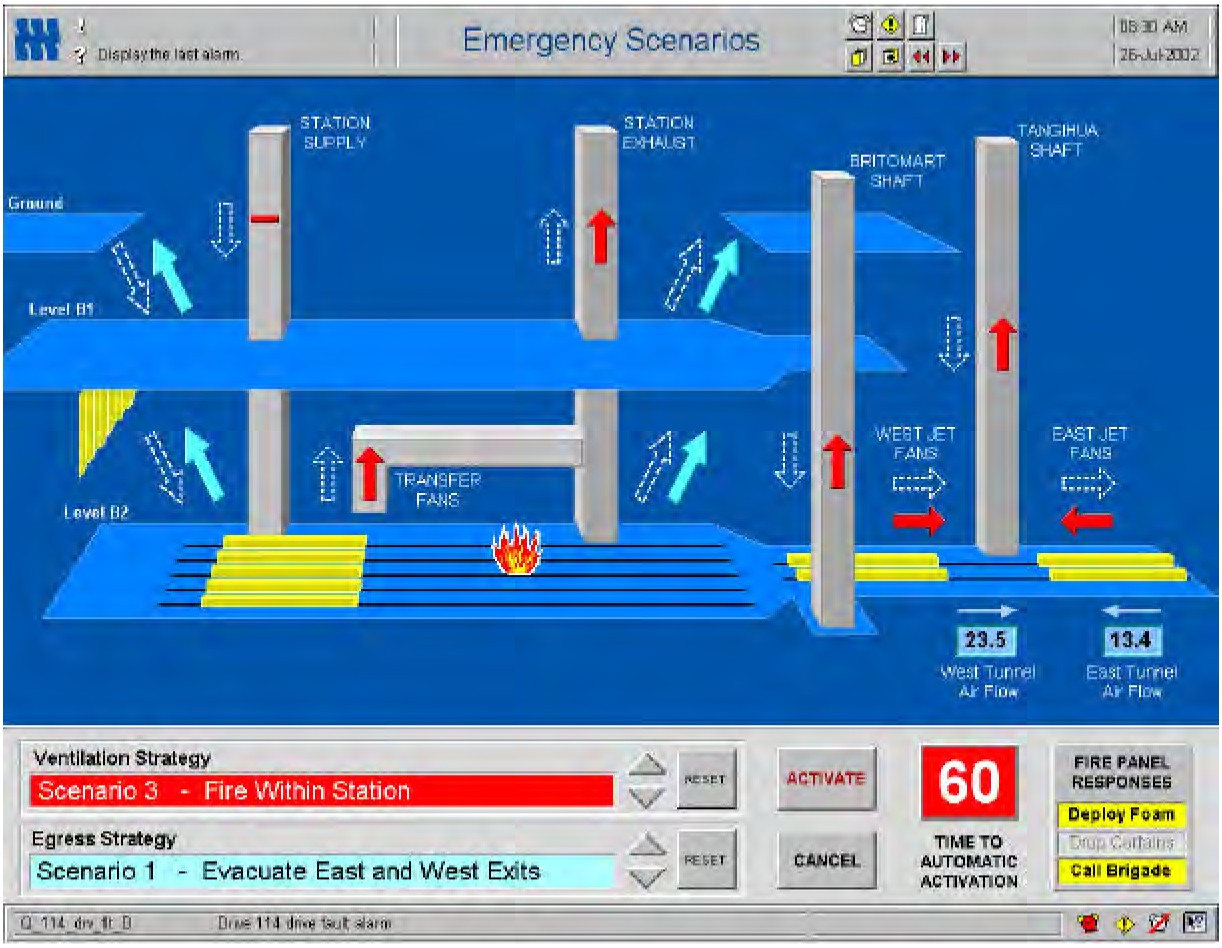

Figure 6 Emergency Response Scenario SCADA Screen

Foam Deployment System

The Foam Deployment System is designed to work in coordination with the DTS System. The Foam Deployment System is comprised of 32 Foam Deluge Valves installed over the 32 zones of the DTS and water / foam concentrate system to supply low level foam discharge nozzles at a pressure level to ensure adequate aeration of the foam concentrate / water mix .

Manual activation of Foam Deluge Zones is provided via the SCADA Emergency Touch Screen and via each SCADA Workstation given appropriate User Access rights. The Foam deluge system incorporates a standard 60 second delay, in order to protect against false alarms and also to ensure that the operator has time to acknowledge the alarm event. Alarm verification is achieved by automatically switching to CCTV and viewing the corresponding zone.

The SCADA system is interfaced to the DTS System by a dedicated Modbus communications link. This communications link provides the SCADA system with analog temperature feedback for each of the 32 zones in the platform and tunnel areas.

The SCADA system has a dedicated DTS and Foam Control Screen to display the current temperature in each of the zones and foam deluge system status. This screen presents temperature feedback in a numeric format, but also show a colour representation of the temperature (eg gradation from yellow (cool) to red (hot)). This provides the operator with some visual feedback as to the temperature map for the DTS monitored areas.

7. CONCLUSIONS

DTS System solutions are developing further in terms of measurement capability and detection algorithms employed. System architectures are also more flexible than before, with respect to the integrity of the sensor cable connection and well as the networking options available.

DTS Systems are LPCB approved as class A1R heat detection devices in accordance with EN54 parts 2 and part 5.

There are many standards in existence which provide guidance on how automatic fire detection systems should behave with respect to alarm response times and also with respect to false alarms. These standards continue to be referred to within fire system design, in buildings and in tunnels. There are relatively few standards available which are particularly well suited to the special hazard environment of tunnels. Steps are currently being taken to address this particular application area.

DTS systems are proven to be reliable components in fire detection systems. They offer critical time, temperature and position data to facilitate more effective alarm decisions. DTS Systems are implemented in an ever increasing range of Special Hazard applications.

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Acknowledgements:-

VdS Schadenverhtung GmbH, Cologne, Germany, Contact - Martin Hessels (for information regarding Table 1

Downer RML, Australia Head Office, Level 7, Compaq House, 76 Berry Street, Sydney NSW 2060 Australia, Contact Rod Harle (for information regarding the Britomart Case Study).

NEW APPROACHES IN TRAFFIC SURVEILLANCE USING VIDEO DETECTION

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ABSTRACT

ArtiBrain has installed numerous incident detection systems in various tunnels across central Europe. Because of their complexity, modern detection systems present a new challenge with regard to their integration within an existing structure. So it is enormously important to make a careful assessment of the surveillance system during the planning and implementation process. Furthermore, new developments offer the opportunity to move ahead in tunnel security by upgrading to new technology.

Key words: tunnels, video detection, digital storage, traffic surveillance, safety, event related

1. INTRODUCTION

Two years ago ArtiBrain presented its newest product for tunnel video surveillance. In cooperation with the Joanneum Research Institute and with crucial support from important Austrian industry, ABT2000 was designed as a comprehensive solution in video surveillance, storage and detection. The aim of the ATB2000 was to provide security for the work on and in the tunnel and to create the most modern, innovative product for this task.

ABT2000's proximity to market conditions and its good design have brought success against competition in several projects. In the meantime the small Austrian company has carried out an impressive list of reference projects. After these early achievements it is time to summarize the experiences and to think about new approaches and possibilities in digital video surveillance.

Tunnel	Cameras	Length [km]
Semmering (A)	120	14
Gräbern (A)	41	4.4
Munt la Schera (CH)	30	3.3
Heidelberg (D)	14	0.9
Amberg (A)	48	7.6
Lermoos (A)	26	3.1
Losenstein (A)	6	0.6

Figure 1: ABT2000 system schematics

1.1. Company profile

ArtiBrain, a research and development company based in Austria, sees its main focus in industrial image recognition and in the development of digital storage systems. In addition, ArtiBrain has proved itself as an expert in the use of neural networks.

Through the strengthening of its own development group and close cooperation with institutes for basic research, such as Joanneum Research in Graz, ArtiBrain was able to assemble excellent experience in the field of video detection for streets and tunnels.

1.2. Short product overview on ABT2000

During the design phase of the structure of ABT2000, ArtiBrain paid a lot of attention to the concept of a modular structure in order to be able to offer a broad, but still affordable, video system. The modular structure gives the opportunity to equip small and micro tunnels efficiently, as well as large installations with several hundred video cameras.

One further important aspect was the concept of an all-in-one solution for the coverage of the entire video subject. This is the reason why ABT2000 contains – apart from detection modules – modules for storage and streaming.

1.2.1 Streaming

ABT2000 offers the possibility to spread video signals by using a codec as a digital data stream via IP networks.

Through the opportunity to use the pre-existing engineering of analogue cameras and monitors, existing installations can easily be upgraded by being refitted with the new technology.

1.2.2 Detection

ABT2000 offers a comprehensive solution of video detection on a high level. The development goal was always to produce a high performance and a minimization of the frequency of false alarms.

The system offers the calculation of all detections in real time for each frame. (25x per second). Through this the system is able to detect events within a few milliseconds.

2 lanes per camera
Classification (cars, trucks)
Counting (>98%)
Distance measurement (<1/10s)
Speed measurement (<2.12%)
Traffic analysis
Slow traffic
Stopped vehicle
Traffic jam
Wrong lane driver
Breakdown bay
Pedestrians
Visibility measurement
Smoke detection
Hazardous goods transport

Figure 2: Overview of possible incident detection modules

1.2.3 Storage

The digital video storage is designed to record permanently 50 frames per second per camera. Because of the modular storing concept there is, in fact, no expansion boundary in the storage size. Through the linkage of the information of the incident detection, the storing concept can be extended from a pure ring storage to an incident storage. Therefore it is possible to use the available storage capacity efficiently by limiting the storing to only relevant incidents.

The connection with the video streaming makes it further possible to watch stored archive pictures directly on the analogue surveillance monitors. This facility can be extended to allow switching between live and playback modes because the pictures are stored in the ring buffer. The graphical user interface (GUI) with full VCR functionality (including frame-by-frame stepping) allows cutting, deleting, printing and exporting of videos.

1.2.4 Integration

To make the handling of the video installation as simple as possible without burdening the monitoring staff more than necessary, ABT2000 can be integrated seamlessly into any desired process control system. This happens through the usage of standardized industry interfaces that can be extended by modules.

Through this the operator is able to control all functionalities directly from his usual visual GUI of the process control system.

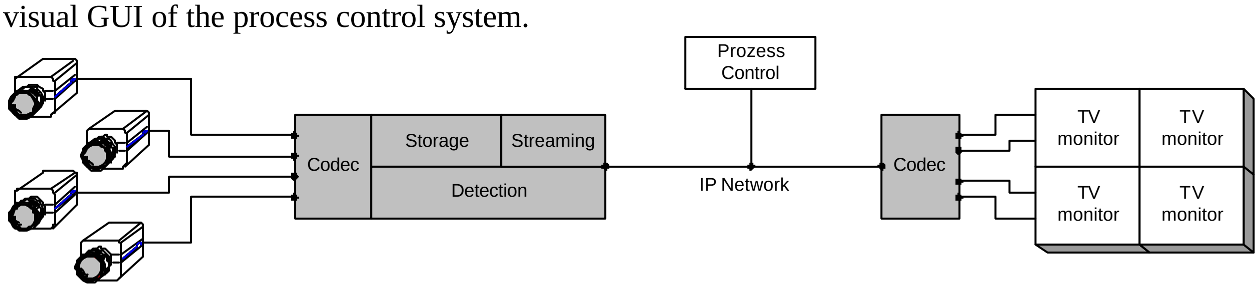

Figure 3: ABT2000 system schematics

2. SUMMARY OF THE FIELD EXPERIENCE

The complexity of modern video detection systems presents a new challenge in the integration of tunnel security. Not only black-boxes are installed. New systems offer a number of new possibilities:

- Smooth integration of new technology into existing systems
- Successfully managing complex detection tasks
- The union of several systems into one platform

For the usage of such systems it is enormously important to focus more on the planning and the implementation phase. This is the only way for the video surveillance systems to achieve their full potential. Especially emphasized points:

- Planning and design
- Selection and maintenance of the cameras
- Integration process and its implementation
- Conditioning of the detection tasks

The complexity of video detection tasks increases constantly. Therefore, an increase can be expected in the work to implement and operate such systems. But the benefit which is provided by these systems is enormous. Additionally, they open up specific possibilities which were previously difficult or impossible to realize - for instance, in the operation of large central control rooms.

The necessity for, and the importance of video detection is becoming greater and greater because of other factors. The two main factors are: the need to make the work easier for security personnel and the actual security of tunnel traffic, drivers and passengers.

Some of the most important advantages of modern systems are:

- Precise speed measurement by only one camera
- Precise distance measurement by only one camera
- Stable detection algorithms and fewer false alarms
- Fast detection time (only a few milliseconds) and therefore significant shortening of the reaction time
- Simple and quick integration into existing systems
- Synergy through the linkage of different modules. For instance, the knowledge of the positions of vehicles enables smoke detection even at road level
- High flexibility through the use of a software solution for the detection algorithms
- Open standardized interfaces guarantee communication with every process control system

2.1. Comparison Grid Scan versus object detection

Instead of using Grid Scan in video detection it has proved to be better to use complex object recognition.

In the case of Grid Scan, the video picture searches for a modifications in defined points/fields and compares them with the previous picture. Through the combination of such movement points to groups vehicles and objects can be pursued.

The advantages of this method are:

- Usage of simple algorithms
- Simple implementation
- Smaller computer capacity necessary
- Manageable options in the parameterisation

This procedure, however, comes to its limitations very fast, as far as detection accuracy and frequency of false alarms is concerned:

- Inaccurate relocation of the vehicles (no possibility to measure the speed)
- Overlapping vehicles cannot be separated
- Inaccurate measurement of the size of vehicles
- Difficult distinction between reflections, cones of light, lens flares, etc.

In the case of the object detection, a moving object is registered completely and it is identified by unmistakable characteristics. Afterwards these objects can be found with a very high accuracy. Through the knowledge of the precise size and position, as well as exact speed and distance, measurement between single objects is possible.

Combined with the capability of modern computer systems and an evaluation of all 25 pictures per second the movement of all objects can be pursued and examined very precisely. Reflections, lens-flares and similar disturbances can already be filtered out by means of the characteristics of the objects.

Figure 4: Live image taken from the camera

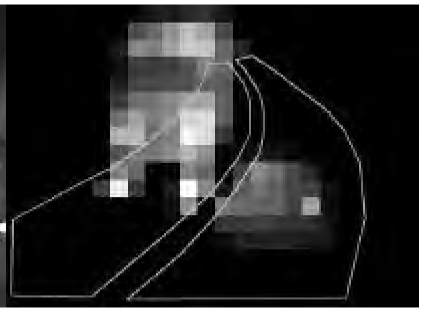

Figure 5: Movement detection by using Grid Scan

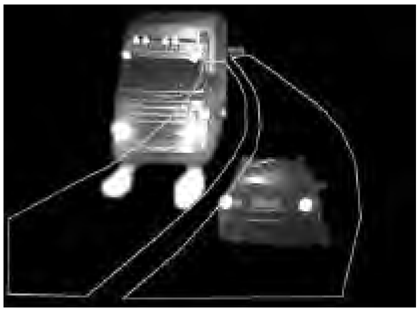

Figure 6: Separation and measurement by using object detection

3. CURRENT DEVELOPMENT AND FUTURE STEPS

3.1. Providing Information to the emergency task force

Especially in the case of emergency it is important that information is provided to the emergency services quickly and in a goal-oriented way. ArtiBrain is developing, in cooperation with the Austrian fire-brigade, a new tool for the head of operations - a graphic information system.

This system should provide current and pre-stored video pictures from the tunnel. Furthermore the task forces receive important additional information from the tunnel, which helps them to co-ordinate its action. (i.e. the number of cars involved in an accident or the present air flow conditions in the tunnel).

A special feature is, however, the connection to the information centre via a specific WLAN interface. This means that this ad-on gives the team the opportunity to have an exact picture of the situation of the accident before its arrival, so that the team can be provided with reinforcements as quick as possible.

3.2. Detection in the street

After the success of ABT2000 and the experience it has accumulated, ArtiBrain prepares for the next the logic step and moves with the video detection from the tunnel onto the street. Here you can find two difficult conditions for detection through a video camera: environmental conditions like snow, rain, sun etc. and a great number of zoom/pan cameras.

Presently ArtiBrain is trying to face these challenges in co-operation with the Joanneum Research Graz through several research projects.

Solution topics for problems which occur during outdoor operations:

- The occurring environmental situations are trained through databases. Specific background databases are responsible for different circumstances such as light and shadow.
- Through new detection algorithms, it is aimed to minimize the frequency of false alarms.
- The object recognition is extended to vehicle recognition on the basis of specific characteristics. These characteristics are also trained by databases and neuronal networks.
- Through self-learning methods it is tried to minimize the conditioning effort in new systems.

Through the use of dynamic cameras (zoom/pan cameras) the video system is constantly confronted by the problem of new situations. If a zoom/pan camera is used that can assume a number of predefined positions very precisely, detections can be configured for each of the positions (let us say - a number of virtual cameras for each physical camera).

The software activates the corresponding configuration as soon as such a position has been reached. While the camera is moving, detections are inactivated. In order to achieve this goal there is a need for close cooperation with manufacturers of exact repositioning cameras.

Video detection outside means new tasks for the detection systems:

- Automatic release of the breakdown lane of whole motorway sections in the case of strong traffic volume within a few minutes.
- Continuous controlling of the breakdown lane through the detection system.
- Cameras position themselves automatically to survey special incidents.
- Recognition of ‘wanted’ vehicles by evaluation of the licence plate.

3.3. New Video Codec for storing and streaming

Currently used video codecs provide good picture quality between 4 and 16 Mbit/s bandwidth. New, modern compression solutions offer the possibility to transport considerably more video data via even thinner networks. At present the development concentrates on three codecs.

3.3.1 MPEG4

MPEG4 provides fundamentally a strongly lossy compression This procedure is organised so that only changes between pictures are transmitted as data. In addition, moving information in the picture is evaluated in the form of mathematical vectors. A genuine change to video material is made by this procedure.

All MPEG procedures suffer by the fact that a single picture is only be represented by the surrounding of the preceding pictures. If an individual picture has been lost, the video stream may be disturbed for a long time.

3.3.2 JPEG2000

JPEG2000 is the successor of the JPEG standard. The designers decided to look at the overall environment in which images would be tasked in future and decided that a compression scheme that worked well in network environments was the most desirable. In comparison to MPEG4 in JPEG2000 each frame is coded individually. So there is no change in the video content itself. Additionally this standard may offer the possibility to store results given from the detection directly in the video.

In addition to the benefits of scalability, JPEG2000 delivers a better compression than JPEG. And, at more extreme compression ratios, JPEG2000 delivers significantly better quality. JPEG2000 is intended to be royalty free and is an international standard.

3.3.3 H.264

H.264 (aka MPEG-4 Part 10) offers a clear decrease in bandwidth compared to all previous codecs. Full picture PAL streams become possible with less than 300Kbit/s.

All current Codecs provide good quality pictures at very low bandwidths. However JPEG2000 and H.264 will be favoured clearly as future codecs. JPEG2000 on account of its simple handling and its good cost efficiency.
H.264 on account of its amazingly small bandwidth with outstanding picture qualities. MPEG4 on the other hand still suffers from the problem of missing standardization and has often been badly implemented.

MODERN AIR VELOCITY SENSORS IN TUNNELS

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ABSTRACT

The air velocity in tunnels is an important parameter for all tunnel management systems. The quality of a tunnel management is only as good as its sensors. Today the selection of a robust and reliable air velocity sensor is possible at reasonable costs.

There are several sensing methods that are actually used for measuring the air velocity in tunnels: Their advantages and disadvantages will be discussed. The focus will be on reliability, robustness, calibration, maintenance and the functionality in emergency cases. It will be shown that up-to-date signal processing techniques have a severe impact on the selection of the best sensor.

1. INTRODUCTION

A tunnel management system has to guarantee safe and sound conditions at a low cost. Road and railway-tunnels have to allow for the wellness of human beings. Under normal conditions a sufficient amount of fresh air needs to be supplied. The air supply will be generated in four ways:

1. Natural wind
2. Traffic
3. Passive Ventilation
4. Active Ventilation.

1)

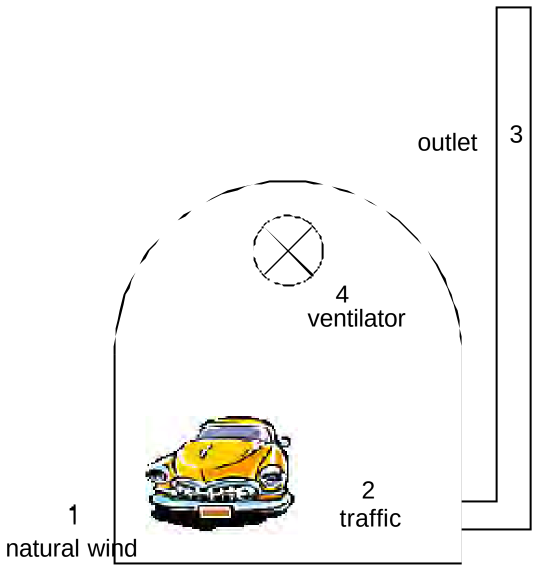


Fig. 1) A road tunnel and the different sources of the airflow

Increasing the amount of fresh air requires huge amounts of energy. Information about the different airflows allows for optimized ventilation schemes and can save a lot of costs.

The information about the different airflows allow to predict the pollution of the air in the tunnel and to generate a good value for the visibility and CO, without blowing lots of fresh air into the tunnel.

In tunnels that are divided into several ventilation sections the information on the different airflows can be used to prevent the airflows from crossing the section borders and to reduce the amount of polluted air, that is carried through the tunnel.

In case of fire the information about the airflows is important for the rescuing operations.

So, without doubt, the information about the airflows in a tunnel is a very important parameter for the tunnel management system.

2. AIRFLOW SENSORS

There currently are four different types of airflow sensors used in road tunnels:

1. Propellers
2. Heat transport sensors
3. Ultrasonic wave sensors
4. Pressure tubes

The sensors have to measure the airflow velocity and the bivalent direction of the airflow with respect to the tunnel-axis. Furthermore, they have to be reliable and robust enough for the severe tunnel conditions and – in emergency cases – they should keep functioning as long as possible.

2.1. Propellers

Propeller-type sensors have been used ever since, because the simplest ones (Fig.2a) need no electronics at all. The propeller drives a small AC-generator. Using a flag, whose position operates several mechanical switches (reed contacts) or a potentiometer measures the direction of the airflow. This sensor is also used for measuring the wind outside for meteorological purposes. It is not very good adapted to the tunnel conditions.

2a)

2b)

Fig. 2a) A propeller-type airflow sensor as also used for meteorological purposes
Fig. 2b) A different propeller-type sensor adapted for road-tunnel environments

The sensor shown in (Fig. 2b) is a propeller-type sensor as it has been installed in many tunnels in Switzerland (e.g. Gotthard, Seelisberg). The propeller is inside a tube and protected by grids at both ends of the tube. A flag is no longer needed, because the rotational direction of the propeller is detected and gives the direction of the airflow. This sensor uses some simple electronics. They were installed between 1970 and 1985 and are still in use. The main disadvantage of these sensors is the delicate moving parts that need maintenance every three years.

2.2. Heat-transport sensors

Heat-transport sensors consist of a heater and two temperature sensors, one upstream and one downstream. Without airflow the heater will cause an equal temperature rise in the two temperature sensors. With airflow one of the temperature sensors will get more heat as the other will. Comparing the temperatures the direction and the velocity of the airflow can be calculated. The heater and the sensors are built in a tube (Fig. 3).

3)

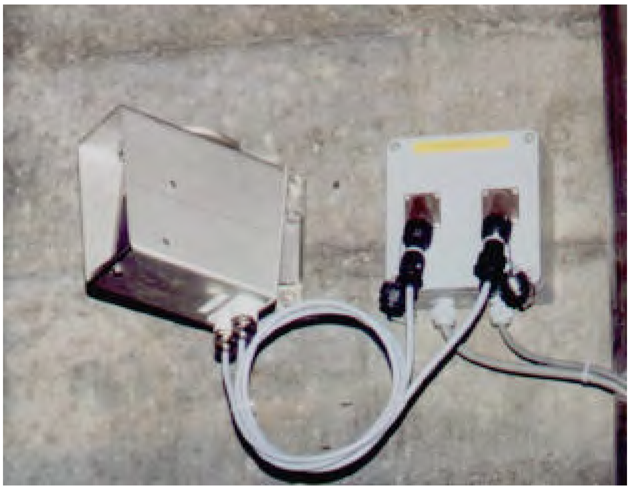
Fig. 3) A heat-transport sensor for use in road tunnels (.....,http:// wwwjes-et.at)

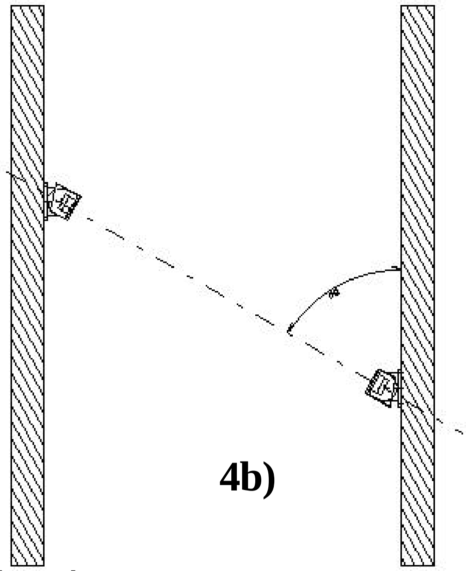
The heat-transfer method is very sensitive for contamination of the heater and the temperature sensors. The zero-point can be readjusted by closing the tube on both sides and compensating for the offset between the temperature sensors. However, the closing mechanism adds moving parts to a sensor that basically has no moving parts.

2.3. Ultrasonic-wave sensors

Ultrasonic-wave sensors use the dependency of the speed of sound on the velocity of the air. Sonic waves move faster along with the wind and slower against the wind. The speed of sound is about 300 m/s. In order to detect the airflow velocity, the speed of sound has to be measured very precise. More, the speed of sound depends strongly on temperature, barometric pressure and humidity. Making two measurements in opposite directions and calculating the differences in the measured speed of sound can eliminate all of these influences. The ultrasonic sender and receiver (Fig. 4a) are mounted at the tunnel walls and the ultrasonic waves travel across the road (Fig 4b). The angle between the ultrasonic wave and the airflow can be included in the calibration of the sensors.

4a)





4b)

Fig. 4a) An ultrasonic-wave sender and receiver unit for use in road tunnels
Fig. 4b) The positioning of the ultrasonic-wave units in the tunnel.

The ultrasonic-wave sensors basically have no moving parts. However, the membranes of the sender and the receiver have to make very small movements and are subject to contamination, especially to the sticky dirt. A protection by a fine grid is possible, but has to be cleaned or replaced regularly.

The ultrasonic-wave sensors rely on the highly sophisticated electronics, available today. The electronics have to be placed close to the sender and receiver, or the delicate signals from the receiver and the powerful signals for the sender ask for special cables. The ultrasonic wave sensors have to be calibrated after mounting, because the angle between the wind and the ultrasonic-wave and the distance between sender and receiver are important parameters for the calibration.

The ultrasonic wave has to be very powerful, since at higher velocities of the wind the waves do not travel along a straight line. They are bent away by the wind and middle of the wave front moves away from the detector, causing the need for a very wide wave front. If the number of lanes is increases the ultrasonic-wave power needs to be higher, too, and the wave fronts have to be wider. The danger increases that the ultrasonic wave cannot be detected anymore.

The ultrasonic-wave sensors have the advantage, that they measure a mean value of the wind across the tunnel. As the ultrasonic wave travels across the tunnel its speed is affected by the local speed of the air. A disadvantage is that an obstacle, e.g. a larger truck that crosses the ultrasonic wave path, may block the ultrasonic wave. This reduces the number of measurements, that can be made in case of a larger number of trucks is passing the tunnel. In case of a fire, where the traffic stops, no more airflow measurements will be available, if a larger truck stops just in front of the ultrasonic wave sensors.

2.4. Pressure tubes

Pressure tubes are a very well known method for measuring airflow. A special directional pressure tube also detects the direction of the airflow in a tunnel. The small pressure differences can be sensed by micropressure-sensors commonly available today. The pressure tube signal has to be linearized and corrected by using the density of the air (barometric pressure and ambient temperature). These signal conversions can easily be made by modern microprocessor electronics.

An advantage of the pressure tube is, that all electronics can be placed outside of road area, leaving only the stainless steel tube (Fig 5) and the temperature sensor in the tunnel. This makes this sensor very robust. If the pressure connections to the tube are metallic and a high temperature sensor is used (e.g. Pt100) the measurement might operate up to several hundred degrees C. So it would not be affected be a nearby fire.

5)

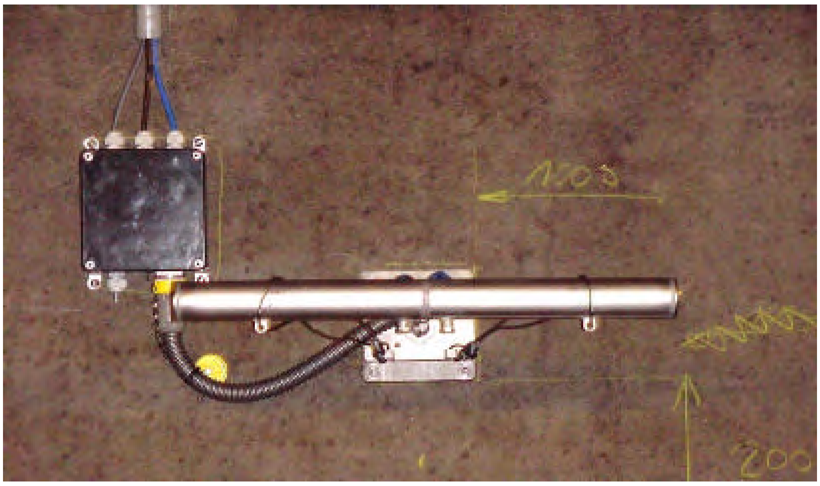


Fig. 5 The directional pressure tube for road tunnels.

In order to allow for a slow drift in the zero setting of the pressure sensor, the pressure sensor can be periodically zeroed (e.g. every 10 minutes). The pressure tube is disconnected from the pressure sensor and the actual zero value of the pressure is stored. Because of this the pressure tube airflow sensor has a very stable zero point.

The most remarkable feature of the pressure tube is its resistance against contamination. Having on each side large holes, a labyrinth and chamber for taking up any dirt or liquid makes it very suitable for use in road tunnels. In case needed, brushing can clean the outside. The dirt and liquid in the chamber can be removed by opening an outlet valve.

The pressure tube can be calibrated before installation and any accredited calibration laboratory can supply a calibration certificate, simplifying the installation and validation of the airflow measurement.

3. COMPARISON

Parameter for comparison	Propeller	Heat transport	Ultrasonic wave	Pressure tube
Flow range	++	++	+	+++
Zero point stability	+++	+	+	+++
Maximum tunnel width	+++	+++	+	+++
Mechanical moving parts	+	++	++	+++
Electronics outside road area	++	+	+	+++
Heat sensitivity	+	+	+	+++
Dirt and contamination sensitivity	+	+	+	+++
Ease of cleaning	+	+	+	+++
Factory calibration / certification	+++	++	+	+++
Line /Point measurement	P	P	L	P
Traffic independence	++	++	+	++
Cost	++	++	++	++
Robustness	+	++	+	+++

The comparison table shows that all airflow sensors considered can be used in a road tunnel. The pressure tube, however, is the one that has almost no drawbacks.

4. AIRFLOWS OUTSIDE THE ROAD AREA

The airflow in the road area is the most important airflow for the tunnel management. The information on airflows outside the road area is also very helpful.

Outside the road area the most important airflows are:

- The natural wind outside the tunnel
- The airflow in the air outlets of the tunnel.

For the natural wind outside the tunnel a standard meteorological wind sensor can be used. The special features - desired inside the tunnel - are not of interest here.

For the airflow at the outlets of the tunnel the same sensors as in the road area can be used. The sensors have to withstand excessive dirt in addition to rain, snow and ice that might enter the outlet from above. Even the robust pressure tube will have its problems here. But, with special modifications the rain can be prevented from entering the pressure tube. The tube can be designed to have a chamber that even can take up some water.

6)

Fig. 6 Modified pressure tube for the outlets of a tunnel

5. CONCLUSIONS

Several types of sensors are being used for airflow measurement in road tunnels. All the sensors considered here are suitable for the road tunnel. The pressure tube, however, is the one that has almost no drawbacks. It even can be modified to measure the airflow in the outlets of the tunnel, where excessive dirt is combined with rain, snow and ice.

The pressure tube is not a new way to measure airflow. Modern microprocessor technique can be used for linearization, compensation for barometric pressure and temperature and for eliminating the zero drift of the pressure sensor. These new signal processing techniques eliminate the original drawbacks. The construction of the tube can be optimized for the severe conditions in the road tunnel. In this way, the pressure tube becomes a very robust and reliable sensor at a reasonable cost.

PRACTICE[2]- TRAINING IN THE CONTROL ROOM BY UTILIZATION OF THE TECHNOLOGICAL FEATURES OF THE SCADA[1] SYSTEM

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ABSTRACT

Operating personnel in tunnel control rooms are supervisory staff and task forces. They monitor the smooth running of traffic and technical infrastructure. In case of emergency the tunnel operation relays on their cautiousness and their rapid and correct reaction. Thereby the staff receives support by means of technical equipment, however, they could not be replaced by technology. As a consequence, the continuous improvement of training is at least as important as the further development of technical installations.

Similar to a pilot of a passenger plane operators are instructed as far as the handling of their installations are concerned, and alarm plans direct them how to act in predefined critical situations. Different from the training of aircraft captains, the current training possibilities of control room staff precisely confine them to these options. However, experiences and complex situations are, for the most part, only dealt in theory with.

Today's tunnel control systems offer all important sub-components in order to facilitate practical training. One approach of how this training can be utilized through innovation shall be presented in this paper.

1. STATUS QUO

Nowadays the partly dynamic simulation of individual installations, e.g. tunnel ventilation, is already put into practice as primary technical training tool in the tunnel control room. It has the aim to learn how the system has basically to be operated, e.g., set values of ventilation, ventilation programs. Rarely installations are already connected to the simulation so that a simulated fire can, for instance, activate a simulated ventilation program. This procedure is an important factor with reference to the performance test of the entire plant. However, sequences do hardly correspond to the complexity which an operator is confronted with in reality. There are various pieces of information which have to be evaluated and related to each other:

- Plant status
- Continuously changing traffic situation
- Video images provide additional information
- Language communication: emergency call, etc.
- Acoustic signals (signal horn, …)
- Status of the control system (e.g. faults and breakdowns in situation of danger)
- etc.

These processes and techniques can financially acceptably be realised with the hitherto applied methods in a simulation that is fit for training. In order to arrange an experience-based training system, it is additionally necessary to analyse undergone (or constructed) experiences in a way that is easy to understand for people. Only so the respectively ideal reactions can be discovered and practised so that the right steps will be taken in case of emergency.

[1] SCADA = Supervisory Control And Data Acquisition

2. THE IDEAL TRAINING ENVIRONMENT

The ideal training environment is a prerequisite for best training. Thus, it is necessary to go beyond the present possibilities and to reasonably complement the available, applied methods, i.e. the application of a plant and the execution of standard alarm schedules. Hence, the operator is offered a training which is as practical as a flight simulator for the pilot. In order to fully accomplish this task each tunnel would require hardly affordable expenditures, as the entire plant would have to reproduce the real performance (i.e. even a video installation would have to "construct" visual images). Since this is neither efficient nor economical, an alternative method shall be suggested which comes close to the target value and only amounts to a fraction of the financial means required.
A practical training environment shall at least meet the following requirements:

- During the training sessions the entire control room has to offer the operator a real environment, similar to that of a flight simulator. Only in this way can real behaviour and situations under pressure be simulated.
- All pieces of information have to make up a correct and coherent context for the operator.
- The plant operator has to be able to develop training scenarios in an easy and practical way. They have to be adjustable according to sequences of events which have actually taken place in the tunnel. Only then training can be referred to as practical and experience-oriented. This, of course, requires a straightforward and realistic analysis of events.

For the acceptable setting of arising costs the following restrictions have to be taken into account:

- The training aims at the identification and correct initial reaction of the operator. As soon as a case of emergency is correctly identified and reacted to, it can be proceeded according to the standard-theory-procedure.

When a training session takes place, the trainer takes actively part in the background.

3. TECHNICAL REALISATION

The basic technical concept determines the following rough procedure:

1. The entirety of data and information which the operator has learned about in the control room will be stored digitally with real-time information and can be drawn upon as basis for simulation scenarios.
2. The entire control room can be set to the "simulation mode". As from this time the control room interacts with the simulation and training system.

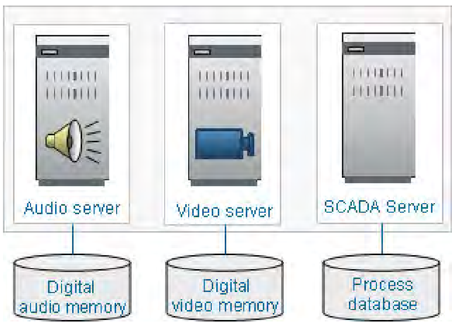

Figure 1: Available data sources

The training system can process conserved data and the entire control room displays sequences of the requested time frame. In this manner a straightforward analysis is possible.

4. The course of events, based on system history, can be adjusted and stored as training scenario.
5. When a training session takes place the trainer runs the scenario on a separate workstation. The operator watches this scenario in the control room (incl. video, visualisation, acoustics, etc.) and sets actions which are displayed at the trainer's workstation who can again dynamically intervene in the process. The correct reaction of certain installations (e.g. ventilation) will be taken over by the simulation as already known.
6. The training results incl. trainees' activities and trainer evaluation can be stored and printed for subsequent "inquest".

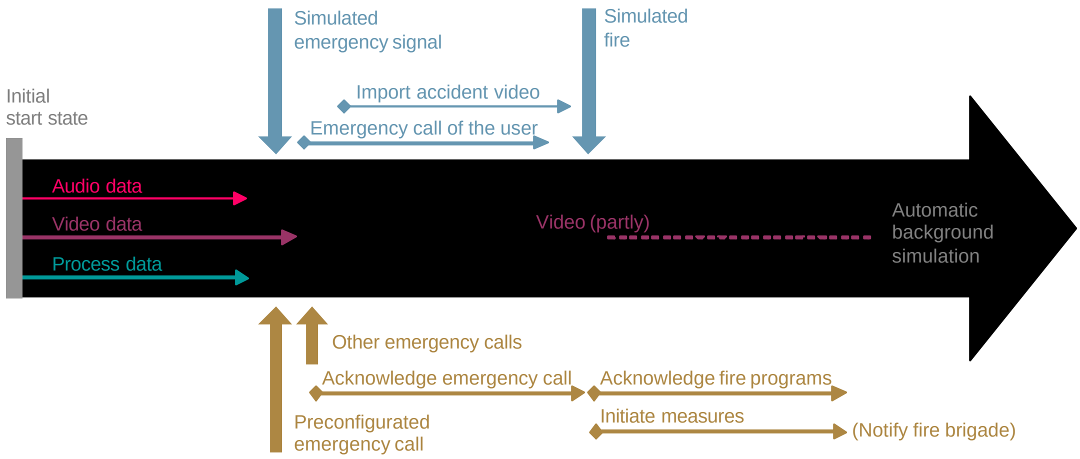

Figure 2: trainigsession

The example shows the temporal sequence of events of a training. All data (video, audio and process data) simulate the overall behaviour of the installation. The trainer systematically activates selective events of faults (emergency call, fire alarm ...) which cover normal operations as an emergency situation . The trainee has to set adequate activities (acknowledge emergency call and fire alarm).

When realising the project costs play a significant role. In order to achieve the goal of an affordable realisation, the existing technology has to serve as a solid basis. Thereby the respective storing mechanisms as data source are fundamental.

The realisation of the training simulator will be illustrated according to the following criteria:

- Analysis and conservation of real scenarios of the past

Generation of training procedures

- Holding training sessions
- Evaluation of training results

The result is a producer-independent, practicable and economical concept.

3.1. Analysis and generation of training scenarios

Real sequences of events are the basis of training scenarios that have to be analysed and processed accordingly.

Historized data in the installation form the basis:

Data description	Source
Process data and alarm messages	SCADA system
System status information of the process technology	SCADA system
Video tapes	Digital video memory
Language data (radio, emergency call, etc.)	Digital audio memory
Acoustic signals in the control room (signal horn, …)	SCADA system
Operating actions (commands, screen change, etc.)	SCADA system
Control room situation (large screen display, user, …)	SCADA system

Via a synchronic start and end time all courses of events of the respective sources can be retrieved and displayed. Effects and messages will directly be displayed in the control room which has been set to simulation operation (video displays on monitors, images and data on the workstations, etc.) Actions of the user will be filtered in the SCADA system and

separately displayed for the analysis (e.g. on a workstation) as well as

- filtered for further usage in the training scenarios, since actions shall then be set by the trainees.

The resulting series of actions will then be stored in order to retrieve them in the training sessions or for further analysis (e.g. analysis of exceptional situation and accidents).

Note: The communication interface for communication with all systems will not be elaborated on separately. Typically communication paths are already specified, since such activation, at least partly, is provided for in real time operation. If that is not the case one of the common communication protocols can be employed.

3.2. Holding training sessions

The "generated" training scenarios can be drawn upon for active training sessions. A trainer-trainee situation looks typically like the following:

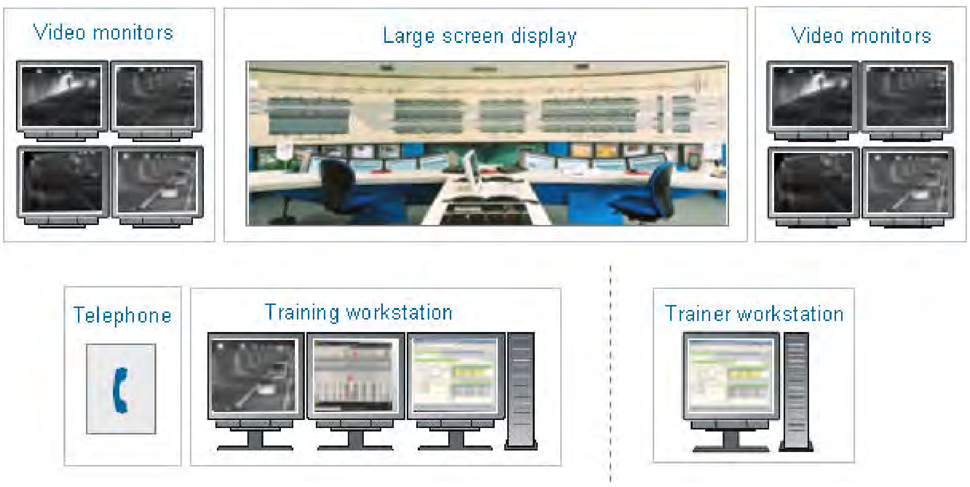

Figure 3: trainer, training environment and trainee in the control room

At the beginning of the training the control room gets entirely set to simulation mode. A different control room (or a single workstation in an adjoining room) takes over the guidance of the real installation.

The trainer starts the desired scenario via his remote workstation:

- First of all a central scenario management system identifies the initialized installation state. All relevant datapoints in the SCADA system will be set to the correct state.
- As from this time the simulation starts. The prepared linear course of actions specify the real (since data is obtained from the past) tunnel operation. This approach to emergency takes then some time in order to allow the trainee to accommodate to the simulation. Therewith long-term-tests can be conducted in order to find out how longer observations phases affect the proband.

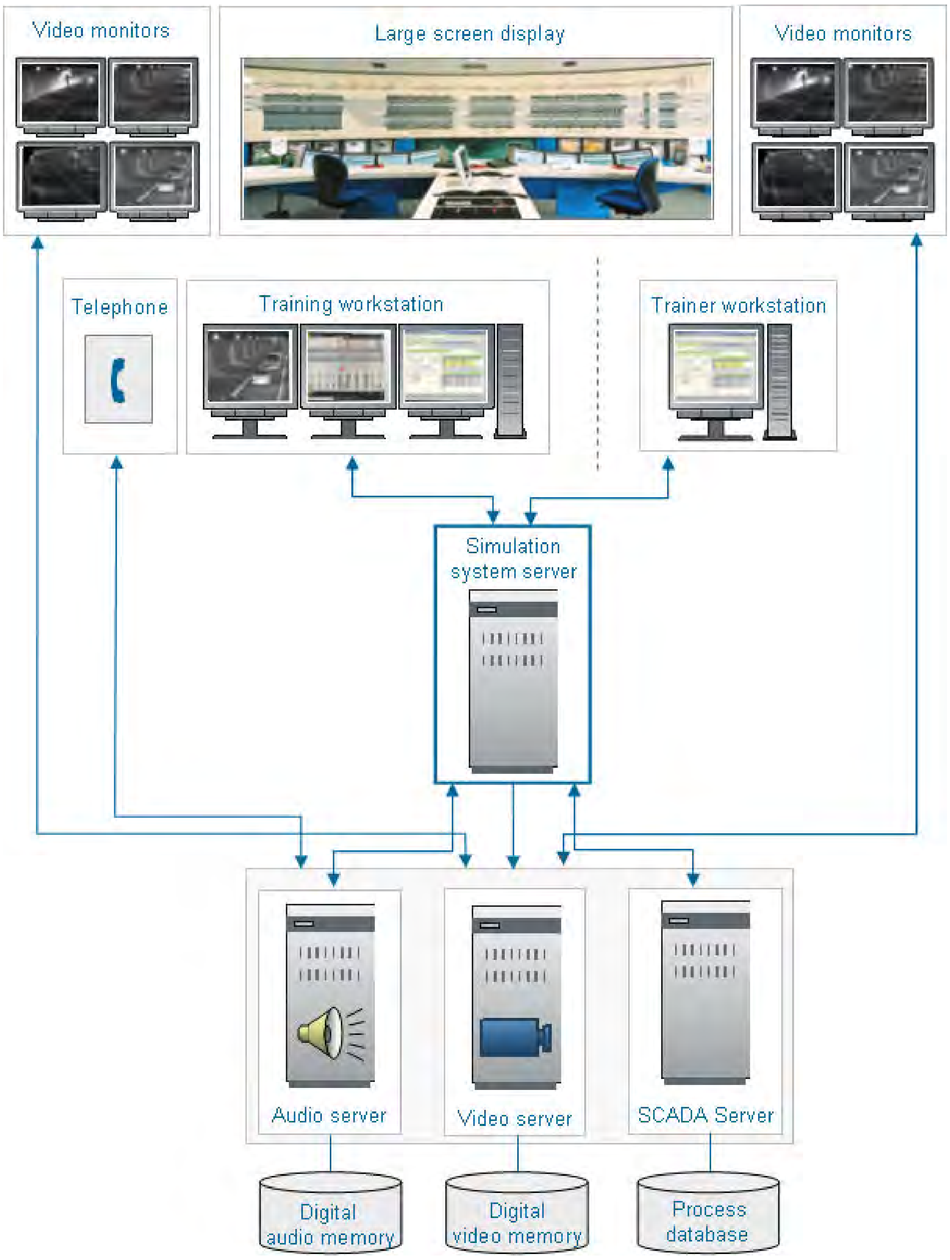

Figure 4: System architecture

- As a further step the operator (trainee) is asked to design the system according to his desires and to switch on relevant visual images on the workstation, cameras and monitors.
- Depending on the point of time of the planned failure a respective scenario initiates.
- The operator starts to react. The simulation per tool (e.g. momentum of tunnel ventilation) sends information back if requested. The trainer can intervene into the complex situation any time he wishes to do so. He also functions as counterpart in order to either trigger reactions of the installation or to bring in a human component by activating emergency calls or causing operational faults.

Thanks to this method highly real events and actions can be simulated. It also lays the basis for regular practice of available alarm schedules and they can be tested according to their efficiency. This is particularly true since the simulation of an entire control room allows several operation staff members to participate in the training at the same time. The disadvantage is, however, that the dynamics, as from the time of interaction by the operator, are strongly dependent on the cautiousness and intervention of the trainer. He replaces a hardly affordable complete-simulation in a tunnel plant.

3.3 Evaluation of the training results:

All user entries and trainer interventions, comments included, will be stored by the trainer and can be retrieved or printed any time in connection with the scenario.

4. CONCLUSION

Thanks to today's technological tools the presented technical concept can be realised by almost all suppliers of event and real-time oriented control systems that rest upon databases. The implementation on existing installations is possible provided that all technical criteria of the data storage are met. Increased safety through practical training and reused operational experience exceed the funds necessary by far. For the purpose of improved traffic safety it would be highly desirable, if comparable investments were taken into account and realized for future installations.

SIMULATING FIRES IN TUNNELS USING LARGE EDDY SIMULATION

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ABSTRACT

Full tridimensional simulations of fires in tunnels can be useful for safety assessments. In such a case, the flow is naturally turbulent. These simulations are therefore usually performed using the Reynolds averaged form of the Navier-Stokes equations (most often in their k-e form). The use of Large Eddy Simulation (LES) is still recent and raises important issues. The hope with LES is to have a better picture of the smoke flow, and to have access to a better understanding of fine grained turbulence, involved in the de-stratification of the smoke layer.
This work uses the code FDS (developed by the NIST – USA) which is designed for simulating fires in buildings. Being designed for fire calculation, FDS already incorporates combustion and radiation models in a low Mach number description of the fluid flow. However, flows in tunnels differ from flows in buildings, especially because of a relatively large mean flow, thus creating turbulence by shear along the walls.
The simulations performed with FDS are compared with an existing k-e simulation and with the results of a small-scale model representing a tunnel. It shows that the existing version of FDS is already giving satisfactory results compared to the k-e code, but still needs improvement compared to the small-scale model data. Further work will attempt to implement such improvement.

Key words: numerical simulation, Large Eddy Simulation, turbulence, FDS, fires, tunnels, Smagorinski, comparison with experiment, low Mach approximation

1. INTRODUCTION

Progress in computer science have made it possible to run tridimensional simulations of tunnel fires. Flows in tunnels are naturally turbulent. Direct numerical simulation for turbulent flows in such large domains requires too much CPU and memory, so that turbulence has to be modelled, either with Reynolds Average Navier-Stokes (RANS) models, or with Large Eddy Simulation (LES). Usual industrial simulations are performed using the Reynolds averaged form of the Navier-Stokes equations (most often in their k-e form). However the use of these models for theoretical research is limited due to their poorly detailed turbulence results.

The use of LES is still recent for tunnel simulation and raises important issues. It gives a better picture of the smoke flow, and access to the understanding of fine grained turbulence, crucially involved in the de-stratification of the smoke layer.

This paper presents results of simulations performed with the code FDS on the basis of a small-scale experiment. The code FDS (Fire Dynamics Simulator) was initially designed for fires in buildings, so its ability to simulate correctly fires in tunnels has to be checked out, especially regarding turbulence created by shear. The simulations presented here aimed at knowing in which ways FDS had to be trusted or improved.

Equations and hypotheses used for stratified flows with large density gradients are first recalled. The small-scale experiment and the LES simulations are then described and their results compared. We conclude with expectations for future work.

2. LARGE EDDY SIMULATION FOR STRATIFIED FLOWS WITH LARGE DENSITY DIFFERENCES

2.1. Low Mach number approximation

Flows in fires are three-dimensional, turbulent and strongly influenced by buoyancy forces. Their behaviour is described by the Navier-Stokes equations for compressible and viscous fluids, namely conservation of mass, momentum and energy (or enthalpy). The state equation for ideal gases is also used:

$$p = r\frac{R}{M}T \tag{1}$$

where p is the pressure, r the density, R the universal gas constant, M the molecular weight of the gas mixture, and T the temperature.

Velocities expected in tunnels are limited so that the Mach number can be considered as low. However the flow is not incompressible, because of strong temperature gradients inducing large density variations. The flow is said “nearly incompressible”, and a low Mach number approximation can be used to filter out acoustic waves. This is done by neglecting pressure variations in the state and enthalpy equations. So the equation of state is rewritten:

$$p_0 = r\frac{R}{M}T \tag{2}$$

where p_0 is the constant atmospheric pressure.
Besides, the production of heat due to mechanical dissipation in the enthalpy equation:

$$S_{ij}d_{ij} = \frac{m}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\frac{\partial u_k}{\partial x_k}d_{ij}\right)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{3}$$

(where m is the dynamic viscosity, u is the velocity, and d_{ij} is the Kronecker symbol)
can also be neglected in low speed flows.
Further approximations are made in FDS and will be discussed later.

2.2. Filtering the equations

Turbulence flows involve many length scales. In a numerical simulation such as the ones made with FDS, the size of grid cells acts as a filter to separate “large” scales from “small” scales. The velocity is decomposed as follows:

$$u = \hat{u} + u' \tag{4}$$

where u is the total velocity, $\hat{u}$ the filtered velocity and u' the sub-grid perturbation.
Large-scale (filtered) variables are calculated by solving the filtered Navier-Stokes equations, where the influence of small-scale turbulence is modelled. The sub-grid stress appearing in the filtered momentum equation is modelled using a sub-grid viscosity hypothesis:

$$t_{ij} = m_{LES} \times \left(\frac{\partial \hat{u}_i}{\partial x_j} + \frac{\partial \hat{u}_j}{\partial x_i} - \frac{2}{3}\frac{\partial \hat{u}_k}{\partial x_k}d_{ij}\right) \tag{5}$$

Different models can be used to determine the sub-grid viscosity m_{LES}. The Smagorinski model, where the viscosity is modelled as follows, is used here:

$$m_{LES} = \hat{r}\,(C_s\Delta)^2\left(\frac{1}{2}\left(\frac{\partial \hat{u}_i}{\partial x_j} + \frac{\partial \hat{u}_j}{\partial x_i}\right)^2 - \frac{2}{3}\left(\frac{\partial \hat{u}_k}{\partial x_k}\right)^2\right)^{\frac{1}{2}} \tag{6}$$

where C_s is an empirical constant and Δ is the typical mesh size. The constant C_s is generally taken equal to 0.2.

The main drawback of this Smagorinski model is its strong dissipation effect. It may prevent the turbulence to develop in an initially laminar flow. Moreover, it is not adaptable to the flow configuration. This is a problem in the wall shear layer if the flow speed is not very small. That is why the Smagorinski model works fine for LES of fires in buildings, where the flow is mostly laminar out of thermal plumes, but might prove insufficient in tunnels.

2.3. FDS specificities

The code FDS is being developed by the NIST (National Institute for Standards and Technology – USA). It was primarily designed for simulating fires in buildings. Being designed for fire calculation, FDS already incorporates combustion and radiation models, whose equations are not discussed in this paper but are available in FDS technical reference guide (NIST, 2002). Equations used in FDS are the following ones:
The pressure is decomposed into a background component and flow induced perturbations:

$$p = p_0 + \tilde{p} \tag{7}$$

In the case of tunnels, p_0 is constant, equal to the atmospheric pressure.
The enthalpy is written as:

$$h(T) = C_p T \tag{8}$$

where the specific heat C_p is considered as independent from temperature. Then an approximated divergence equation can be derived from the enthalpy equation:

$$\vec{\nabla} \cdot \vec{\hat{u}} = \frac{1}{\hat{r} C_p \hat{T}} \left(-\vec{\nabla} \cdot \vec{\hat{q}} + S \right) \tag{9}$$

with $\vec{\hat{q}}$ being the diffusive and radiative heat flux vector, and S a source term.
After dividing by the density, the filtered momentum equation is rewritten using the vorticity $\vec{w}$:

$$\frac{\partial \vec{\hat{u}}}{\partial t} - \vec{\hat{u}} \wedge \vec{\hat{w}} + \vec{\nabla} \hat{H} = \frac{1}{\hat{r}} \vec{\nabla} \cdot \left(\overline{\overline{s}} + \overline{\overline{t}} \right) + \vec{g} + CT \tag{10}$$

with the total pressure divided by density, H, defined as: $H = \frac{p}{r} + \frac{1}{2} |u|^2$

$\overline{\overline{s}}$ being the viscous stress tensor, $\overline{\overline{t}}$ the sub-grid stress tensor, $\vec{g}$ the gravity vector, and where CT is a corrective term accounting for the baroclinic torque due to the non-alignment of the density and pressure gradients. Its expression is the following:

$$CT = \tilde{\hat{p}} \vec{\nabla} \left(\frac{1}{\hat{r}} \right) \tag{11}$$

According to FDS technical reference guide (NIST, 2002), for most large-scale applications the baroclinic torque is relatively small compared to buoyancy. Thus the corrective term can be neglected. However the code offers the option of restoring the baroclinic torque. This option was tested in the simulations (see paragraph 3.3).
The divergence of the previous equation is taken to obtain the Poisson equation for the pressure:

$$\nabla^2 \hat{H} = -\frac{\partial \left(\vec{\nabla} \cdot \vec{\hat{u}} \right)}{\partial t} - \vec{\nabla} \cdot \vec{F} \tag{12}$$

with: $$\vec{F} = -\vec{\nabla} \cdot \left(\vec{\tilde{u}} \wedge \vec{\tilde{w}}\right) - \frac{1}{\hat{r}}\left(\hat{r}\,\vec{g} + \vec{\nabla} \cdot \overline{\overline{s}} \right) \tag{13}$$

Variables of the filtered equations are discretized on a structured cartesian grid. Spatial derivatives are approximated by second order central differences. Scalar variables are assigned in the centre of each cell, while vector quantities are assigned to cell faces.
The flow variables are updated in time using an explicit second order predictor-corrector scheme. The CFL stability condition is checked every time step.

3. PRESENTATION OF THE SIMULATIONS

The purpose of these simulations was to evaluate the capacities and limitations of FDS. They were based on a small-scale experiment and a k-e simulation providing thermal and dynamical results.

3.1. Description of the test case

The experiment was performed on a 1/5-scale model of a 100 m long tunnel (Ingason and Werling, 1999). Froude similitude was used to determine the dimensions of the model, which are 20 m in length, 2 m in width and 1 m in height. The fire zone is located at 2.5 m from the inlet, and its area is 0.16 m^2. The mean velocity of 0.75 $m\,s^{-1}$ and the heat output of 49.2 kW correspond to full-scale values of 1.12 $m\,s^{-1}$ and 2.9 MW. Velocity and temperature values are measured in vertical sections D, E, F, G, respectively located at 2.5 m, 6.5 m, 11.5 m and 16.5 m downstream the fire, and in horizontal section H, 0.1 m under the ceiling.

A k-e simulation of this experiment was run previously at Cetu (Demouge, 2002). Results show that the temperature is generally under-predicted, especially near the fire. Two counter-rotating eddies appear in the fire plume. Thus FDS results are expected to better represent temperature gradients alongside the tunnel and to give a finer picture of those eddies.

3.2. Inlet conditions

Flows in buildings are very slow. Turbulence in such cases is mainly created in the region of strong buoyancy, i.e. in the fire, so that inlet velocity profiles can be defined as non fluctuating in time. So is it in FDS. However LES of flows with higher speeds requires turbulent inlet velocity profiles, fluctuating in time according to statistic considerations.

Two types of inlet velocity profiles are available in FDS: constant or parabolic. As a constant profile is more turbulent-like than a parabolic one, the inlet velocity profile is chosen constant and its value is 0.75 $m\,s^{-1}$.

3.3. LES simulation with FDS

The boundary condition is rejected away from the fire by introducing an entry zone in the simulation upwind of the actual inlet. Thus the domain is 25 m long, 2 m wide and 1 m high, and contains 120000 cells. A pressure boundary condition is defined at the outlet. Walls are defined as thermally thick, that is, a one-dimensional equation of conduction through walls is solved. Other conditions can be used, such as thermally thin or adiabatic. A simulation has been done with adiabatic walls. The fire heat output is 49.2 kW when radiation is calculated. However when radiation losses are only evaluated that number is diminished by 30 %, that is 34.4 kW. The fire zone is a 0.4 m sided square releasing a certain rate per unit area, depending on whether radiation is modelled. The initial ambient temperature is 20°C.

Several simulations were run to evaluate the influence of each sub-model in FDS (the name referencing each run is written in brackets):
- adiabatic ;
- without baroclinic torque, combustion or radiation (R1) ;
- with baroclinic torque only (R1b) ;
- with combustion only (R2) ;
- with combustion and baroclinic torque (R2b) ;
- with combustion and radiation (R3) ;
- with combustion, radiation and baroclinic torque (R3b).

The computing time was about one day on a Dell Xeon with Linux.

4. RESULT COMPARISON

4.1. Temperature profiles

Temperature values are slightly higher in the LES simulation than in the k-e simulation (Demouge, 2002), but the experimental values are still higher, especially under the tunnel ceiling (figure 1). However the sharp elevation of temperature over the fire is far better taken in account with FDS than in the k-e simulation (figure 2).

Temperatures found near the fire in the adiabatic case are remarkably similar to the experimental ones (figures 1 and 2). Besides the back-layering is far longer than in non-adiabatic cases. (figure 2). Therefore the flow behaviour near the fire seems to be close to adiabatic.

The baroclinic torque was taken into account in runs R1b, R2b and R3b. Figure 3 shows that the temperature near the ground is not affected by this term, and that it becomes higher near the ceiling. An other effect of the baroclinic torque is that it completely suppresses the back-layering (figures 2, 5-c and 5-d).

The combustion model was used in runs R2 and R2b. Temperature values in those runs are slightly lower than in runs R1 and R1b respectively, especially in the region near the ceiling (figure 4). Modelling the combustion apparently decreases temperatures.

The radiation model allows temperatures to rise slightly near the ground (figures 5-a and 5-b). That temperature elevation was not found in the k-e simulation, whereas it appears in the experiment. Even though, temperature values remain far below the experimental ones.

The radiation model influence below the ceiling is shown on figures 5-c and 5-d: when comparing runs R3 and R3b with runs R2 and R2b, it appears that in the first 10 meters downstream the fire the temperature rises when radiation is calculated, whereas the contrary happens in the last meters.

In conclusion, the existing version of FDS is already giving satisfactory results compared to the k-e code, but still needs improvement compared to the small-scale model data. The considered solution is to modify the definition of the inlet velocity profile.

4.2. Turbulence results

Velocity vector slices show the expected counter-rotating vortices over the fire. Turbulence is visible on velocity and temperature slices (figure 6), though a finer grid would give a better representation. More figures can be found in Rahmani (2003).

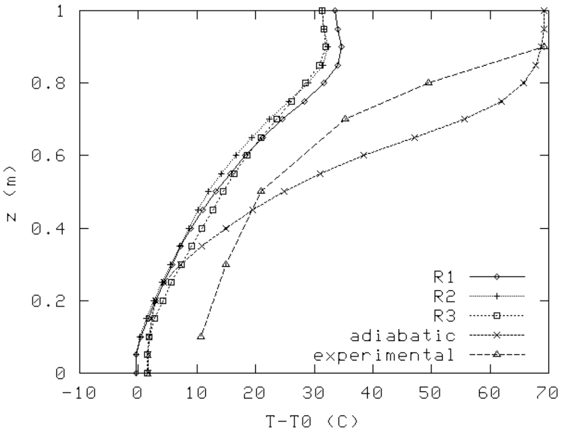

Figure 1 – Temperature profiles, section F

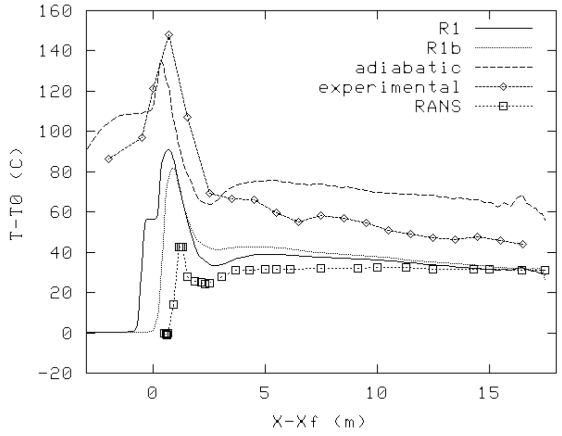

Figure 2 – Temperature profiles, section H (horizontal)

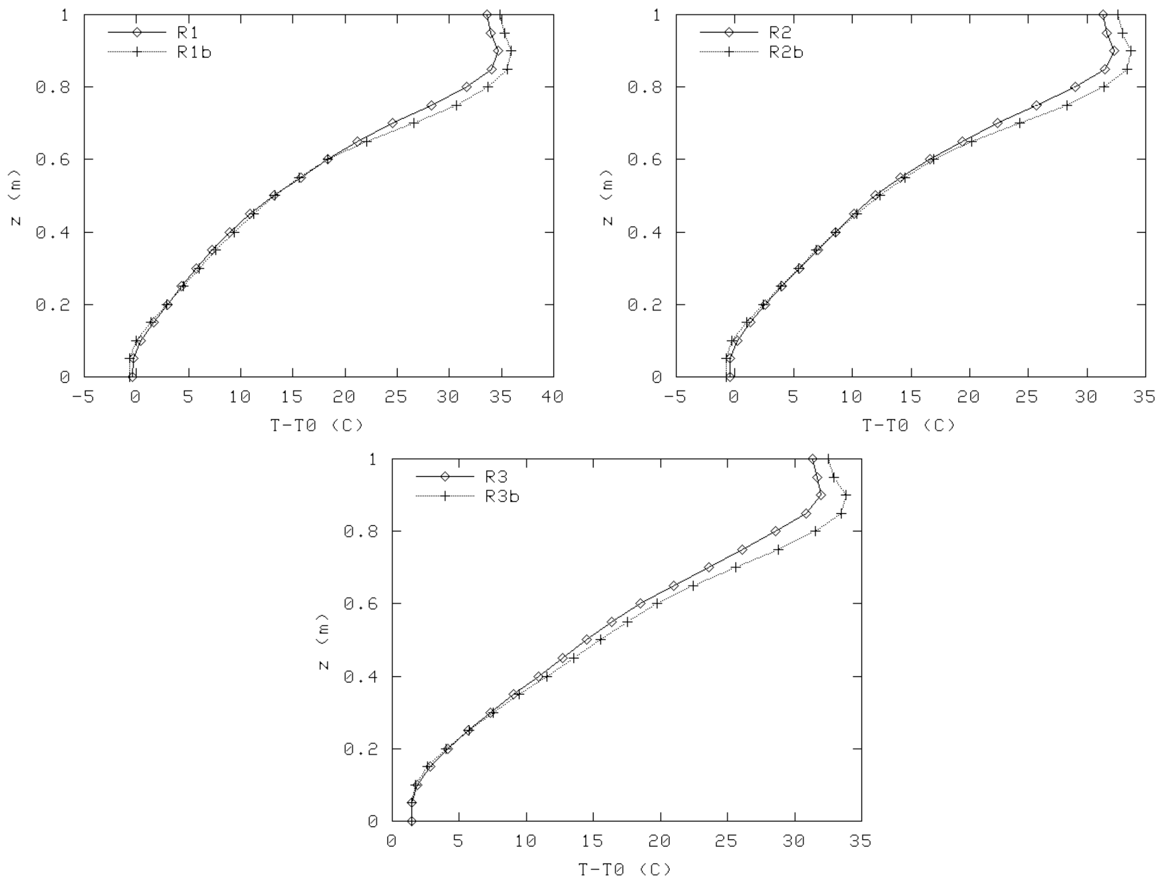

Figure 3 – Temperature profiles, section F – Influence of baroclinic torque

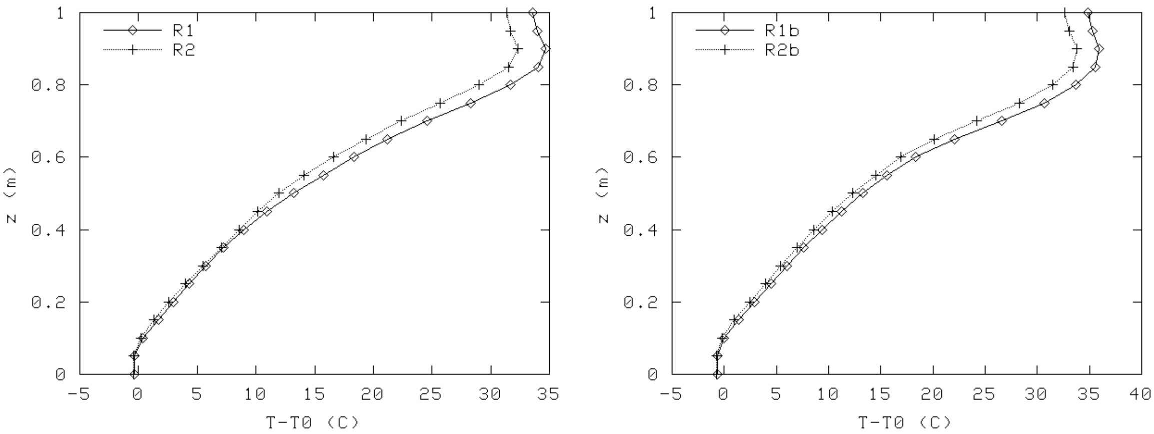

Figure 4 – Temperature profiles, section F – Influence of combustion model

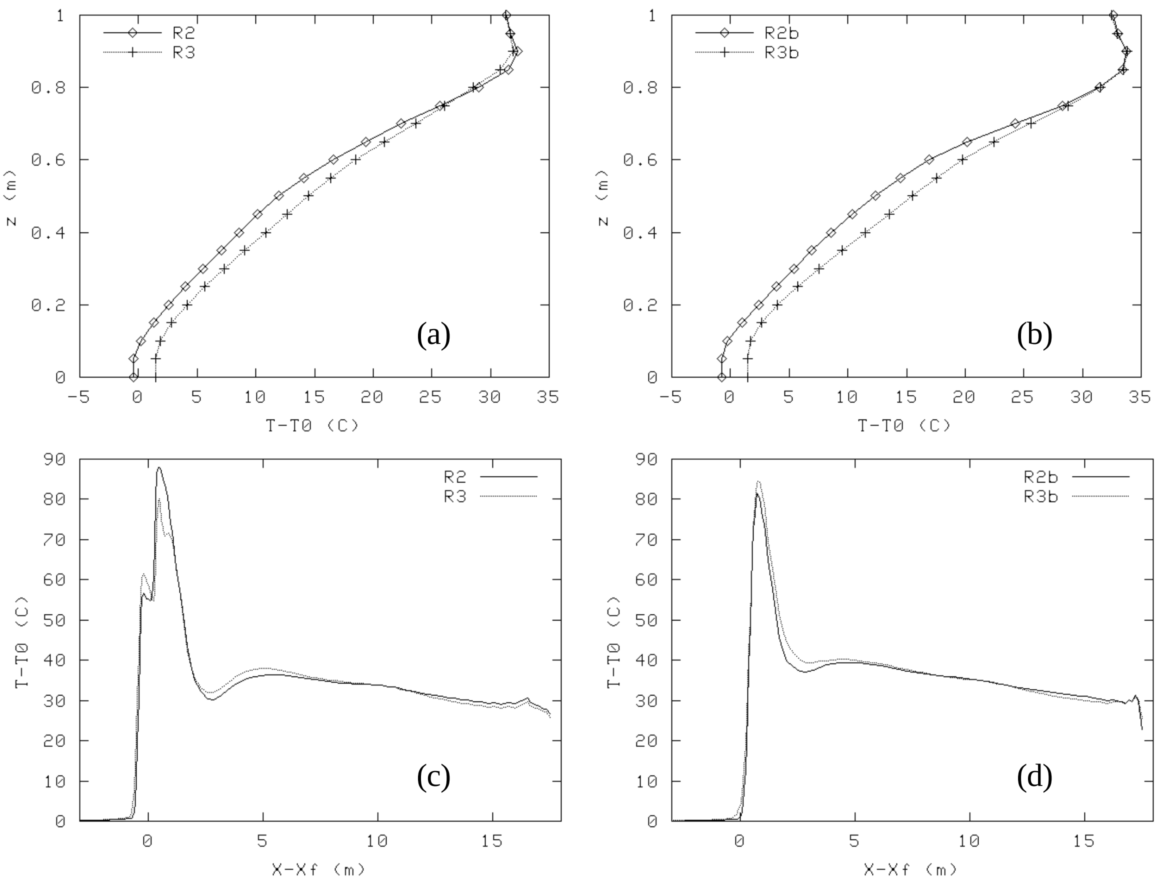

Figure 5 - Temperature profile, sections F (a, b) and H (c, d) - Influence of radiation model

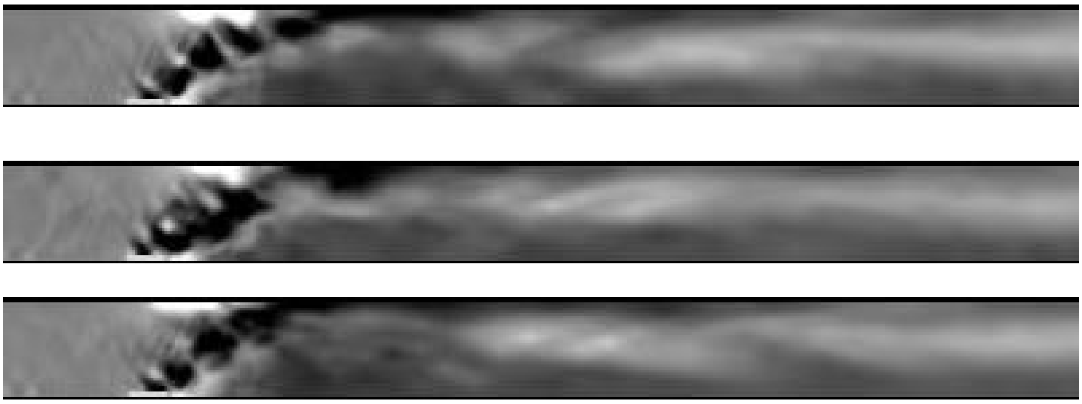

Figure 6 – Velocity slices – time: 935 s, 1033 s, 1095 s

5. CONCLUSION AND FUTURE PROSPECTS

Further improvement may be gained in two directions. As already noticed, the inlet condition in FDS does not incorporate a fully turbulent flow. This issue could be addressed by using a synthetic turbulence at the inlet, or by running a sub-model with periodic boundary conditions. This sub-model is being implemented and preliminary tests seem to give satisfactory results. Second, the sub-grid model does not take into account very well turbulence created by shear. In order to consider this, the sub-grid scale model, at the present time a simple Smagorinski model, should be modified. An idea is to use meteorological considerations to adapt this Smagorinski model to wall flows (Redelsperger et al. 2001, Carlotti 2002).

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DATA ANALYSIS OF NATURAL VENTILATION IN A FIRE IN TUNNEL.

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ABSTRACT.

It is known that the availability of jet fans in tunnels assures a higher safety degree in the longitudinal ventilation pattern. But these installations have a remarkable cost, especially if the number of tunnels is high. In this paper, we want to explore the behaviour of the natural ventilation in presence of fire in tunnel in those cases in which a favourable slope occurs. Another issue is the emergency management.
The study was performed on the basis of the experimental data supplied from "Memorial Tunnel Fire Ventilation Program". The analysis is made on the two natural ventilation tests available in this Program. A comparison with the Memorial Tunnel tests which have forced longitudinal ventilation patterns is made to understand how effective the behaviour of natural ventilation is. The analysis has been carried out considering the (P/Q) ratio between fire power P and air flow Q. This ratio is a parameter which gives a better information, about the danger of a situation, in comparison with the simple fire power.
Moreover, in the ventilated tunnel, the P/Q ratio is a function of the power P released by the fire, that is substantially independent of our action, and the air flow Q which depends on our action.

Key words: tunnels, fire in tunnels, data analysis, ventilation, safety

1. MEMORIAL TUNNEL DESCRIPTION

The Memorial Tunnel (MT) (MTFVTP, 1995), in fig. 1a, is a two-lanes 853 m long straight motorway tunnel with a medium slope of 3,2 % from the north to the south portal.

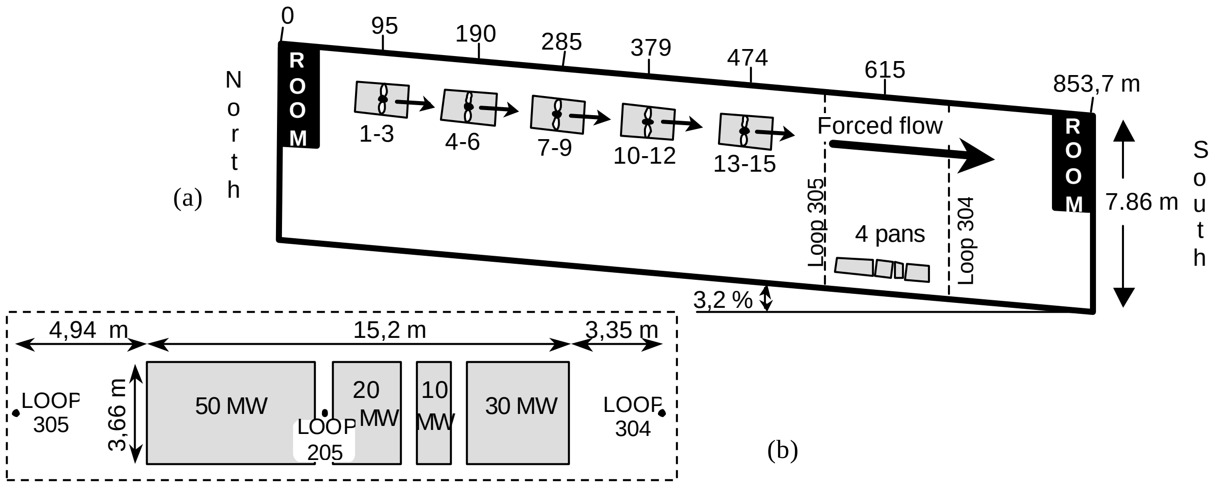


Figure 1. (a) Schematic overview of the Memorial Tunnel. MT is characterized by a slope of 3,2 % and by unusual obstructions on the ends, due to the two rooms. In the natural ventilation tests the 15 Fans are not provided. (b) Map of the pans layout with position of the near instrumentation loops. In each loop, 8 measurements are taken at 8 different vertical levels

The full section is 60,4 m^2. On the ends two unusual obstructions (rooms), are present. Fifteen jet-fans are provided inside the tunnel in group of three for the longitudinal ventilation experimental phase. The fire is generated by means of fuel floating on filled pans placed about 240 m far from the south portal. Four pans, shown in fig. 1b, allow to achieve fires from 10 to 100 MW. During the natural ventilation (NV), the jet fan are not provided.

2. TREND OF THE TWO NATURAL VENTILATED TESTS

The analysis was undertaken elaborating the experimental data of "Memorial Tunnel Fire Ventilation Program" (MTFVTP, 1995). At the beginning of the analysis of the longitudinal ventilation on the MT tests, our concern was not to create too many graphs that might ingenerate confusion. We had 17 tests to observe with many measured variables in the time and in the space. Then the intention was to create few graphs with the more possible useful information for our considerations. Thus, to evaluate the situation, we realized to observe the maximum temperature just few meters downstream of the fire exactly at the 305 loop (fig 1) for NV and 304 loop for forced ventilation (FV). The longitudinal forced ventilation tests were already analysed in (Giuli, 2003).

Here the trend of this maximum temperature versus time, is observed, as reported in figg. 2(a) (20 MW) and 2(b) (50 MW) for the two NV tests. This maximum temperature T_{max}, measured downstream, is every time observed at the highest level on the loop 305. The fire power P (MW) and the air flow Q (m^3/s) are reported in the same graph. Q is taken near the south portal upstream, where density is determined, to avoid the influence of the temperature. Thus, in every instant, Q has substantially always the same density.

2.1. Observation on the 20 MW NV test

In fig. 2(a) we observe that, from the fifth minute to the end, the air flow changes from ~32 m^3/s to ~90 m^3/s, while T_{max} decreases (due to the increased flow) of only about 10%.

Another observation is that the maximum temperature seems to be low, considering the low air flow rate, respect to the FV tests (Giuli, 2003). For comparison, one of the four 20 MW forced ventilation tests is reported in fig. 3(a).

2.2. Observation on the 50 MW NV test

In fig. 2(b) it is observed that the flow rate has no regular increase and has an average value of 65 m^3/s, that is smaller than the other FV tests with the same power.

Here the maximum temperature is very high, for this delivered power, due to the small natural flow. For comparison, one of the five 50 MW forced ventilation tests is reported in fig. 3(b).

3. COMPARISON OF NATURAL AND FORCED VENTILATED TESTS

A comparison has been made with the FV tests analysed in (Giuli, 2003) to understand better the behaviour of the NV tests. The measured data for natural and forced ventilation are represented in fig. 4. In this figure the P/Q [kJ/m^3] ratio is reported on the X-axis and the maximum T measured on the loop downstream (305 for NV and 304 for FV) is reported on the Y-axis.

In each test T_{max}, P and Q are measured every 30 seconds; Q is read near the portal where the air is incoming in the tunnel. Instead of representing all the points taken every thirty seconds, the time averaged maximum temperatures $\overline{T}_{max}$ for each test is reported; the same time averages are made for the values of P/Q.

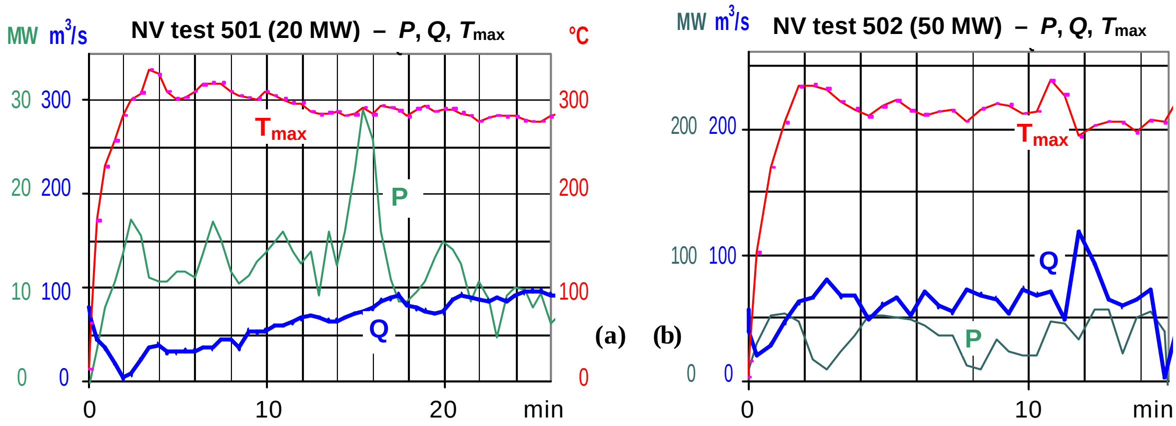


Figure 2. NATURAL Ventilated tests. Trend vs time of: air flow *Q*, power *P*, and T_{max} at few meters downstream. (a) 20 MW test. The *Q* is reported in absolute value. It goes in direction of the stack effect except for the first 2 initial minutes where it goes from north to south. (b) 50 MW test. This test is stopped after only 15 minutes.

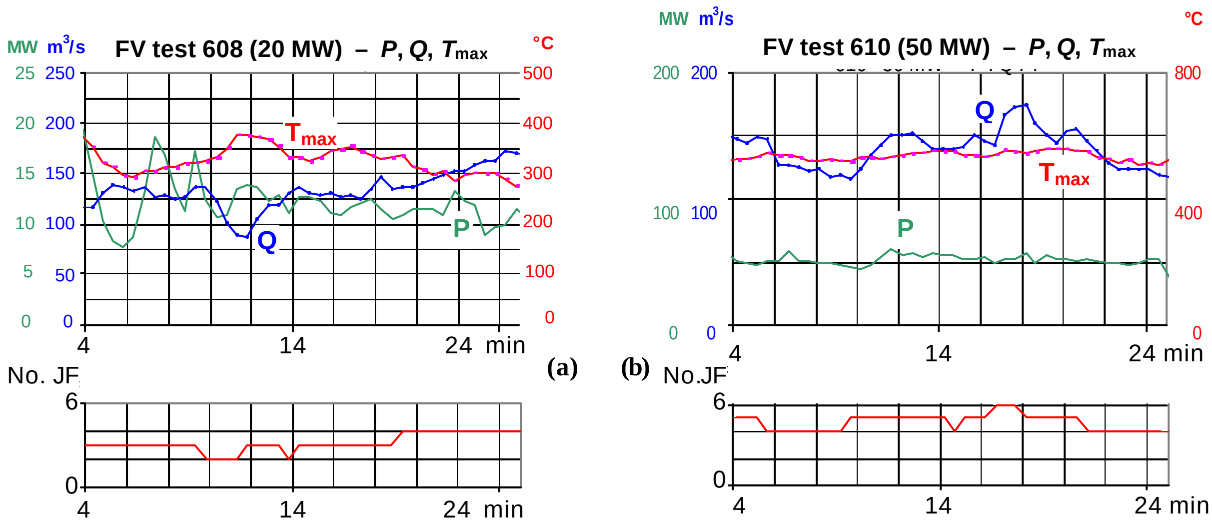


Figure 3. FORCED Ventilated tests. Trend vs time of: air flow Q, power P, and T_{max} at few meters downstream. (a) 20 MW test with the No. of JF in operation. (b) 50 MW test with the No. of JF in operation

The time average is calculated until the shut-off, having discarded the initial transient (usually the initial two-four minutes of the time interval).
In the graph the dashed straight line represents the temperature of an air flow rate Q [m^3/s], at the initial temperature T_0, which absorbs the total power P [W] reaching an uniform temperature T [°C] according to the following well known law:

$$T = T_0 + \frac{1}{c_p} \frac{P}{r\ Q} \tag{1}$$

where: r [kg/m^3] = air density at T_0; c_p [J/(kg °C)] = air specific heat.
From fig. 4 we can see that FV tests points are distributed in an approximately linear mode, parallel at the dashed line which represents eq. (1). The two triangular symbols (Δ) related to NV are not aligned with the forced ventilation series.

Analysing the position of 50 MW NV point, it is recognized that this is the one at the highest *P/Q* value among the 50 MW cases due to the low *Q* value. Moreover we see that, while the FV points are shifted from the straight line of about 200 °C, the NV point is shifted of about 400°C. This large shift is caused by a strong stratification.
Using the same considerations, the Δ-point of 20 MW NV test is expected at about 500 °C instead of 300°C observed in fig. 4. This different behaviour will be analysed in the next section.

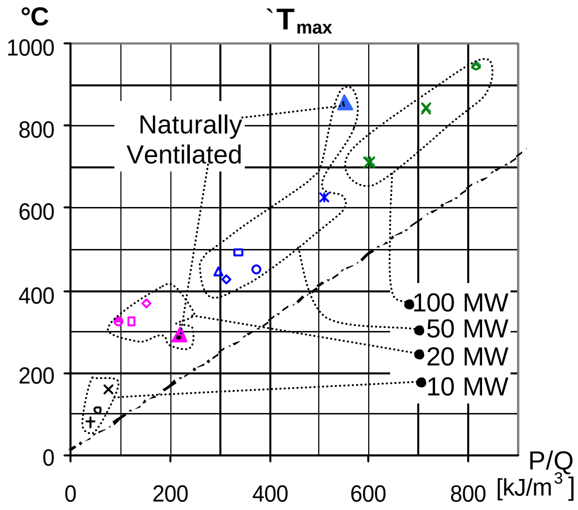


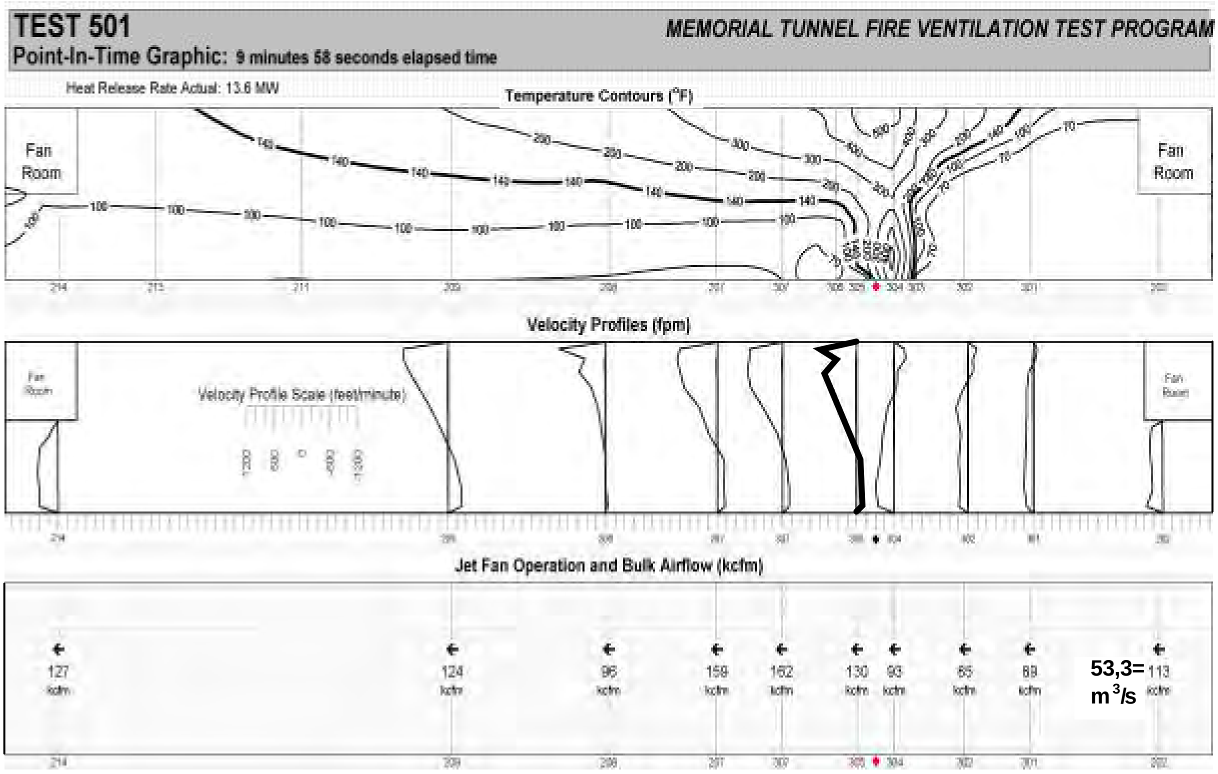
Figure 4. Time averaged downstream maximum temperature $\bar{T}_{max}$, vs P/Q ratio for all tests. The two NV tests are shown with a big D. The dashed line represents eq. (1)

4. ANALYSIS OF THE TEMPERATURE FIELD AND VELOCITY PROFILE

In this section, the temperature fields and the velocity profiles for the two NV tests are analysed and compared with the FV tests. It will be seen how much the velocity profile is important for the heat transport.

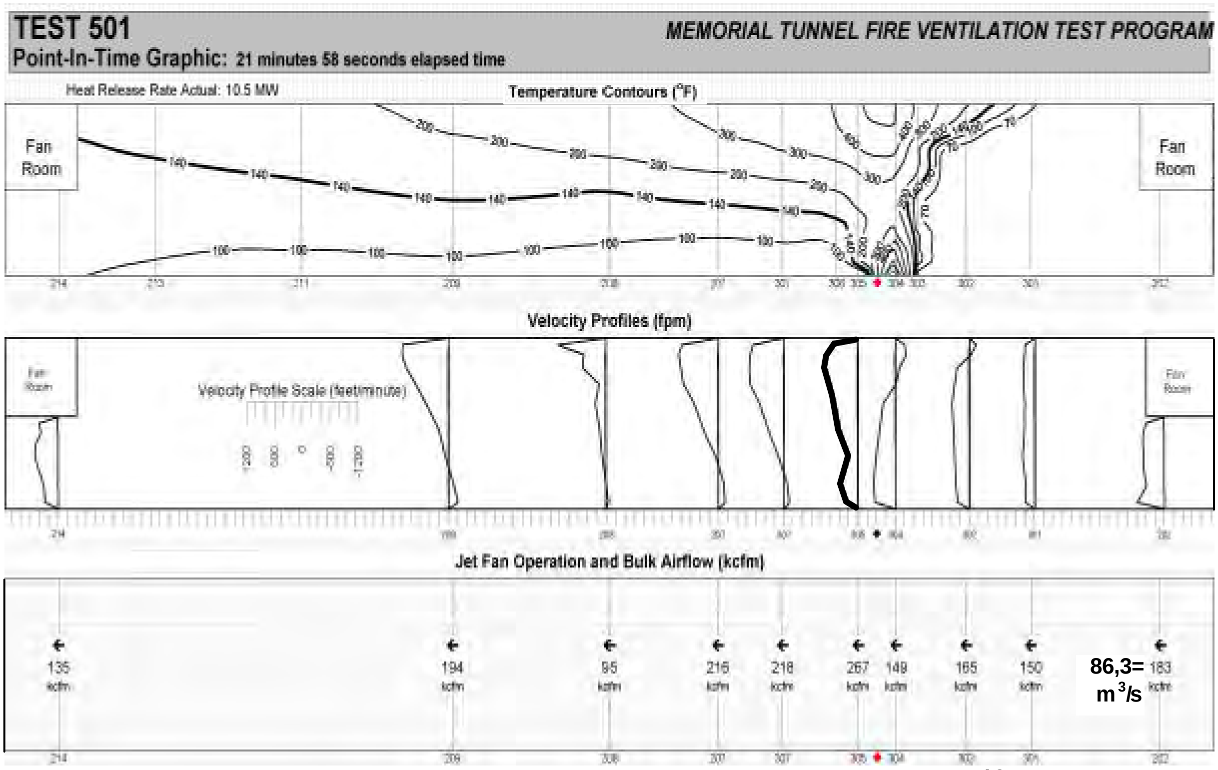
4.1. Analysis of 20 MW test

The fig 5, directly extracted from (MTFVTP, 1995), shows the instantaneous situation at 10 minutes from the fire start for the 20 MW NV test. The flow rate is 53,3 m^3/s and the fire power is 13,6 MW. In fig. 6 the situation at 22 minutes is shown for the same test, with a flow rate of 86,3 m^3/s and a fire power of 10,5 MW.
In the two situations the fields of temperature are similar, with a maximum value of about 300°C, notwithstanding that in the first case the flow rate is less and the power is larger than in the second case. This behaviour is due to the different velocity profiles of the flow. Comparing the two marked profiles (figg. 5 and 6) we can see, in first case, that the *negative* velocity near the floor, concentrates the positive mass flow in the zone at the highest temperatures. So this *positive* mass flow has a larger energy density respect to the second case. So the lower mass flow of fig. 5 is enough to transport an even larger power respect to the situation of fig 6.
In order to better understand the phenomena, a forced test of nominal 20 MW is shown in fig. 7 at the time of 9’50” from the start. The maximum temperature is about 300°C, as in the NV test and the power is 12,4 MW, about the same of fig. 5. The velocity profile is *flatter* than the profile of fig 6 and the flow rate is larger than the one in the NV test.



Extracted from (MTFVTP, 1995)

Figure 5. 20 MW - NATURAL ventilated test after 10 minutes. The marked velocity profile on the 305 loop, just few meters downstream the fire, shows a peak near the ceiling



Extracted from (MTFVTP, 1995)

Figure 6. 20 MW - NATURAL ventilated test after 22 minutes. The marked velocity profile on the 305 loop, just few meters downstream the fire, tends to a flat profile due to the higher flow rate

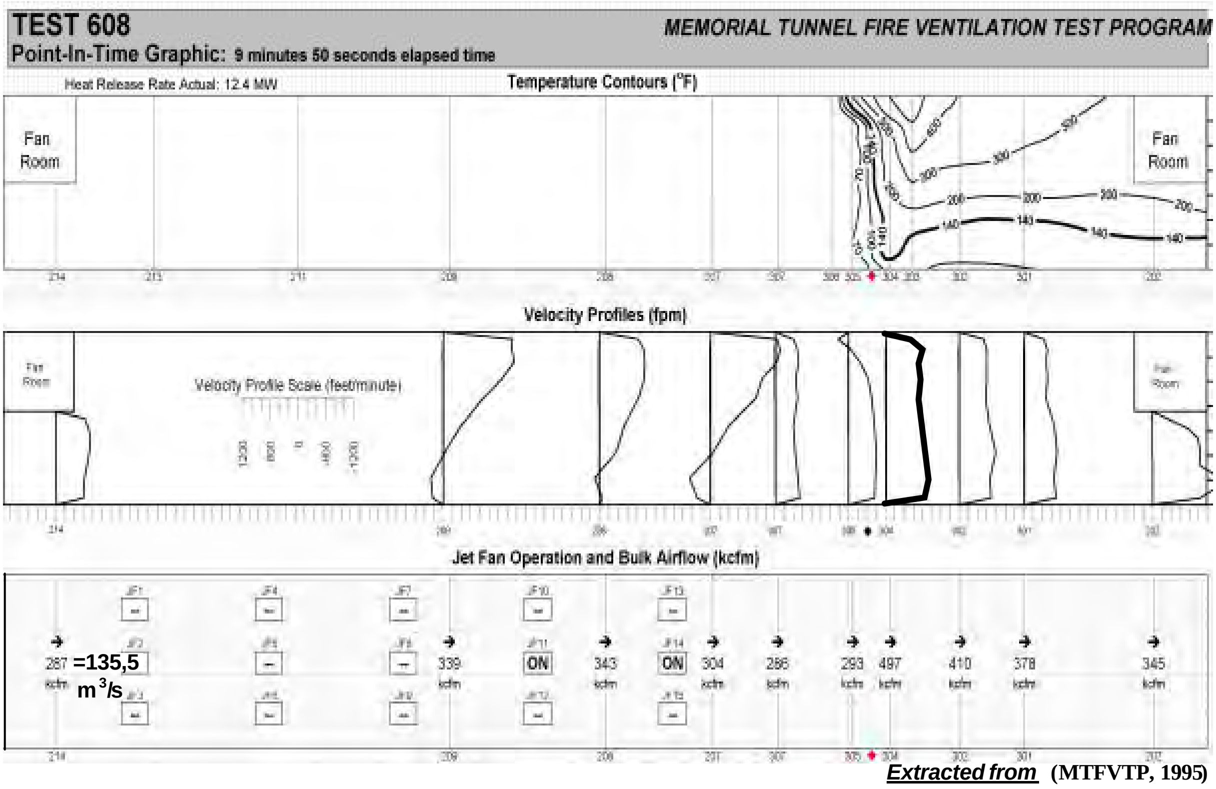


Figure 7. 20 MW - FORCED ventilated test. The marked velocity profile on the 304 loop, just few meters downstream the fire. This is the typical profile of all forced ventilated tests observed at this loop

To show the importance of the velocity profile geometry, the '*counterflow*' profile marked in fig. 5 is represented in fig. 8(a) and is compared with a supposed flat velocity profile with the *same* total mass flow, represented in fig 8(b). Let us divide the total mass flow rate crossing 305-section in 3 subsections: $-M_B$, $+M_B$, M_{305} (fig. 8a). $-M_B$ (backwards flow) and $+M_B$ have the same absolute value, so the remaining flow section M_{305} is the total mass flow rate.

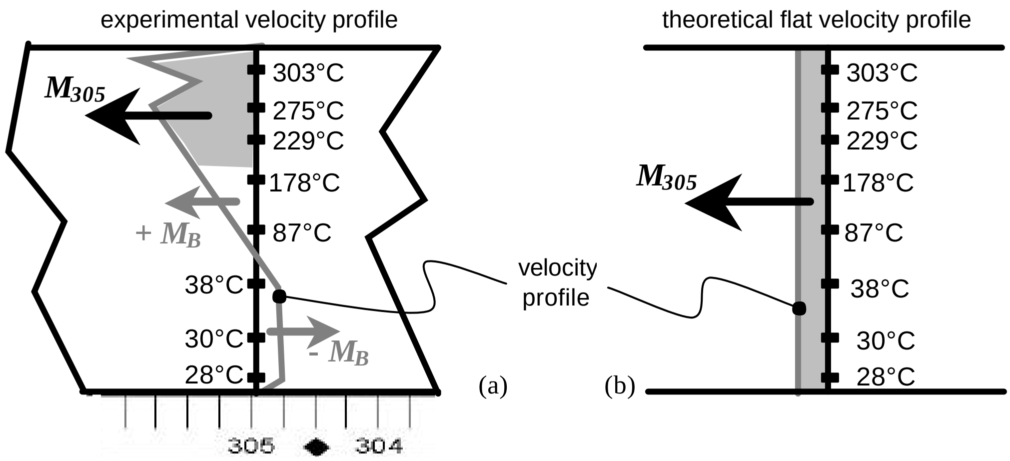


Figure 8. Comparison between different velocity profiles. (a) Experimental "*counterflow*" profile. (b) A supposed *flat* profile with the same mass flow rate M_{305} [kg/s] of the experimental test. Notwithstanding the mass flow rates are equal, in the case (a) more than 3 times the heat power of the case (b) is transported.

Calculating, in both cases, the heat that crosses the section 305, we see that in the (a) case the transported heat is more than 3 times respect to the (b) case. In fact the average temperature of the flux of the (b) case is about 90°C. Instead from the calculation of the only grey flow M_{305} in case (a) the average temperature is about 250°C. Taking into account that the reference environment temperature at the inlet portal is 10°C the M_{305} flux in the case (a) carries exactly 3 times the power of the case (b). Moreover, in case (a), the two fluxes $-M_B$ and $+M_B$, have to be considered. Even if they do not carry any mass, they carry some power due to the different temperatures of the two fluxes.
If we impose. in the case (b), the same carried power as in (a), instead of the same mass flow rate, we need a mass flow about 3 times that in (a) case. This last consideration may explain the different flow rate between the experimental tests of fig. 7 and fig. 5.

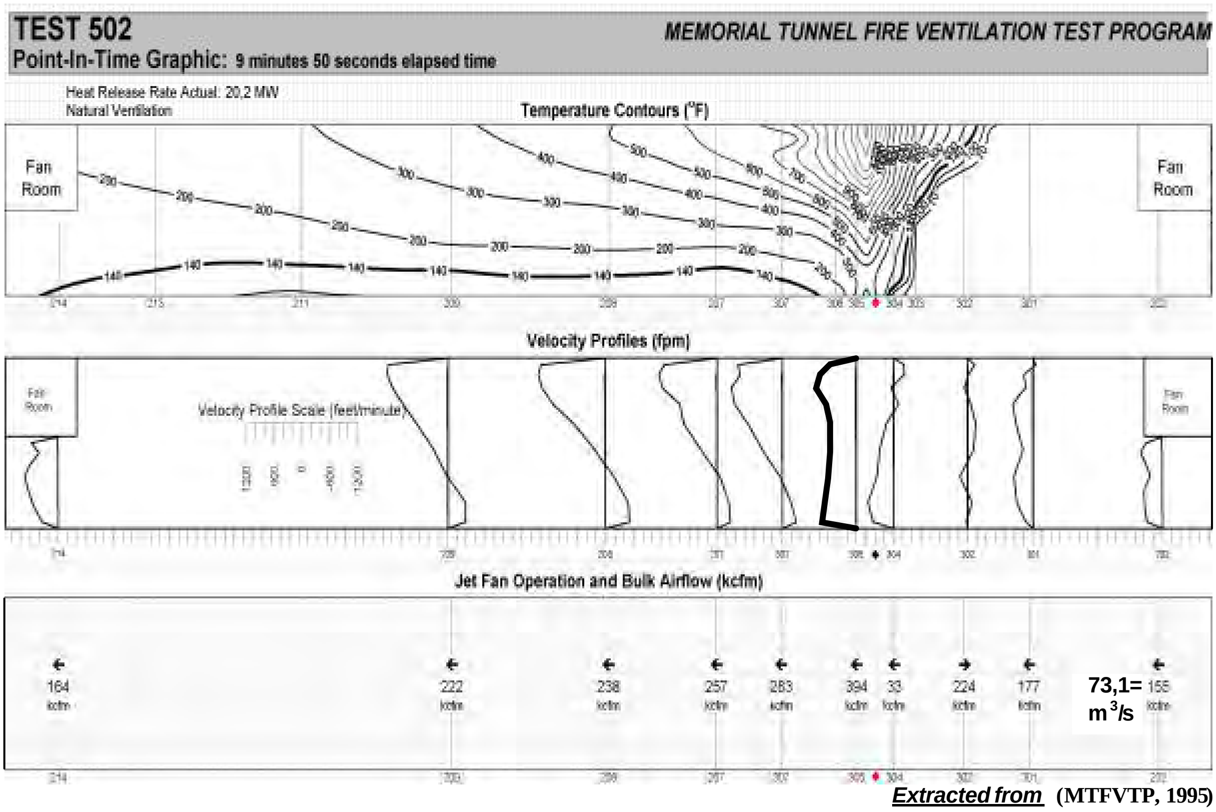


Figure 9. 50 MW - NATURAL ventilated test. The marked velocity profile on the 305 loop, just few meters downstream the fire, has a peak near the ceiling

4.2. Analysis of 50 MW test

As we have observed in the previous fig. 4, $\overline{T}_{max}$ for the NV test of 50 MW is higher than the corresponding FV test of 50 MW. In fig 9 the instantaneous situation at 10 minutes from the fire start for the 50 MW NV test is shown. The velocity profile is quite flat, unlike the 20 MW NV test (fig. 5-6) and is similar to the profiles of the FV tests. The T_{max} difference between the NV and FV tests of 50 Mw is due to the low NV flow rate (~70 m^3/s against ~150 m^3/s for FV) which causes a strong temperature stratification. This stratification with a large T_{max} (~850°C) is observable in fig. 9.

5. CONCLUSIONS

As far as the maximum temperature is concerned, the 20 MW NV test has a better behaviour (T_{max} is a bit lower than the corresponding FV test) than the 50 MW NV test (T_{max} is much higher than the corresponding FV test).
This better behaviour is due to the '*counterflow*' velocity profile downstream the fire, at loop 305, and it seems induced, by a small flow rate. A fire with large power, generating a large natural flow, tends to have a flat velocity profile.
Analysing all the data of the two NV tests, we observe that the '*counterflow*' velocity profile is present below a flow rate 60÷65 m^3/s .
It should be interesting to evaluate other experimental results on natural ventilation, to confirm these observation.

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Particle Image Velocimetry (PIV) measurements in air-curtain systems designed for smoke confining in case of road tunnel fires

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ABSTRACT

Air curtains are plane air jets blown across openings so as to isolate from each other two adjacent volumes. Such apparatus are commonly used in applications where it is sought to minimise heat or mass transfers between two areas while it is necessary to keep free the way for people or material from one area to the next one. Thus, air-curtain-based systems may be useful in case of fire in road tunnels. They can be used to limit and/or slow down smoke propagation while people can easily escape from the smoky part of the tunnel and reach cleaner areas in a self-rescue phase. Additionally, such safety systems make it possible for rescue teams to access the incident place more freely and to take efficient action faster.

An experimental facility was designed to investigate various air-curtain arrangements with the aim to work out efficient solutions for smoke confining in case of fire in a road tunnel. In the first stage, the emphasis was put on flow dynamics. The different configurations considered in this work include systems made of one or two curtains of single or double jets. They were experimentally investigated using Particle Image Velocimetry (PIV). Results presented herein are given in terms of velocity fields and profiles for some of the tested configurations. The so-called double-jet double-flux configuration seems to promise the best response to the problem of smoke (or pollution) local confining.

Key words: air curtain, tunnel, plane impinging jet, smoke confining, PIV, FID.

1. INTRODUCTION

Underground transport facilities are sensitive links in the economic chain that carry thousands of people and tons of goods every day. They are constantly growing in number. By far the greatest risk is an out of control fire.

There are about 2 vehicle fires per 100 Mio Veh km in Europe (Peter, 2000). Although this is not much, their consequences can be dramatic (table 1). This nevertheless triggered a wide public debate on the safety of road tunnels leading to demands for more comprehensive safety procedures.

One of the most hazardous factors is the release of hot and toxic combustion gases and smoke. Smoke spread rapidly and reduce visibility. Consequently, most deaths are due to asphyxiation because people cannot find their way fast enough to reach clean and safe areas.

Structural and organisational measures such as escape tunnels, and rescue concepts are an important first step towards improved safety. Equally important for the prevention of a catastrophe are:

- Efficient fire detection and alarm systems,
- Automatic activation of traffic control systems,

- Activation of emergency ventilation system to control smoke propagation until the fire department arrives at the scene of the accident.
-

Year	Tunnel	Length	Deaths	Note
2001	Guldborgsund, Denmark	460 m	5	Front-rear collision in dense fog. Fire started 100 m after tunnel
2001	St Gotthard, Switzerland	16,918 m	11	Duration of fire : 2 days
1999	Tauern, Austria	6,400 m	12	Collision, paint/lacquer (total loss : 24,7 M€)
1999	Mont Blanc, France/ Italy	11,600 m	39	Serious damage to about 100 m of ceiling (total loss : 392 M€)

Table 1: Fire accidents and their consequences in some road tunnels (Source : PIARC)

Among safety measures required to limit fire damage, it is of utmost importance to control smoke propagation to provide free access to emergency services and safer movement of people.

In this paper, we focus on the issue of smoke confining with air curtains. Only a few studies have addressed this approach. None of them give detailed information on relevant flow characteristics. As per our current knowledge, the only air curtain installed in a road tunnel is in the underground interchange A13 of the A86 West Underground Link-up of Paris, France (figure 1a). The single-jet air curtain installed in this tunnel is inclined towards the higher pressure side (Altinakar, et.al., 2001). Results showed that for U_o = 30m/s and for an inclination α = 35° the apparatus has an almost zero leakage up to a pressure difference of 80Pa.

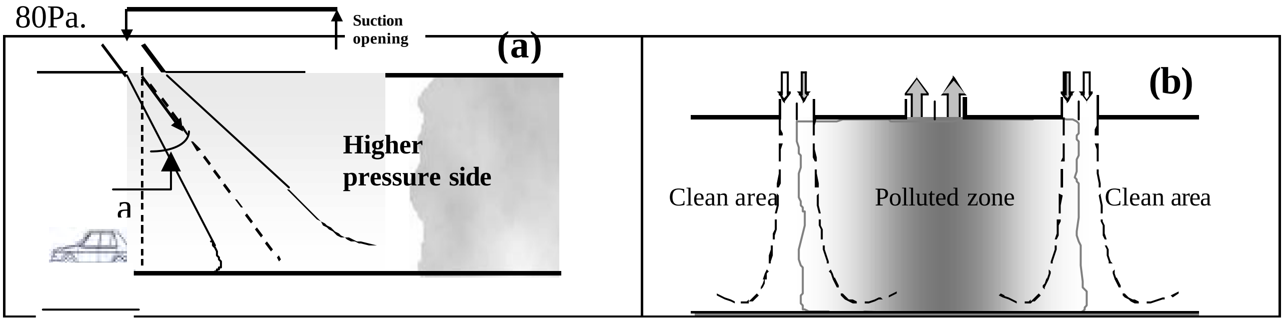


Figure 1: Application of air curtain in tunnels (a) traditional air curtain, (b) present curtain configuration

Traditional air curtains are efficient for area separation. However, such systems are unable to provide confinement because of the unidirectional flow. This paper intends to give information on arrangements involving two curtains for smoke confining (figure 1b). The flow dynamics of various curtain configurations with one or two jets were studied with PIV. Tracer gas experiments were conducted to quantify the efficiency of these configurations.

2. EXPERIMENTAL SET-UP

A sketch of the experimental set-up is shown in Figure 2. The experimental facility consists of a wind tunnel that is 6000 mm long, 1000 mm wide, and 300 mm high. These dimensions correspond approximately to a 1:17th scale reduction for a standard road tunnel. The test facility hosts two curtains at 3000 mm from each other (approx. 50 m on full scale) and two exhaust vents (50cm each) between the two curtains. The curtains could be operated in various modes. The width e of all the inlet nozzles was 15mm. The height to nozzle width (H/e) ratio was kept constant at 20 for all cases. The jets were supplied through totally independent air circuits. During experiments, the pressure difference between the tunnel ends was approximately 0.02 Pa. The initial velocity U_0 of each jet at nozzle exit could be adjusted independently. The results presented here have been obtained for the three configurations of air curtains shown in figure 2a (presented herein is arrangement in one curtain, same arrangement was used in another curtain).

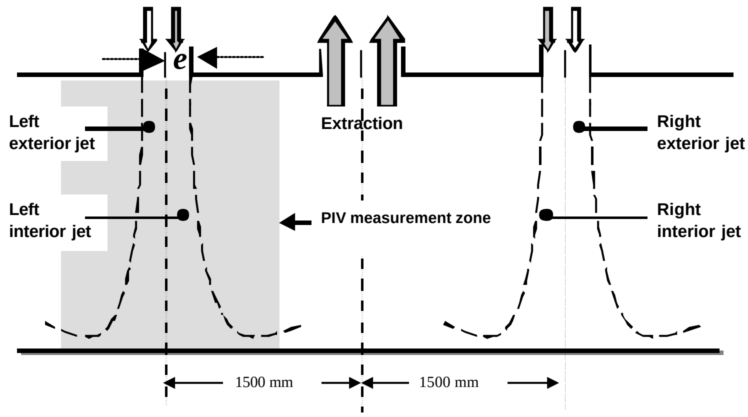


Figure 2: Sketch of experimental set-up

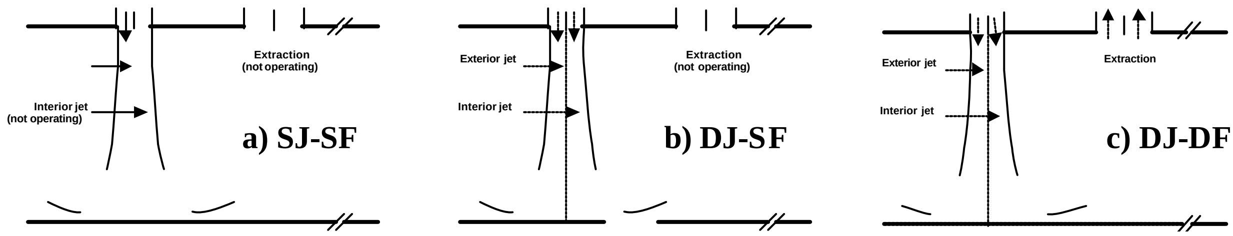


Figure 2a : Various configurations of air curtains : a) single jet- simple flux (SJ-SF), b) double jet- simple flux (DJ-SF), c) double jet- double flux (DJ-DF)

3. INSTRUMENTATION

3.1 Particle Image Velocimetry (PIV)

PIV is a non-intrusive whole-field-view technique providing instantaneous velocity vector measurements in a cross-section of a flow. Technique consists in illuminating the measurement domain with a laser. Taking two images shortly after each other and correlating these two images allows estimating the distance seeding particles have travelled within the time interval that separates the two pictures.

Measurements were taken in X-Y plane. The measurement section was illuminated by a Nd:YAG twin laser system (Quantel Inc.). Three smoke generators were used to avoid conditional sampling. Images were captured using a 1k x 1k Kodak Megaplus ES 1.0 cross-correlation CCD camera synchronised with the laser. The software FlowManager (Dantec Inc.) was used for image acquisition and post processing. Pairs of images were recorded at a frequency of 15 Hz. To ensure the statistical independence of average results, 500 image pairs were recorded for each measurement series. The images were divided into 16 x 32 pixel interrogation areas with 75 x 50% overlap. This generated 15438 vectors in each vector map. Raw vector maps were post-processed by applying various validation methods (peak validation, velocity range validation, and moving average validation) prior to estimation of statistics.

4. RESULTS AND DISCUSSION

4.1 Flow Dynamics

Measurements were taken for Reynolds number (Re=$U \cdot e/u$): 1000, 3000, 5000, 7000, and 10,000 for the three configurations mentioned in section 2. This paper presents results for Re=1000 and 7000 only. The exit velocities for all operating jets were kept equal for a given configuration.

Flow structures in studied configurations changes due to the presence of splitting plate in case of double jets. In case, mixing of surrounding air takes place in two lateral shear layers. In addition to these two shear layers, in the case of double-jet air curtains (configurations 2 and 3), a Von Karman vortex street forms in the wake downstream of the nozzle splitting plate (figure 3a). No ambient air is present in the wake up to a distance *x* about 8*e*. Further downstream, the surrounding air starts to mix with the wake structures. The mean velocity field corresponding to the instantaneous image of figure 3a is given in figure 3b.

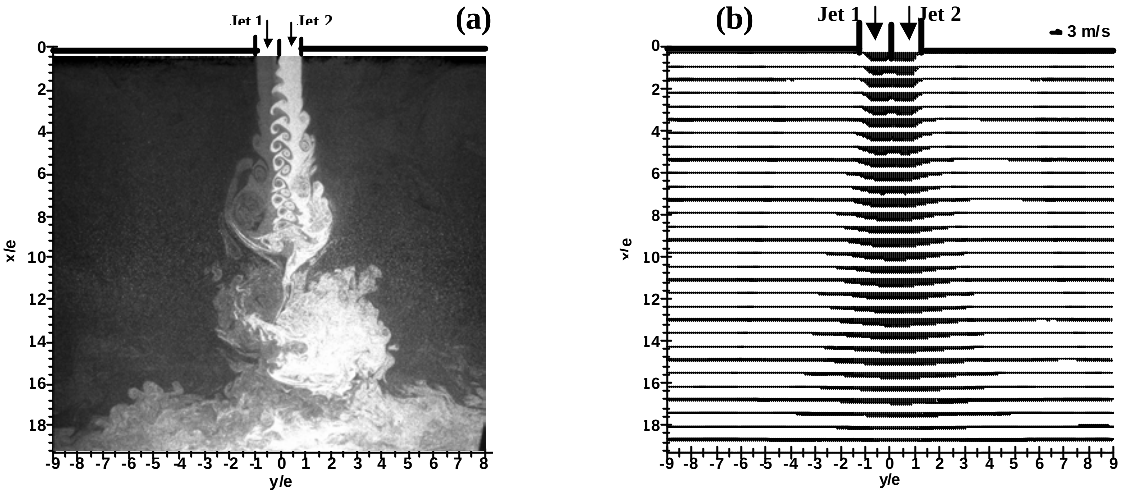
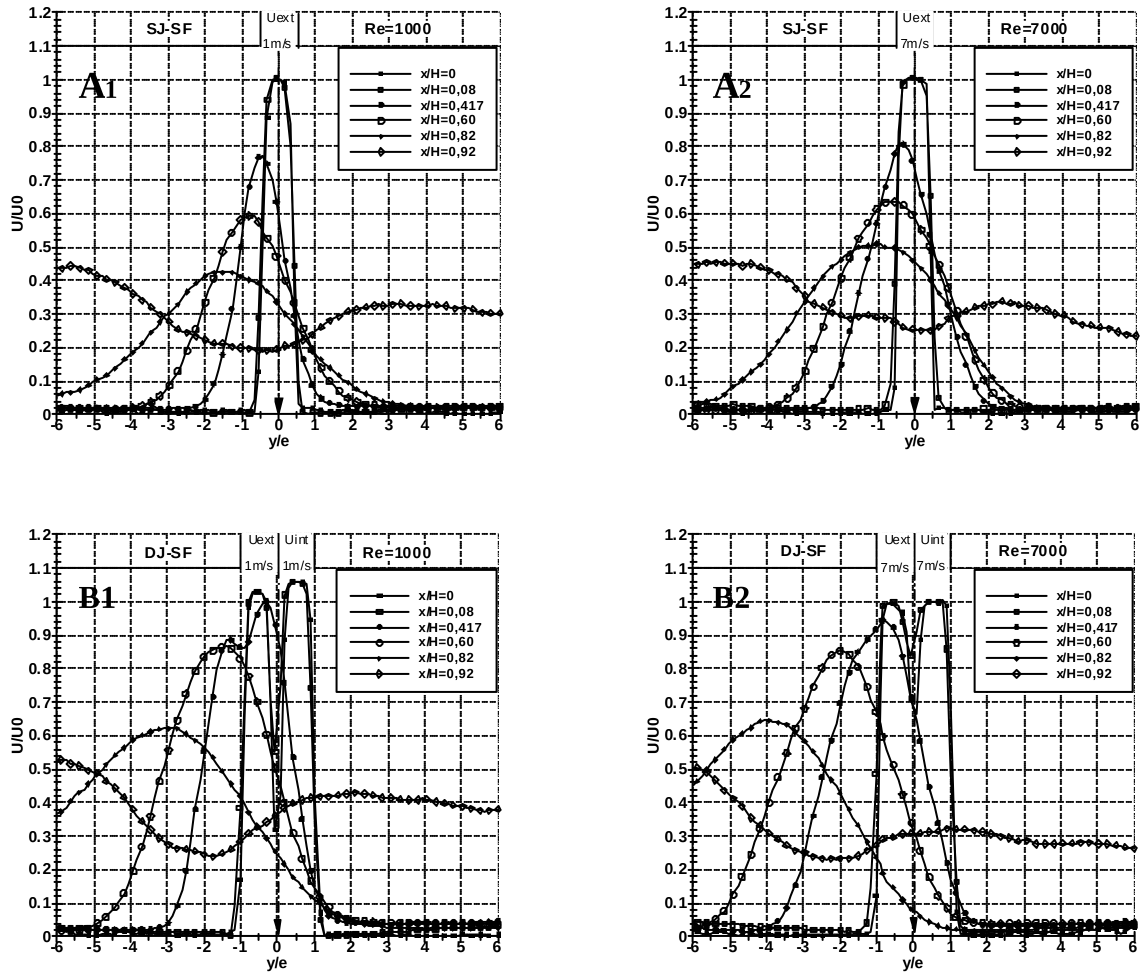


Figure 3: Double jet 'double flux' (DJ-DF) curtains: a) Image map, b) vector map for Re=3000

In figure 4, mean velocity transverse profiles have been plotted for *x/H*=0, 0.08, 0.30, 0.417, 0.60, 0.82 and 0.92, i.e., for streamwise distances within the 5 flow regions as defined by Maurel et al. (2004) for a single jet. Exit velocity profiles exhibit 'top hat' shapes for both single and double jet configurations at Re=7000. Such profiles could not be achieved for Re=1000 profiles. In this case, profiles were parabolic because the channel flow upstream the nozzle exit is laminar. Simple and double flux curtains were having deviation in the presence of another curtain. The length of potential core was found to be of the order of 4 to 5 times '*e*' for simple and double flux curtains. That is in accordance with previous study (Maurel et al., 2004) on simple plane turbulent impinging jet.
In the double jet configurations, velocity profiles exhibit 2 maxima until *x/H*=0.417. Till this distance, the interior and exterior jets behave almost as separate jets till this distance (figure 4 B1, B2, C1, C2). However, there is a tendency for the two initial jets to mix earlier downstream of the splitting plate with increasing Reynolds number. Further downstream, the flow behaves like a single jet. In the case of a single jet, it is known that the potential core, which extends up to about *x=5e*, is rather impervious, i.e., no mixing with ambient air takes place in this region. Although double jet air curtains are more impervious than single jet curtains (see section 4.2), it is yet to find out the influence of near field region that differs from single jet curtains.

In cases 1 and 2, which both correspond to a ‘simple flux’ arrangement, the two simultaneously operating curtains deviate towards the tunnel ends whatever the Reynolds number is (the right hand side air curtain behaves symmetrically to the left hand side curtain). Although the results presented here concern solely the left hand side curtain, this was verified numerically on the basis of simulations with the CFD code Fluent[TM] and experimentally by means of flow visualizations with smoke. In the double flux case, the curtains deviate one towards each other for Re=1000 while they impinge perpendicularly to the floor at Re=7000. This can be explained rather easily from considerations on mass conservation. From this, it can be anticipated that double flux configurations may be tighter than simple flux configurations.



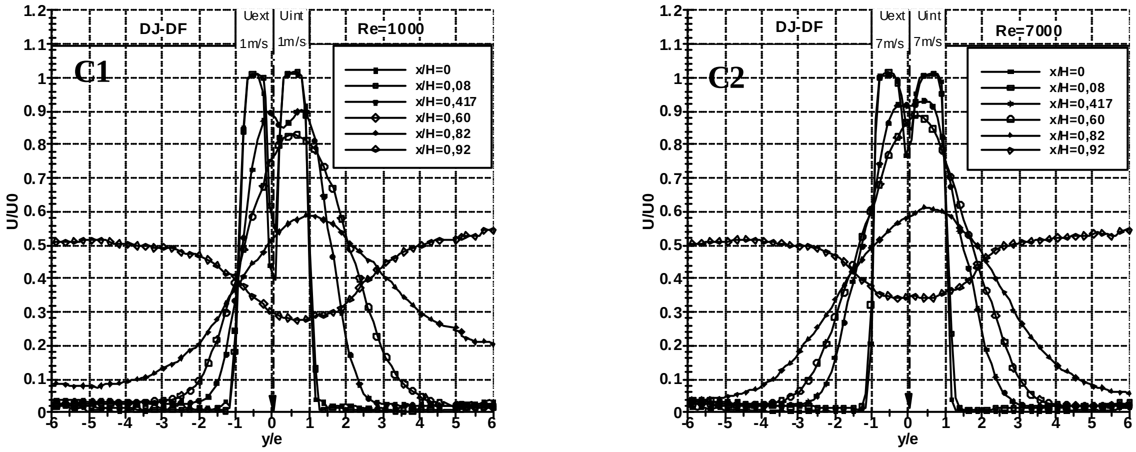


Figure 4: Transversal velocity profiles for single, DJ-SF, and DJ-DF air curtains for Re=1000, and 7000

4.2. Confinement efficiency

Global information on flow dynamics is not sufficient to conclude about the efficiency of the proposed solutions. A finer analysis of the turbulent characteristics (Reynolds stresses, turbulent fluxes, instability modes, coherent structures and their role, etc.) of the investigated configurations is necessary. This is in progress. However, tracer gas experiments were conducted to get a better idea of the confining efficiency of the configurations tested throughout this work.

This allowed us to estimate the neat leakage flow rate (Q_l) of the investigated apparatus. During the corresponding experiments, only one curtain was operated. Only half of the whole tunnel was used as shown in figure 5a. The confinement volume achieved this way was 0.30 or 0.45 m^3 case depending. The experimental procedure was similar to the one used by Pavageau et al. (2001). The cavity was filled with ethane until an initial concentration of about 8000 ppm was reached. Note that the open end of the tunnel was closed during filling to limit gas losses by diffusion to the ambience. Note also that the value of the initial concentration C_0 was not very important since we were only interested in the concentration decay rate within the confined area. The source was then turned off before operating the air curtain. During experiments, the ethane concentration was measured with a Fast Ionisation Detector (FID) for hydrocarbon concentration detection. The sampling capillary tube was placed at 40 cm away from the curtain centreline, at a height of 150 cm. The output signal from the FID was monitored online and recorded at a sampling frequency of 1Hz until the concentration of ethane inside the volume had decreased to nearly ambient value. Typical concentration records resemble the one shown in figure 5b.

It can be shown analytically that $C(t)$ is given by equation (1), where V is the cavity volume:

$$C(t) = C_0 \exp\left(-\frac{Q_l}{V} t\right) \qquad (1)$$

Figure 5c and 5d show the concentration decay for Re=1000 and 10,000, respectively, for all tested configurations. For Re=1000, the curves for simple flux curtains (with either one or two jets) exhibit larger fluctuations than for the double flux configuration.

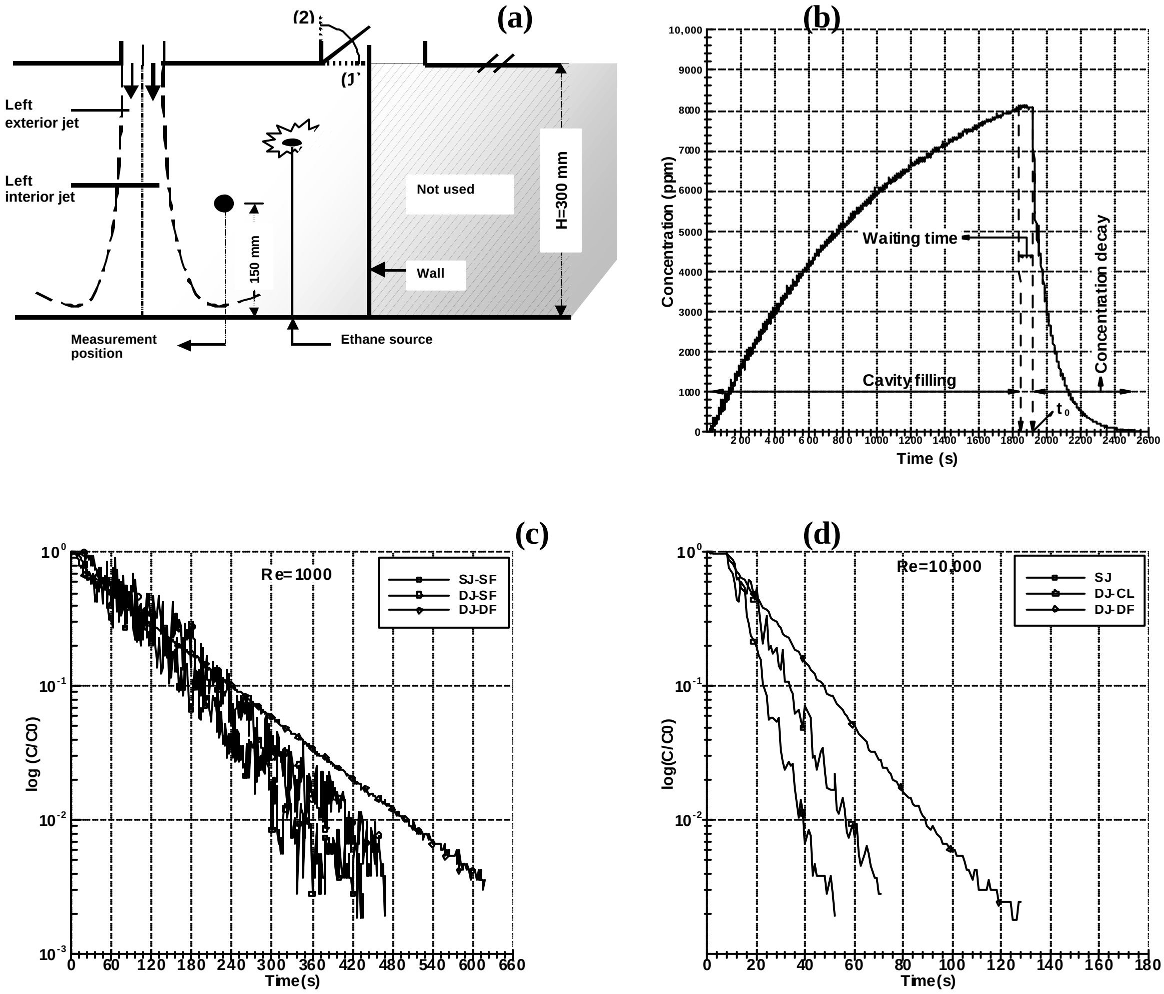


Figure 5: a) Set-up for FID measurement (position flap 1: Simple flux curtains; position flap 2: double flux curtain), b) Typical concentration record, c) Decay curve for Re=1000, d) Decay curve for Re=10,000

This reflects strong differences between the single and double flux arrangements in terms of stability (reduced flapping of the jet for the double flux configuration) and regarding the flow structure of the recirculated air in the cavity. The extraction provided in the double flux configuration additionally ensures enhanced mixing of the gas mixture in the confined area. The standard deviation of theses fluctuations tends to decrease with increasing the Reynolds number. This indicates higher stability of the apparatus at higher Reynolds numbers and, again, better mixing.

The leakage rate to the jet discharge rate ratio Q_l/Q_j has been plotted as a function of the Reynolds number in figure 6. It can be seen that, at a given Reynolds number (i.e., at a given exit flow rate or energy input), the double flux configuration turns out to be the most efficient. No clear tendency towards an optimal inlet flow rate could be drawn although the ratio Q_l/Q_j seems to converge from Re about 3000. These results are in good agreement with previous experiments (Pavageau et al., 2001).

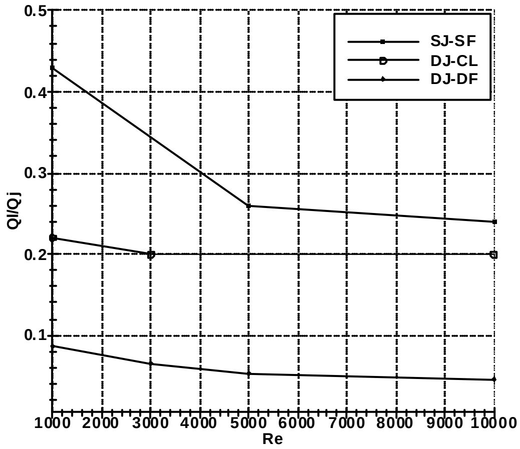


Figure 6: Ratio of leakage rate (Q_l) to jet discharge rate (Qj) vs Re

5. CONCLUSION

The results of the present study indicate that double-jet air curtain systems can reduce smoke and toxic gases propagation more efficiently than single-jet curtains. Moreover, double-flux arrangements seem to be more efficient than systems based on the supply of only fresh air. It should be added that we know from earlier works that the air curtains designed in this study (straight jets for a ratio *H/e* about 20 correspond to the worse situation in terms of tightness. This choice was deliberate so as to investigate the upper limits of such arrangements. The systems presented here can be made much more efficient with little effort by using inclined curtains for example.

The results presented here are rather limited. Much more data are available. For example, the effect of an inlet velocity differential in the case of double-jet systems has been investigated. Numerical simulations have been carried out also for heated flows. The corresponding results will be presented elsewhere in future communications.

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EFFICIENT TUNNEL VENTILATION

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ABSTRACT

Considering as example of an existing tunnel (length 5.5km) there will be shown that with a modern re-fitting of the entire ventilation system you can achieve energy cost savings of about 30 per cent. These possible cost savings are quite evident against the background of the most important fire preventions. Cost savings gained from the normal tunnel-operation can be reinvested into safety. The approach to this can be with intelligent aerodynamic calculation methods as CFD for the entire tunnel ventilation system composed of fans, dampers for supply-and exhaust air on one hand and on the other hand with a completely new designed fan. The numeric design methods for tunnel-ventilation are a must, because complex tunnel-architecture demands the Modern Cost Efficient Tunnel Operation. It will be demonstrated that new lightweight 600°C resistant materials are qualified to replace the conventional fan materials which can help to reduce the GD² of the rotating mass. With non ferric materials you can get better fan profiles for better aerodynamic efficiency. The consequences are smaller electrical drives. Especially bad electrical network conditions at older tunnel installations could effort very cost intensive changes. Under the mentioned circumstances the electrical installation must not be refitted. Control elements can be designed for less power. The fan run up period can be cut. New fire prevention scenarios can be fulfilled. Effective aerodynamics paired with modern control and measurement devices (e.g. quicker blade adjustment, frequency converter) will enlarge the characteristic diagram of the ventilation system towards cost efficient operation. In a three layer integration model it will be shown that the connection of a fan redesign, new aerodynamic calculation attempts and state of the art controls brings considerable operation cost reductions for the carrier. (mechanics-aerodynamics-electrics) All mentioned steps are not limited on new tunnel architecture. Far from it. In most cases of older tunnel systems Modern Cost Efficient Tunnel Operation can be achieved.

Key words: tunnels, virtual design, numerical simulation, CFD, FE, ventilation, safety

1. BACKGROUND

Ventilation is an essential part of today’s tunnel operation. Fire fighting as well as compliance with air quality regulation would remain impossible without the appropriate ventilation and fan technology. Such technology including the associated design concepts served us well over decades. However, in last year computer power, simulation software and material science came a long way. The development of computer power is described the observation made in 1965 by Gordon Moore, co-founder of Intel, that the number of transistors per square inch on integrated circuits had doubled every year since the integrated circuit was invented. Moore predicted that this trend would continue for the foreseeable future. In subsequent years, the pace slowed down a bit, but data density has doubled approximately every 18 months, and this is the current definition of Moore's Law, which Moore himself has blessed. Most experts, including Moore himself, expect Moore's Law to hold for at least another two decades. This seams to be a rather abstract description; relevant to us is that everything from fan to full tunnel can be simulated with a PC type computer or computer cluster over night. CFD and FE software producers have been encouraged by computer hardware development and integrated full multi physics models in their codes. Highlights of such are detailed chemistry models, moving geometry, fluid structure interaction and acoustic models. Sometimes these models can even be used combined and in real world problems. While in recent decades simulation was the domain of highly specialized gurus it becomes the tool of the design engineer today. This is possible due to ease of use and quality assurance of the software where in some tools the user is not even seeing the computational grid anymore. Also material science has made much progress. Our fathers lived in a world of steel and cast and had to obey the associated design limitation like high mass etc. The present generation enjoys the gifts of glass and carbon fiber and the very expensive but extreme heat resistant carbon carbon technology used in challenging projects like the space shuttle. Present research will hopefully enable our offspring to use Titan and Titanaluminate. The advantage of this technology is obvious to everyone even if tunnels mostly seam belong the world of our fathers. In this paper we want to show the benefits of new technologies like FE, CFD and modern material usage and compare profit and cost for one particular tunnel. First, the fan will be discussed in all aspects, followed by control elements; finally a holistic view of the full tunnel will be given.

2. FAN

The core element of each ventilation system is the fan. Fans are available as industrial standard fans including data sheets from various manufactures. However, the way these fans are designed and certified is no optimized for tunnel operation. The industry standard is based on DIN 24163 T2 or the ISO 5102/5103. All mentioned performance data is focused on that. Following a comparison of a ‘catalog’ fan and a designed blade under regular operating conditions is given. Therefore a CFD and FE analysis were conducted. The new blade geometry was generated by using a semi empirical but state of the arte design software. One blade of an industrial fan was placed in a 72 degrees periodic segment with semi sphere upstream and tube with symmetric wall downstream condition. Zero total pressure at the pressure inlet and zero static pressure at pressure outlet. Figure 1 shows geometry and evaluation planes.

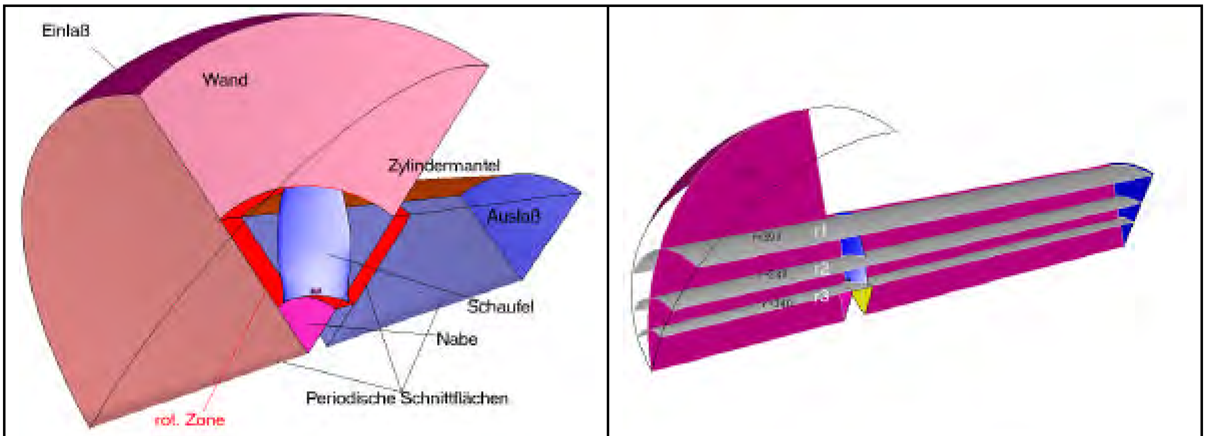


Figure 1 Geometry and evaluation planes.

The operational speed was 1450rpm. Following tables show a comparison of vectors, plots and oil flow lines of old and improved design.

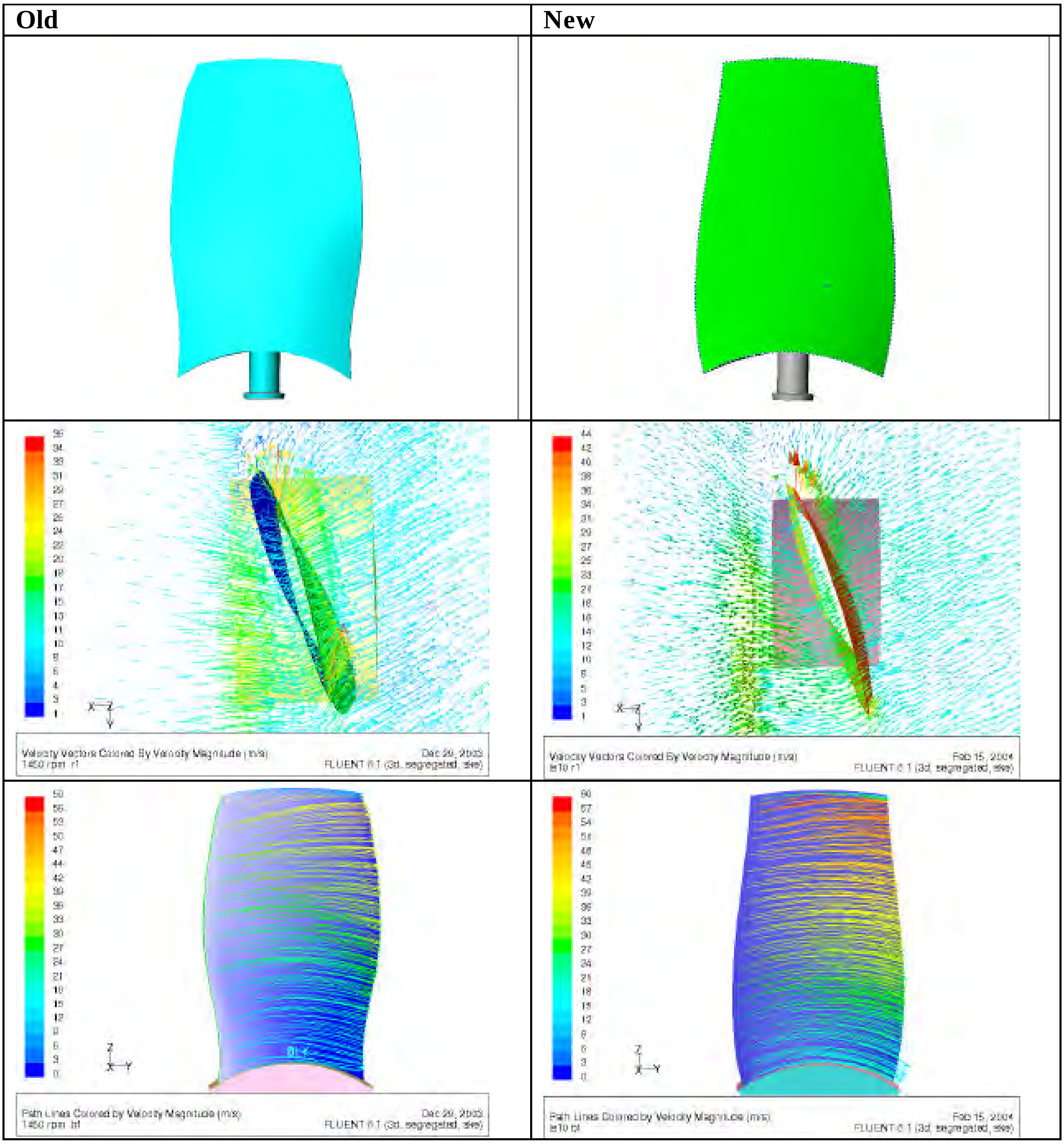


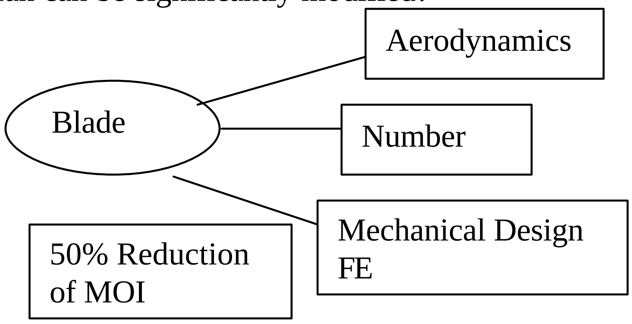
Figure 2 Results Fan

For the reason of simplicity we normalize all output values base the old case

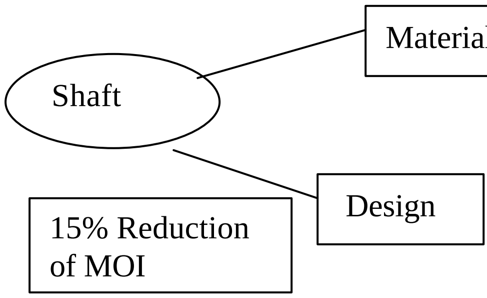
old	New
Normalized mass flow: mdot=1	mdot=1.06
Normalized pressure gain: p=1	P=1.15
Normalized momentum: M=1	M=0.93
Normalized aerodynamic efficiency: eta=1	eta=1.21
Normalized blade mass : m=1	M=0.93

3. FAN AND FANMATERIALS

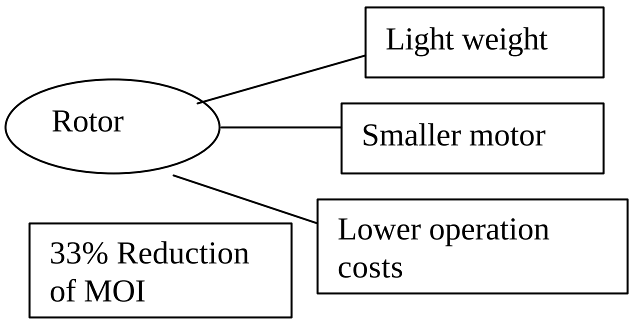
What elements of a fan can be significantly modified?



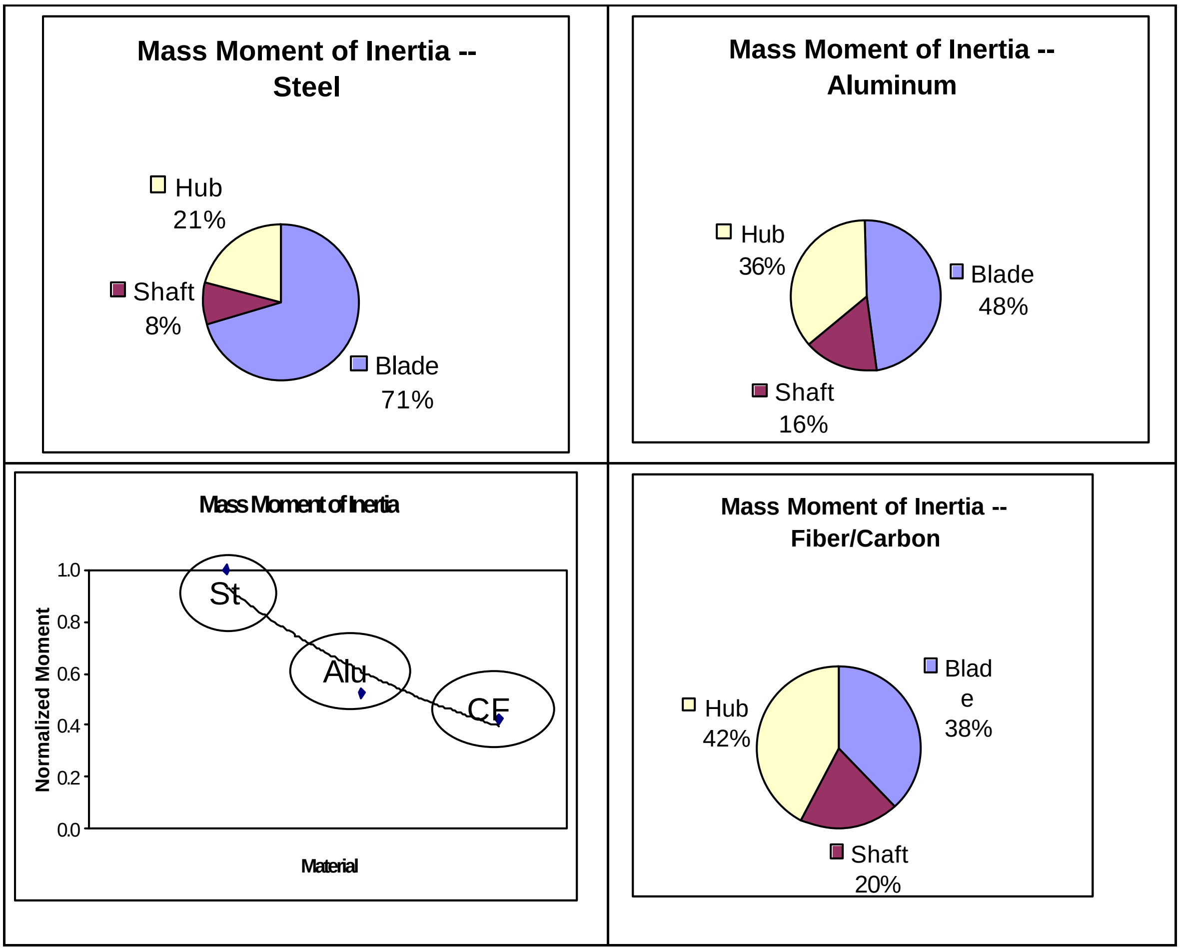
The chances to reduce the moment of inertia are the highest by changing the blade material to other than steel or cast. Using the possibilities of reducing blade number and better aerodynamics can provide a total reduction of moment of inertia of 50%.



The situation at the shaft is not as prominent. Overall 15% of moment of inertia can be saved here. Design parameters are materials (SiC, CFK etc.) and a very slim geometry with light bearings.



The rotor itself can be reduces in weight by 33%. The design can be lighter due previous reduction discussed. Therefore also the motor can be reduced to 30% of it's power. The following figures show again the moment of inertia distribution of various materials. Material properties are the most important design parameters in the new generation of low-pressure fans. Heat resistant synthetic materials will replace steel and cast. In aluminum technology alloys with resistance up to a temperature of 400°C are already available.

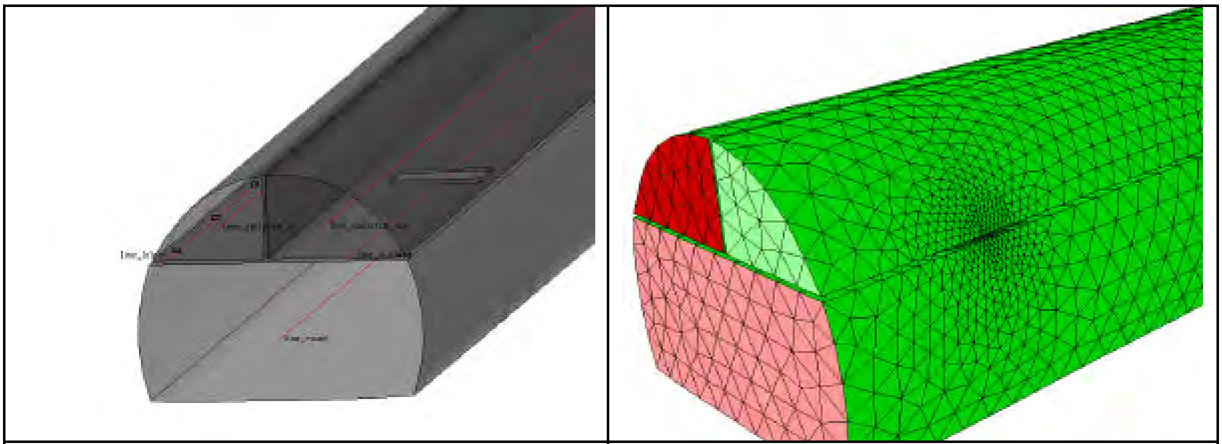


Example calculation:

Common fan	**New fan**
Diameter = 2200	Diameter= 2200
Theta= 6.05E+06......	Theta=2.58E+06
P el = 750 kW	P el = 250 kW
Rotor mass = 5500 Kg	Rotor mass = 2000kg
Start up time = 70 s	Start up time = 25 s
(with FU and stabile supply!)	(Even with unstable power supply!)
rpm = 1.000/500	rpm= 1000/500
Blade number = 20	Blade number= 18
Adjustable pitch	No pitch adjustment
Hydraulic system needed	
Delta p = 180 Pa	Delta p= 200 Pa
Volume flow = 200 m³/s	Volume flow= 230 m³/s

4. SIMMULATION FULL TUNNEL

To validate CFD results of full tunnel simulations the recently renovated Felbertauern Tunnel has been modeled. The geometry was implemented assuming symmetry halfway though the tunnel respectively after 2.8 km. The tunnel has a road level and two calottes one for ventilation inbound and one for ventilation outbound. The inbound calotte is distributing fresh air via small inlets close to the wall from the ceiling of the road level. The outlet calotte is sucking outbound air from the road level via few big holes in the ceiling. The outlet calotte serves also as escape way in case of fire. A huge fan at the tunnel portal feed the inlet calotte.



Tunnel segment | Computational grid

Figure 3 Geometry and evaluation planes

This fan was replaced during recent renovation of the tunnel. Ventilation target is to provide an even airflow from inlet to outlet and at least 5 Pa relative pressure with reference to the road level. The ventilation was designed by semi empirical methods and could not reach target. Our CFD simulation could provide explanation. Figure 3 shows the used mesh and Figure 4 the boundary condition used. Furthermore we show path lines in various segments of the tunnel. Also we compare experimental measurements and simulation.

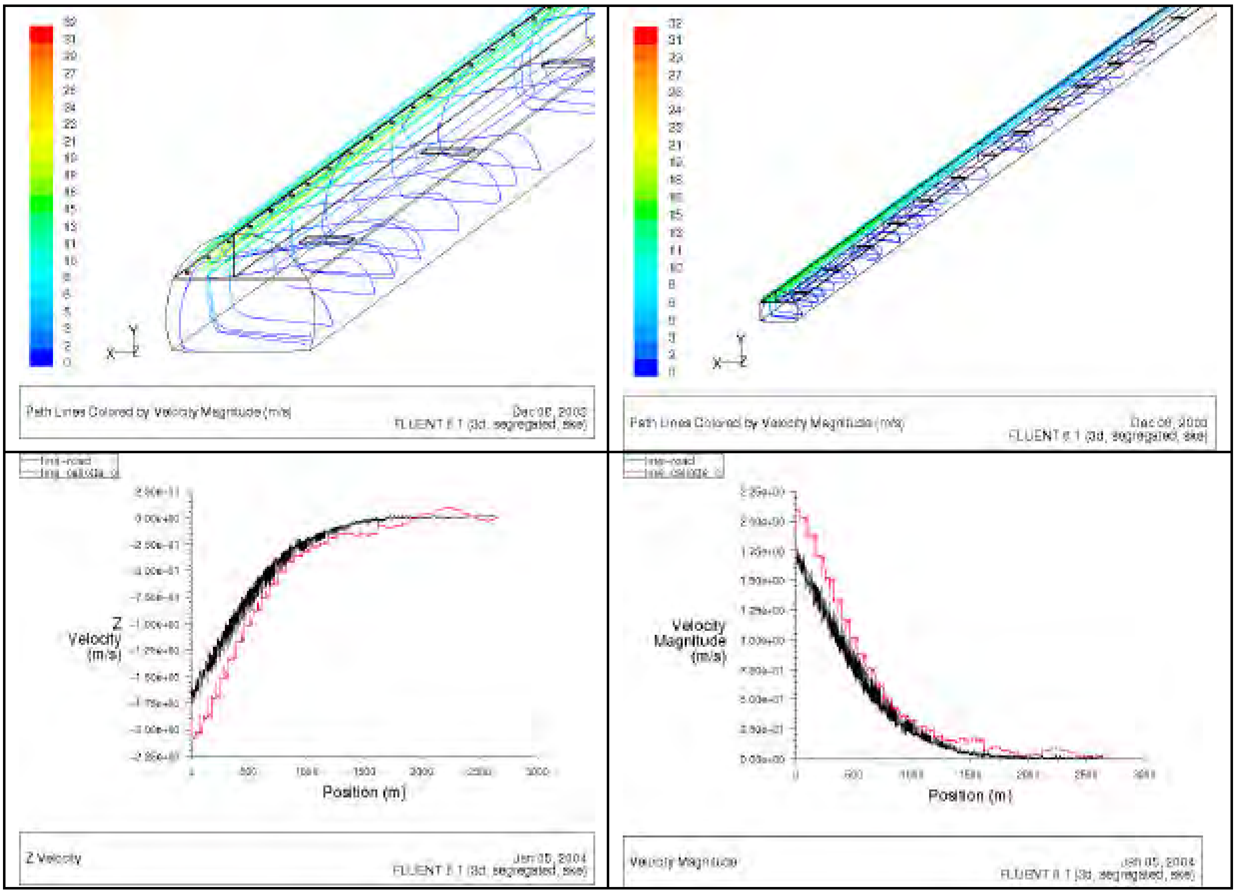


Figure 4: Results Tunnel

One can easily spot that this design cannot reach ventilation target. If CFD would have been used earlier in design this problem could have been avoided. Finally we show results of a simulation run where traditional tube fans have been added to the ventilation system. Adding a momentum volume source in parts of the inbound calotte numerically did this. If these would be added in reality ventilation targets could be fulfilled. CFD can be valuable tool in choosing an appropriate location for such additional fans.

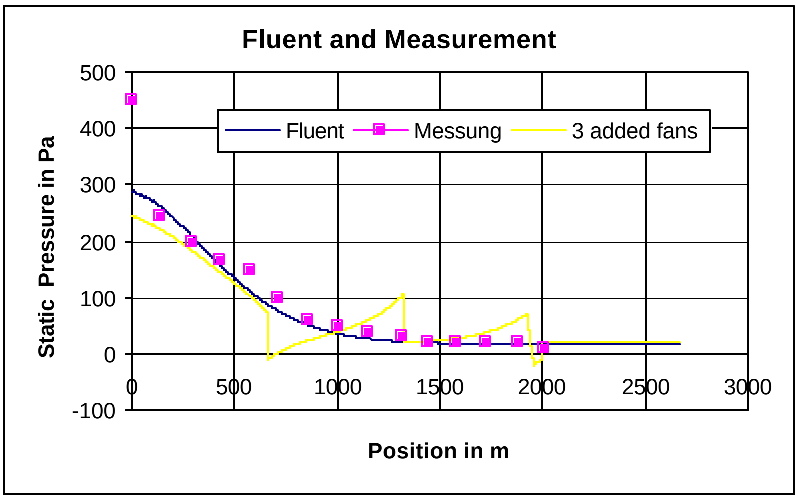


Figure 5: Fluent Results and Measurements

Safety- and economy- advantages with CFD

The modern method of partial air injection or partial air suction needs fundamental knowledge of the participating fans, dampers etc. during design or redesign period of the tunnel. This needs highly sophisticated calculation tools like CFD or FEM. The great advantage of this kind of ventilation method is the presence of fresh air sources over the length of the tunnel. The most important requirement is the consistent distribution of fresh and suction air. This is evident for the different complex ventilation scenarios. The consideration of these complex operations (pressure-, mass flow-, temperature-, velocity-and geometry references) gives sense to switch to numerical methods for safety and economic considerations.

Safety at tunnel ventilation in future stands for:

Early detection danger situations	modern sensors
Quick activation of the relevant process chain	Modern process computing
Start of all units for supply- and exhaust air (fans, dampers etc.) calculated airflow under normal conditions and at hazard	Electrical control elements
Initiation of all controlling mechanism Control of all safety installations	Process software

Efficiency at tunnel ventilation in future stands for:

Only so much linked hardware as necessary	CFD gives clear aspects about mass flows, pressures etc. (fans, dampers) Demands on the hardware construction of fans up to the aerodynamic design of the blades

Light but heat resistant fans	FEM gives clear aspects about the necessary hardware configuration and the joint start up times at fire.
Small electrical drives are quicker at rated power Lower primary energy consumption	
Auxiliaries (e.g. hydraulic) are much smaller, modern sensors giving a clear picture at a disaster	

It is now shown that modern design tools will allow to increase the efficiency of complex air management in tunnels.

3-layers model

CFD	aerodynamics	to be influenced
	Tunnel design	no
	Damper design	yes
	Fan design (number of blades)	yes
FEM	mechanic	
	Hub weight	yes
	Blade weight	yes
	Blade pitch	yes/no
Process control	electronics	
	Integrated sensors in dampers or ceilings	yes
	learning systems for the fan	yes

5. COSTS

Taking the purchase costs of a conventional portal fan with 700.00 €, without assembly, than adding the annual operating costs over a operating time period of 30 years, you will get direct costs without maintenance of 1.3 Mio € .If you choose a "light weight" axial fan with modern design you will effort costs for the fan only by 350.000 €. Also the operating costs are cut down to the half, namely 10.000 €.

Production costs axial fan conventional design (large theta)	700.000 € (without assembly)	Production costs axial fan modern design (small theta)	350.000 € (without assembly)
Operating costs over 30 years*	600.000 €	Operating costs over 30 years*	300.000 €
Total	1.3 Mio. €	total	650.000 €

* averaged times of operation

6. SUMMARY

The last shown figure shows what chances you will get taking the right material for developing a modern axial fan with small mass moment of inertia. Not yet mentioned are the also reduced secondary energies like hydraulic power for the blade pitch and the bearing system. All auxiliaries can be defined smaller.
The fan will be smaller.
The efficiency will increase.

TUNNEL OPERATION : THE E40-E25 LINK (LIEGE, BELGIUM) SPECIFIC SAFETY MEASURES AND EXPERIENCE FEEDBACK

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ABSTRACT

At the end of the last century, due to the increasing of the traffic, it was necessary for Liège to develop this motorway. In order to remedy this situation, the 'E40-E25 link' was built. The new motorway, characterised by dense urban traffic (over 60 000 vehicles/day), has allowed improvements to traffic flows inside and outside the city of Liège.

Concerning the safety facilities, in addition to more classical facilities that equip modern tunnels, particular measures include: lay-bys, link tunnels, central evacuation tunnel, dynamically managed diversion routes (with rotating dynamic prism signs), a central scenario management server (which can command over 450 dynamic signalling units to automatically activate scenarios in case of incidents).

For all these aspects, it is interesting to analyse the information feedback after three years of operation especially concerning the need for lay-bys, diversion routes and a central scenario management server.

It is important to note that all these operation procedures would not exist without a lot of upstream effort concerning the operations strategies. A working group was created with all the actors concerned (Police force, fire brigade, ambulance services, operation agents, etc). This working group defined a set of operation guidelines with two main phases: firstly a concertation phase defined basis points, and secondly a phase to determine the main principles of incident management.

Periodically this working group analyses the information feedback to adapt or/and change scenarios. After three years of operation it is valuable to take stock of the developments and to establish whether or not the basic assumptions remain valid. .

To conclude, this project has proved to be rich in terms of learning, both for its urban conception and for the number and quality of infrastructure and equipment put in place to ensure the treatment of incidents. It has also been an education in terms of the multiplicity of actors and the resultant necessity to communicate on the project rising above the technical jargon used by each area of activity in which the various actors are involved.

Key words: tunnels operation, safety measures, experience feedback

1. BACKGROUND

During the development of Belgium's motorway network in the 1960s and 70s, Liège became a key node in the country's road infrastructure. Not having a ring road, the city centre naturally became a transit zone and, with the growth of road traffic in Europe, rapidly became saturated. In order to remedy this situation, the E25-E40 link scheme was proposed. The choice of routing by a new tunnel at Cointe was made during the 1980s. The final scheme comprised three tunnels (one of which is over 1.5 km long) and numerous civil engineering works.

In a European context, the opening to traffic of the link on 7th June 2000 represented an essential link in the Amsterdam – Milan corridor. The new motorway, characterised by dense urban traffic (over 60 000 vehicles/day), has allowed improvements to traffic flows, it has increased transit capacity across the city of Liège for regional, national and international traffic and, of course, led to a significant reduction in congestion in the city centre.

Road operation

The construction and opening of the E25-E40 link constitutes a significant “double first” for the Walloon Region. Firstly, because of the magnitude of the investment and the technical challenges, but also because of the significance of the “road operation” function which was developed. The Walloon Transport Ministry (MET - Ministère Wallon de l’Equipement et des Transports) is conscious of the growing importance that road users, its clients, now attach to the quality of service they receive. The resulting notion of road operation and its corollaries in terms of traffic and incident management therefore received special attention.

In this context, as well as in the context of international sensitiveness following the serious accidents in the Mont-Blanc and St Gotthard tunnels, the co-ordinated implementation of technical and organisational systems constituted a priority for the Walloon Region. Another priority was its integration into the architecture of the WHIST (Walloon Highway Information System for Traffic) project, for which the PEREX (PERmanence d’EXploitation (operation permanence) centre is the central hub.

The options retained by MET in this sense were precursors, in several domains, to the recommendations given in the French ministerial circular on tunnel safety (No. 2000 – August – 20) and to the proposal for a European Directive concerning safety requirements for tunnels.

2. CHARACTERISTICS OF THE LINK

2.1. Overview

The E25-E40 link, of 4 km in length, is an urban motorway with two traffic lanes per direction (without emergency or hard shoulder lanes). It is effectively an extension of the A602, a motorway which enters the city of Liège. It therefore fulfils a function of serving regional traffic as well as national and international traffic.

Due to its technical complexity and a dense urban environment, its route passes through two tunnels (one per direction) and over a cable-stayed bridge, involved cut-and-cover sections and even the displacement of part of the River Ourthe (a tributary of the Meuse). Moreover, the covered section at Kinkempois is situated below a major railway junction (known as “Quadrilatère SNCB (Société Nationale des Chemins de Fer Belges (Belgian State Railways) with more than 11 lines).

Furthermore, the traffic and incident management via the local traffic monitoring centre at Tilleuls covers a motorway section of around 10 km in order to take into account the northern and southern approaches to the E25-E40 link.

2.2. Civil Engineering and Electro-mechanical Equipment

Civil engineering:

The major civil engineering structures on this link comprise the following:

- The Guillemins viaduct (over 600m long),
- The parallel Cointe tunnels (1639m and 1511m),
- The Pays de Liège bridge (cable-stayed bridge over the River Meuse, 327m long),
- Two cut-and-cover sections (Kinkempois, 635m long, and Grosse-Battes, 376m long) and
- The urban intersections at Guillemins (central railway station, including high-speed trains), at Val-Benoît and at Grosses-Battes.

Electromechanical Equipment:

Such a link also requires high-performance electromechanical equipment both from a structural point of view and from an operational one (safety, guidance, user "comfort", etc).

The main equipment used comprises the following:

- Over 200 CCTV cameras;
- An AID (Automatic Incident Detection system) using high-performance cameras;
- Over 450 dynamic signalling units;
- A centralised technical management (SCADA) system, known as the GTC (Gestion Technique Centralisée);
- Emergency call boxes: 25 per direction;
- Technical alarms (pollution detection, visibility-meter, etc): these are managed by a remote management SCADA system; and
- Traffic counting using loops.

3. SAFETY FACILITIES

Concerning the safety facilities, in addition to more classical facilities that equip modern tunnels, a focus on particular measures, such as:

- Lay-bys in the tunnels (every 400m),
- 7 link galleries for the Cointe tunnels,
- and a central evacuation tunnel between the two tunnels of the covered section at Kinkempois,
- Dynamically managed diversion routes (using rotating prism signs),
- A central scenario management server (which can command over 450 dynamic signing units) to activate automatic scenarios in case of incidents.

3.1. Description

Lay-bys

The lay-bys were foreseen at the construction stage and placed on the right side every 400 metres in tunnels (this means 7 lay-bys each direction). Each lay-by has a length of 60 metres with a width of 2.5 metres, which enables emergency parking for all vehicle types.

Cross connections (Cointe Tunnels)

The cross-connection tunnels provide a link to the parallel twin bore Cointe tunnels (1639 m and 1511 m, respectively). Positioned every 200 metres, these cross-connection tunnels have two main functions:

- Enable evacuation of road users in case of incidents, and
- Enable the intervention of emergency service personnel via the second bore tunnel

It is very important that the emergency services have accurate information on the status in the tunnels from the operations centre, especially in case of fire.

Central evacuation tunnel (Kinkempois Tunnels)

The Kinkempois cut-and-cover sections (635m long) include a central evacuation tunnel located under the road bed. This tunnel is pressurised to avoid the spreading of smoke in the event of fire.

The evacuation doors provide access to this escape route and also enable emergency services (e.g. the fire brigade) to pass from side of the road to the other (using a special key system).

Dynamic diversion routes

To minimise the impact on the city of Liège in the event of re-routing, a number of rotating prism VMSs (variable message signs) have been installed at strategic intersections in the city. Furthermore, re-routing for the E25-E40 link was broken down into discrete sections that can be managed independently are as a whole.

All the dynamic signs are managed directly by the operations centre through the use of a specially developed software application package called the "Central Scenario Management Server."

Central Scenario Management Server

This is an operator front-end server that allows scenarios and their activation to be calculated after a validation phase by traffic operators. This system is secured with redundancy of components (i.e. duplication of components to provide a backup in case of failure).

3.2. Information Feedback

The following table provides an overview of statistics related to the use of safety and re-routing facilities between June 2000 and February 2004.

Safety facilities	Number of activations
Lay-bys	Over 2000 "stop and go" per year 200 incidents per year Used 100 times per year by maintenance workers
Cross-connecting link tunnels (Cointe Tunnels)	1 fire incident and 1 serious injury since opening
Central evacuation tunnel (Kinkempois)	1 fire incident since opening
Dynamic diversion routes	10 activations per year
Central scenario management server	Over 500 activations per year

Since the opening of the E25-E30 link in June 2000, there has been frequent use of safety equipment in order to preserve an optimal level of service during incidents.
In addition, since the opening, we never had accident following an accident in progress. This is primarily due to the implementation and use extensive safety facilities. In particular, the lay-bys, used more than 200 times per year, have avoided the need for lane closures.

3.3. Real Example: Fire Incident on 3 February 2004

Chronology of events:

14:15: The AID system detects a lorry on fire in a lay-by
14:18: A dynamic scenario is activated the Central Scenario Management Server whereby the Link is closed
14:27: The fire brigade arrives on scene in the opposite direction of vehicle on fire. They utilise the access doors for the tunnel to pass from one direction to the other.
14:43: The fire is out.
15:15: Vehicles on the link are diverted via pre-defined routes (they were kept in place during the fire to avoid interfering with emergency vehicles and managing the fire).

The fire on the 3 February 2004 has demonstrated the usefulness of the range of safety facilities on the E25-E40 link. Their utilisation has enabled the following:

- Allow for the passage of vehicles at the start of the incident in relative safety (use of the lay-by),
- Enable rapid closure of the Link using the Central Scenario Management Server,
- Facilitate the fire brigade's rapid arrival on scene through the use of the access doors of the central evacuation tunnel, and
- Utilisation of the diversionary routes to manage traffic.

4. OPERATION GUIDELINES AND COMPUTERISED EVENT MANAGEMENT SYSTEMS

All the operations procedures would not exist without a significant level of upstream effort concerning the operations strategies. To achieve this goal, a working group was created with all the main actors concerned (Police force, fire brigade, ambulance services, operation personnel, etc).

This workgroup defines an operation guidelines with two main phases:

- Firstly, a concertation phase to define basis points: typology of incidents, communication procedures, definition of elementary segments for which basic scenarios exist (lane closure, blockage of two lanes, etc)); and
- Secondly, a phase to determine key principles: keeping users on the link in case of blockage, creation of a "virtual" emergency hard shoulder, diversion routes and diversions in the city, etc.

4.1. Preamble: The Consultation Phase

The implementation of an operators' guide implies a co-operative effort with the different actors brought together in working groups (the MET, the fire and rescue services, and the security/emergency services involved in case of an incident on the link).

This co-operation will also allow the project to be further developed, notably on the following points:

- Determining a typology of incidents on the link,
- Reviewing communication procedures,
- Simplification of traffic management on the link: the link is broken down into segments for which the following basic scenarios exist:
    - blockage, keeping users on the link in order to allow access by emergency services,
    - blockage, diverting users on the agreement of the emergency services, and
    - closure of the left-hand or right-hand lanes.

4.2. Incident Management: Main Principles

The main principles developed for incident management on the E25-E40 Link are:

- To keep users on the link upstream of any blockage instead of systematically diverting them away to other route(s);
- Creation of a "virtual" emergency hard shoulder: by closing a traffic lane using the traffic control signals in order to compensate for the lack of a hard shoulder on the motorway link;

- To determine appropriate diversion routes and diversions in the city:
  - Diversions aimed at transit users: This treatments uses different dynamic facilities to guide the user to the most appropriate route; and
  - Urban diversions aimed at local users and transit users trapped by the partial or total closure of the link. The implementation of prism-based changeable direction signs and VMSs at various strategic junctions in the city assists in the management of traffic.

4.3. Information Feedback: Adaptation of Scenarios

The Working Group also ensure the pertinence of the pre-defined scenarios over time. For this reason, the Working Group meets periodicallyto analyse information regarding operations management in order to provide feedback to adapt or/and change scenarios.

After three years of operation it is interesting to note a couple of evolutions in order to ascertain whether or not the basic assumptions remain true:

- During real-time management of roadwork events, an adaptation to the local environment has enabled a more clear understanding of the such scenarios as a whole,
- Debriefing following major incidents such as a fire provide valuable insights for improvements of scenarios.

CONCLUSION

The Walloon Region has put everything in place to ensure a maximum level of safety for users and has also realised an example of traffic management and management of incidents in tunnels.

The project has proved to be rich in terms of learning, both for its urban conception (reduced dimensions of the motorway) and for the number and quality of infrastructure and equipment put in place to ensure the treatment of incidents. It has also been an educational experience in terms of the multiplicity of actors and the resultant necessity to communicate on the project rising above the technical jargon used by each area of activity in which the various actors are involved.

The very low number of incidents can be explained notably by taking into account the factor of reduction in the risk of follow-on accidents and incidents due to the operation tools, but also due to the dissuasive effects of enforcement tools.

Three automatic radar systems (a first in Wallonia) are currently in service (6 systems are planned in total). They allow the average speed to be kept below the 80 km/h limit.

Indeed, to demonstrate the high level of safety, a recent survey undertaken by an independent organisation has classified the Cointe Tunnel as the best equipped amongst a selection of 30 tunnels in Europe (jointly with the Mont-Blanc Tunnel, after its renovation).

This real level of safety is borne out by the very low number of incidents in relation to the monthly traffic level (currently 2 million vehicles per month):

- 30 breakdowns per month (one per day), of which 60% were in the emergency lay-bys in the tunnels,
- 4 accidents per month (one per week), all of low severity, and
- 1 serious accident every 6 months.

The techniques used, as well as the means put into place (financial as well as human), have contributed to ensuring that the E40-E25 link provides a high level of service and quality.

FIRE TEST AND SAFETY CONCEPTS IN THE RENNSTEIG TUNNEL

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ABSTRACT

The Rennsteig Tunnel is a twin tube highway tunnel with 7.9 km length and directional traffic. It is the longest road tunnel in Germany and has been built by the "Deutsche Einheit Fernstraßenplanungs- und -bau GmbH" (DEGES). It provides a crucial link across the hilly area between Bavaria and Thuringia and is part of the overall improvement of infrastructure in the former Eastern German territory. The total costs of this tunnel were €250 Mio. Roughly 20 % of this sum has been spent on ventilation and safety equipment.

Before the tunnel was opened to the public in July 2003, the ventilation system and the safety installations had to be tested. Fire tests were therefore conducted according to the requirements of the German RABT from 2003 and the Austrian RVS 9.261. In total 7 fires were lit at 6 different locations and the automated response of the system carefully observed.

The result of the tests was that the automatic response of the system was, after some minor changes on the control software, as expected.

Key words: tunnel, fire test, ventilation, safety, sensor technology

1. THE VENTILATION AND SAFETY SYSTEM

1.1. Technical Installation

A longitudinal ventilation system with 2 air exchange stations, creating 3 equally long sections, has been chosen. In total 26 jet fans in the west tube and 28 in the east tube induce the longitudinal flow. Both air exchange stations are equipped with 4 axial fans for each tunnel tube (2 supply, 2 extract) with a maximum capacity of 115 m^3/s each. This makes a total of 16 fans and a maximum fresh air supply of 1380 m^3/s for the entire tunnel. Figure 1 shows the cross-section of the Rennsteig Tunnel with the jet fans.

Thirteen pedestrian cross-passages and twelve vehicle cross-passages are spaced 330 m apart. They are closed with T90 fire-rated doors separating both driving directions aerodynamically. The air exchange stations have a vertical chimney for exhaust and a horizontal gallery; that serves as air supply duct, provides a secure area for egress and allows access by the security forces.

The tunnel is monitored by event-driven cameras and environmental measurement stations. The combined measuring stations use the transmission method to determine the visibility and negative gas filter correlation to determine CO concentration over a measuring path of 10 metres. There are 11 stations per tunnel tube, which measure the CO concentration and the opacity; 6 stations per tunnel tube, positioned close to the portals and the air exchange stations, record the flow velocity. The flow measuring instruments used are based on the principle of ultrasonic time of flight difference. The continuous temperature distribution is measured by means of a fibre optic sensor suspended in the vaults of the main tunnels. Additionally, 78 visibility instruments (transmission method) are in operation for early warning of a potential fire. They are mounted above each of the emergency call recesses in intervals of 150 m.

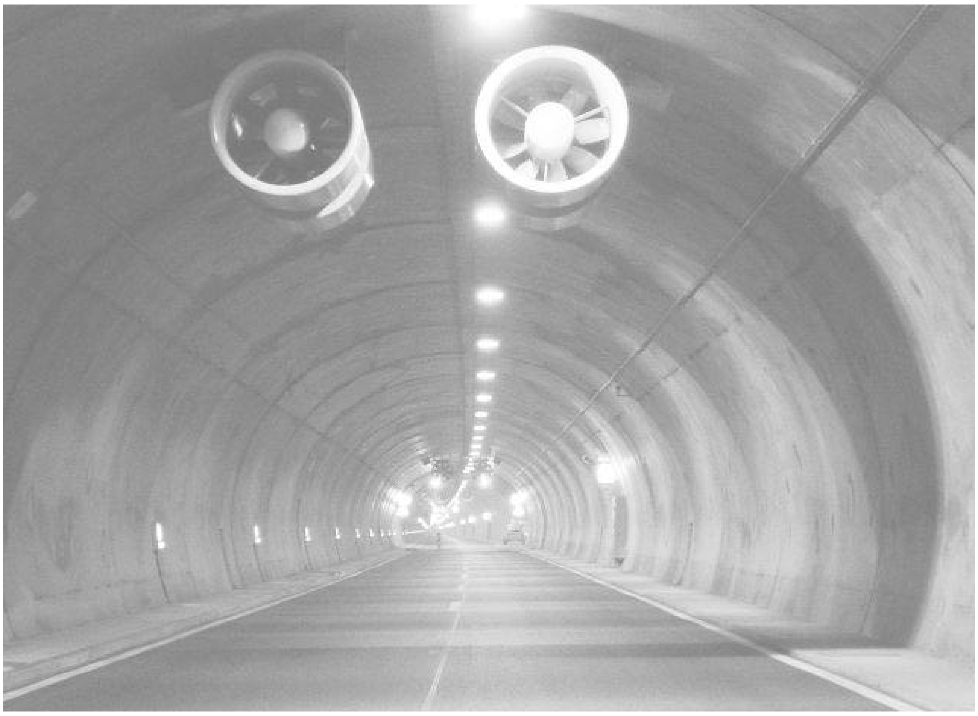

Figure 1: View into the Rennsteig Tunnel with jet fans

1.2. Operational concept

All signals are sent via data link to the tunnel control centre. The number and location of the ventilation and safety installations can be seen in Figure 2. It shows a screen shot of the control monitor. The display gives compact information about the air quality and the flow regime in the entire tunnel. It also displays safety relevant events, like the opening of a door or the failure of communication devices. Individual ventilators can be managed on-screen by adjusting the settings of the corresponding symbols.

The operational concept was initially planned based on the RABT from 1997 /2/; the requirements of the RABT 2003 /3/ were considered in the project as they became available.

During normal operation, the settings for the fans are driven by air quality based on the measurement of CO concentration and opacity. Operational costs are minimized.

In case of a fire in the tunnel, the jet and the axial fans induce a flow velocity of roughly 2-2.5 m/s in the driving direction of the incident section. Jet fans in the immediate environment of the fire location are not used as this would disturb the smoke layer. Counteracting jet fans in the next downstream section block air from penetrating into the next section and ensure sufficient supply of fresh air in the non-incident sections, where the maximum CO concentration is not exceeded during an emergency.

Jet fans at the exit of the non-incident tube create a flow against the driving direction. This creates a higher pressure than in the incident tube and hinders smoke passing over opened cross-passages. In case of a fire in the exit section, parallel flow in the non-incident tube is started in order to avoid recirculation of smoky air by the portals. Staggered tunnel portals also hamper recirculation.

The flow velocity of 2-2.5 m/s has been chosen by the following criteria:

- the smoke layer should not be disturbed by the ventilation at least some 100 m from the fire and thus self rescue through the cross-connections is supported
- the flow velocity should be close to critical velocity for a car fire; small zones of back layering are accepted
- an overshooting to downstream ventilation sections should be avoided

The concept supports the self-rescue and provides quickly suitable conditions for safe access to the incident location by the firemen. Their access routes are:

- lateral galleries at the air exchange stations
- incident tunnel driving against the normal direction through the non-incident sections
- non-incident tube and passing into incident tube via a vehicle cross-passage

An access via the incident section in normal driving direction is also supported by the ventilation concept, but will be hampered by stopped cars.

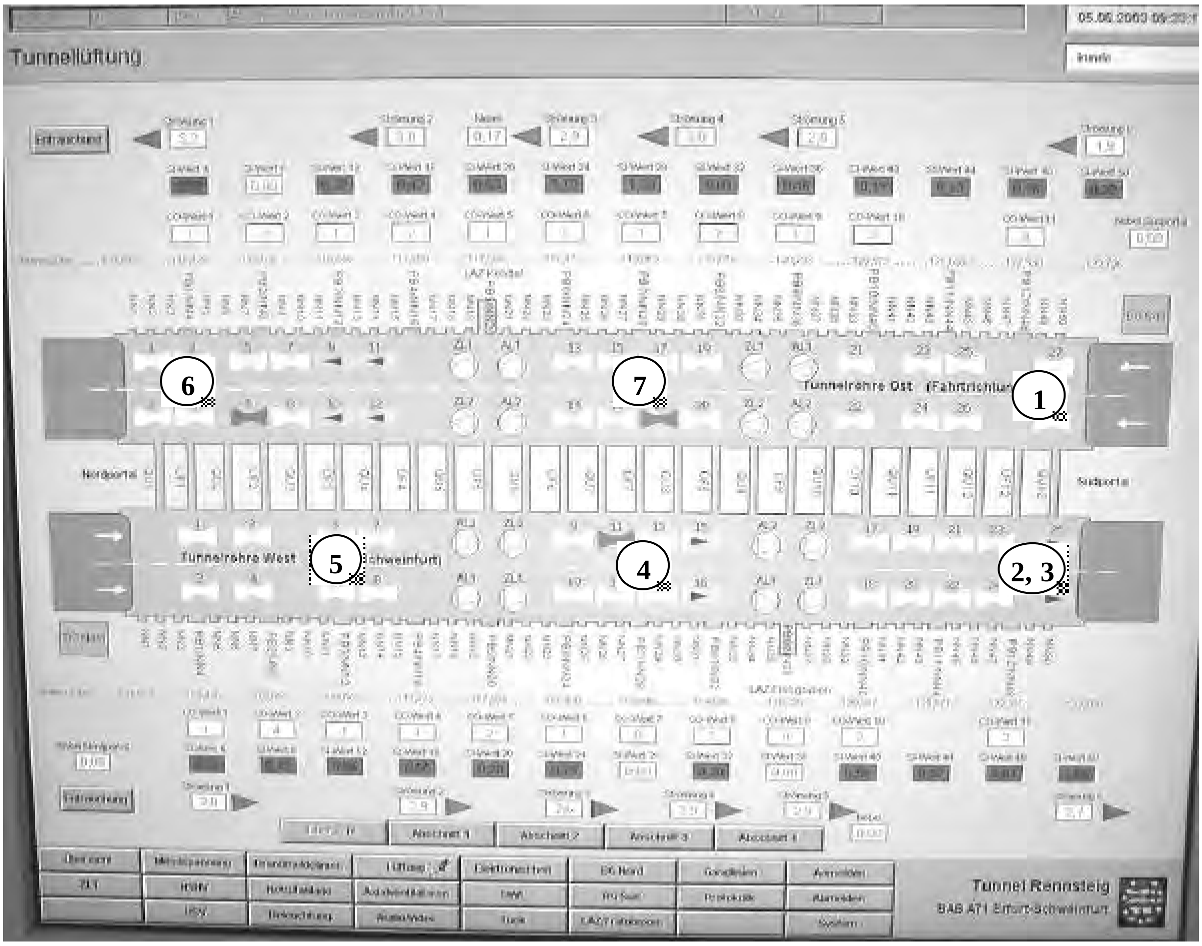

Figure 2: Screen shot of the control monitor, number and location of ventilation and safety installations, numbers in circles indicate test fire locations

2. THE FIRE TESTS

In total there were 7 tests with hot smoke in 6 different locations simulating 3 different fire scenarios:

A. Passenger car fire in the entrance section
B. Passenger car fire in the middle section
C. Passenger car fire in the exit section

The tests have been conducted in both tunnel tubes.

The aims of the tests were:

- Verification of the automated system response to a fire
- Check of the predicted flow regime caused by the mechanical ventilation system
- Test of the safety equipment in case of a fire
- Proof of conformance with the governing standards

The fire tests were conducted according to the requirements of the Austrian RVS 9.261 /1/ and the German RABT /2/. Table 1 gives an overview over the tests and their underlying scenarios.

Table 1 Overview over the fire tests

Test #	Scenario	Location	Fire source	Free surface	equivalent fire power
1	A	km 121.9 / East	20 l Benzine (petrol)	4 m^2	5 MW
2	C	km 122.7 / West			
3	C	km 122.7 / West	20 l Diesel 5 l Benzine (petrol) 10 l Water	2 m^2	2.5 MW
4	B	km 119.1 / West			
5	A	km 116.4 / West			
6	C	km 115.4 / East			
7	B	km 119.0 / East			

2.1. Test No. 1

The RABT 2003 requires an automated system response to a 5 MW fire within 60 s at a longitudinal velocity of 6 m/s. Additionally, the fire location must be determined with a precision of 50 m. As heat and smoke source, a fire was lit with 20 l Benzine (petrol) and a surface of 4 m^2. Natural convection being 3 m/s towards south, the jet fans managed to achieve 5.5 m/s towards north before the fire was lit by local firemen. After 100 s, the fire program was started.

An examination of the event log showed an immediate rise of the temperature in the environment of the fire location. However, the software was programmed to start the fire program only if a rise in temperature of more than 10°C over 2 cycles of 40s had been recorded. The criterion was changed to a rise of 5°C over 2 cycles of 20s and a repetition was planned. The log also showed that the jet fans in non-incident sections of the east tube needed to be reversed. The software was modified accordingly.

2.2. Test No. 2

Test No. 2 was the repetition of test no. 1 with the above-mentioned software modifications. As the following tests were planned in the west tube, the repetition was performed in this location. This time, the automated system response came after 68 s, i.e. the jet fans in the entire incident tunnel, except in the environment of the fire, were turned on and the jet fans in the middle section reversed the flow in the non-incident tube. Dense smoke was produced for about 10 min. Due to the high flow velocity of 5.9 m/s, the entire cross-section of the tunnel was filled with smoke around 20m downstream of the fire source. Visibility in the smoke filled zone was just about the distance to the next emergency light (50 m). As the fire power was considered a bit smaller than the required 5 MW, compliance with the RABT was suggested.

2.3. Test No. 3

In tests 1 and 2 particular attention was paid to the automated system response time. In the following test, the function of the ventilation system was the focus. Therefore, a different combustible mixture was used (see Table 1) and the surface was smaller. This resulted in a reduced power of the fire and longer duration of smoke production.

The underlying scenario was the fire in the exit section (fire scenario C). The fire detection started the fire program 84 s after the fire was lit. The jet fans in the exit section of the west tunnel were started, except for the ones close to the fire. Additionally the southern air exchange station was put on supply for the west tube. This resulted in a flow velocity of 4 m/s in driving direction. The flow in the east tube, initially 1.5 m/s from south to north, which simulated directional traffic, was turned with the jet fans in the middle section. There was no recirculation in the portals as can be seen in Figure 3. The result was as expected.

Figure 3: Smoke exhaustion from the south portal in test no. 3

2.4. Test No. 4

In test 4 the fire scenario in the middle section of the west tunnel tube was checked. Natural ventilation was 1.3-1.5 m/s in driving direction with a temperature difference of 7°C on the portals. Jet fans in the east tube produced a flow velocity of 0.8 m/s before the fire was lit in order to simulate typical flow conditions of directional traffic.
After the fire was lit, jet fans upstream of the fire location were started. Additionally, the axial fans in the upstream air exchange station were set to full supply and in the southern air exchange station to full extract mode. The mechanical ventilation induced a flow velocity of 6 m/s in the fire location. No counteracting jet fans in the downstream section were used.
As a result of the volume flow exceeding the capacity of 230 m^3/s of the southern air extract station, the smoke passed the extraction point and continued towards the southern portal. This test allowed the fire program for this scenario to be improved in 2 ways:
- the upstream air supply station has been set to a flow rate of 30 m^3/s
- downstream jet fans have been turned on against the driving direction

The result of these modifications was tested in test no. 7.

2.5. Test No. 5

In test no. 5 the automated system response of a fire in the entrance section was examined. This natural ventilation before the test was roughly 2 m/s towards south. After ignition of the fire, the jet fans in the incident section, except for the ones very close to the fire, were turned on. The air extract fans in the northern air exchange station were set on full extract. The flow velocity rose to 5 m/s, after which some jet fans were shut down. Flow in the downstream sections was reversed. No smoke passed into the next downstream section. The result was as expected.

2.6. Test No. 6

Test no. 6 is equivalent to test no. 3 except that it was executed in the eastern tube. As the compliance with the ventilation concept was verified there, this test allowed us to make sure that the ventilation system works similar in both tubes. The natural ventilation being about 2.5 m/s from north to south, was turned in the east tube to about 3 m/s from south to north in order to simulate directional traffic. In this case, the fire program had to be started manually based on the measurements of the opacity and the video observation. The emergency lights had to be turned on separately by hand. After the manual start, the ventilation system performed as expected. The software was modified accordingly.

2.7. Test No. 7

The final test was a repetition of test no. 4, where smoke passed into the next downstream section. The volume flow of the supply fan was reduced and flow in the downstream sections of the incident tunnel reversed. This time, the test result was as expected.

3. AIR PARAMETER MONITORING AT THE RENNSTEIG TUNNEL

3.1. Monitoring of Visibility

There are many reasons for visibility deterioration in tunnels: diesel exhaust, soot, dust and smoke. Smoke, especially if caused by a vehicle fire in the tunnel or even by a burning truck tire, reduces the visibility drastically. Therefore, we have to distinguish between two main control scenarios:

1. Normal control and operation of the tunnel ventilation during standard traffic situations
2. Specific control and operation of tunnel ventilation in case of an incident.

3.1.1 Normal control and operation

For operation under normal conditions, a total of 11 stations per tube measure the CO-concentration and the visibility. The distance between two measurement points is approximately 700 m. The tunnel is closed off only when an incontrovertible plausibility test is positive, i.e. if the CO concentration >200ppm, the transmission < 30 % or the *k*-value (Extinction coefficient) > $12*10^{-3}m^{-1}$.

3.1.2 Specific control and operation

In fulfillment of the requirements of the RABT 2003 /3/, a total of 39 visibility measurement systems have been installed; they support the localization of smoke due to a fire. The distance between two measurement points is reduced to 150 m for this purpose. The devices are mounted above each of the emergency call recesses. As mentioned in 2.1, the fire location must be determined with a precision of 50 m. This demand is partially fulfilled by the visibility monitors (see Figure 4). When the visibility monitors detect an incident, the installed video camera is triggered to the measuring point and the operator has to assess the situation. In case of a fire, he has to take the necessary steps.

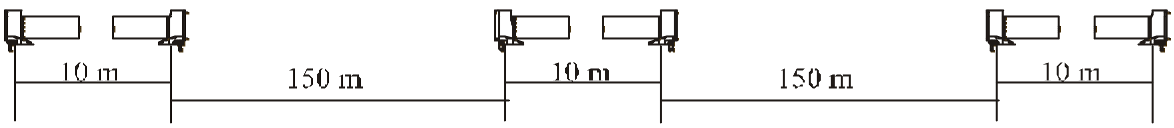

Figure 4: Layout of the visibility measurement system in the Rennsteig Tunnel

3.1.3 Principle of visibility measurement

For several years, the basis for both control scenarios has been the "extinction coefficient" or "*k*-value". Light emitted by a light source with intensity I_0 is attenuated by particles along the measuring distance x and the residual intensity I is measured by a receiver. The light attenuation follows Lambert Beer´s Law:

$$\frac{I}{I_0} = e^{-kx}.$$

This yields $k = -\frac{\ln T}{x}$ with $T = \frac{I}{I_0}$.

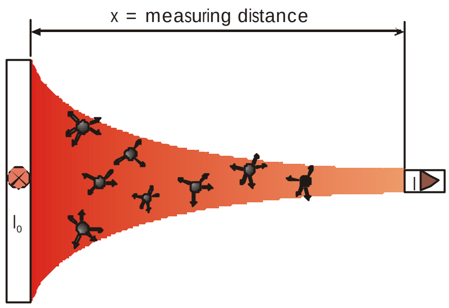

Figure 5: Principle of Transmission

For a measuring distance of x = 20 m, threshold *k*-values used in Rennsteig Tunnel are given in Table 2. This measurement is carried out in a modern system consisting of Sender-/Receiver unit and a Reflector unit. The transmission values are integrated over a time interval (here: 10s) and the *k*-value is calculated. The *k*-value is available as a current loop.

Table 2: Visibility threshold values

I/I_0 = T [%]	k in m^{-1} (x=20 m)	Condition
90.5	$5*10^{-3}$	Fluid traffic 50-100 km/h
86.9	$7*10^{-3}$	Congested traffic
78.7	$12*10^{-3}$	Alarm

3.2. Monitoring the CO concentration by negative gas correlation

The principle for measuring the CO concentration is based on the wavelength-specific absorption of infrared light by carbon monoxide (CO). CO has a distinct absorption spectrum in the mid-infrared region (4.5-4.9 µm) that comprises a variety of spike-like absorption lines. The absorption of IR-radiation at a specific wavelength is measured by a so-called negative gas filter correlator.

The measurement of the CO concentration is used for the normal control and operation of the tunnel ventilation (see 3.1.1).

3.3. Monitoring of air velocity and direction

Finally, in order to control the performance of the tunnel ventilation, especially during a fire incident, but also to reduce energy costs during normal operation, an optimal airflow control system is needed.
One airflow monitor is mounted in each of the 6 sections per tunnel tube. Their task is to measure the air velocity and the „direction in each section. These values belong to the most important group of measurements in the complete safety concept for the Rennsteig Tunnel.
The flow measuring instruments used are based on the principle of ultrasonic time of flight difference across the whole tunnel cross section. This allows exact control of the ventilators, especially at low flow velocities and for the different scenarios during a fire accident in the tunnel. The system has no movable mechanical parts and is therefore extremely robust and requires a minimum of maintenance.

The two transducers are mounted at 45-60 degrees to the axis of the tunnel. Two ultrasonic signal packages are alternatively sent from A to B (see Figure 6) or B to A across the tunnel tube. Each transducer works alternatively as transmitter and receiver. The transit times vary for each respective direction of sound due to the accelerating and braking effects, depending on the angle α and the flow velocity v .The transit times of the ultrasonic pulses differ all the more, the higher the flow velocity and the smaller the angle in relation to the direction of flow.

The flow velocity is determined by the difference in transit times, irrespective of the velocity of sound value. Changes in the velocity of sound caused by pressure or temperature fluctuations bear no influence on the determined flow velocity with this measuring technique.

The evaluation and calculation of air velocity is performed in a separate evaluation unit. This also contains the drive electronics for the ultrasonic transducers. The velocity value is available as current loop, the flow direction as a relay output. Profibus interface is also available

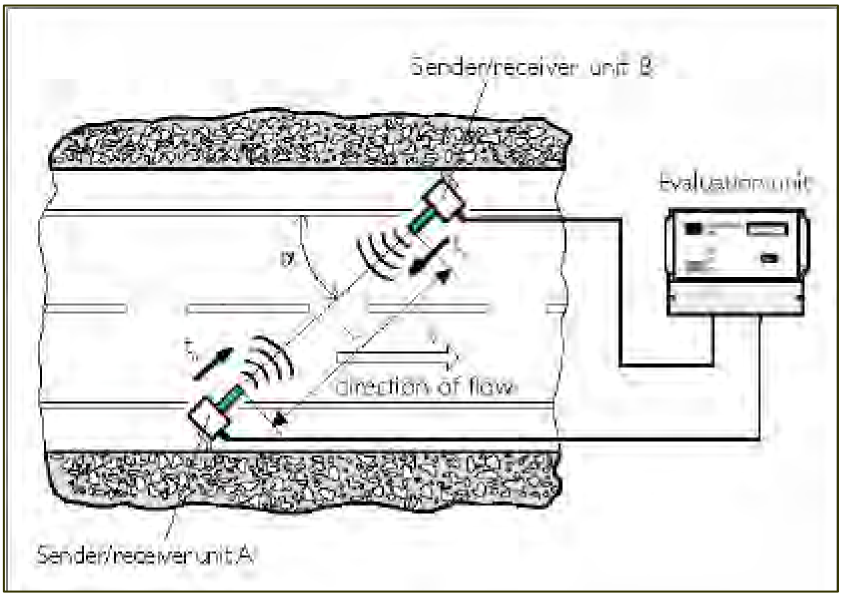

Figure 6: Ultrasonic Air Velocity Measurement System

4. CONCLUSIONS

The 7 tests for 3 different fire scenarios allowed the measurement equipment and the ventilation system to be tested under real conditions. The tests revealed that some adaptations to the control software were necessary in order to comply with the ventilation strategy. Once implemented, the ventilation system was demonstrated to create good conditions for self-rescue to the non-incident tube as well as favourable access conditions for the firemen.

The installed sensor technology was proven to detect the fire location with adequate accuracy of space and time. In particular, the optical smoke detection system reacted within 30 s after ignition of the fire. The fibre optical temperature measurement system allowed to determine temperature variations and their location precisely.

The complex interaction between sensor output, control software and ventilation system was finally proven to comply reliably to the governing regulations. The Rennsteig Tunnel is in operation since July 2003 and is considered one of the safest road tunnels in Germany.

5. REFERENCES

/1/ RVS Richtlinie 9.261, Ausgabe 2001

/2/ RABT Richtlinie Ausgabe 1994 mit Ergänzung von 1997.

/3/ RABT Richtlinie Ausgabe 2003

L E S S O N S learned by F I R E – T E S T S

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ABSTRACT – Fire Test according to RVS

Fire Tests are strictly requested for all the Tunnels, where a Ventilation system is installed. Those test have to be done before opening for traffic and also periodically during lifetime. They are matching a test of the mechanical ventilation device, the measure equipments and also the control system with the fire fighting procedures. Especially the controlled flow of smoke and its sucking off should be shown by the test. Also a good training of action forces, especially the fire brigades is included. However, most of tunnel operators are worrying about damage or at least about pollution of the immediate environment at the point of fire source.

Using cold fog seems to be a simple solution, quick and cheap, without danger for persons and pollution of environment, and therefore, it is often suggested. Yet, one parameter is not offered by a cold fog. It's the thermal one, which is most important for the stratification of smoke under the ceiling and the boost in direction of rising gradient of tunnel.

But empirically considering suitable precautions for technical equipment (cables, shiners, lane) and the right choice of place for the source of fire damage may be almost avoided.

Nevertheless, its almost a pretty effort, considering especially the great number of tunnel plants.

Fire may light at any place in a tunnel. Consequently, quite a few of fire tests should be done. In view of time and costs this is strictly impossible. Therefore, just one fire test at one special place is done. For all other places and ventilation sections the fire fighting programs will be tested by simulation and dry runs.

Yet, there has to be done one real fire test at a special place with extraordinary conditions for the flow of smoke, for instance at the end of a very long ventilation section (long way for air flow, lowest amount of suck off), or at regions of cross passages or escape doors. (possibility of overflowing smoke into escape routs and maybe the second tube)

1. REQUIREMENTS ON FIRE TESTS

1.1. Monitoring equipment

<u>Fire detection device:</u>

Detecting the location of fire source, as quick and accurate as possible. Yet, there is no necessity of resolutions less than 8 m, because when fire is lighting mostly a longitudinal flow is prevailing and thus the detection point is rather transposed from the fire source. Much more important is to detect the direction and speed of smoke movement, especially for allocating the right exhaust air damper to open it.

Velocity Measurement:

This equipment should be quick, and exactly gathering speed and direction of flow, representative for the whole cross-sectional area at the place, where the equipment is situated. This equipment is decisive for controlling the ventilation and consequently the control of smoke dispersion. There should be arranged an air flow measurement equipment at least at any border of ventilation sections.
Air flow measurements have to be performed at least in each ventilation section, two sets per section are preferred.

Smoke detection per video:

This measuring method is quite new and up to now, not a lot of experience is available. It should match for quick detection of smouldering fires without great heat and also in case of fire and smoke development of a moving vehicle. In such a case a tunnel gets rapidly filled with smoke, and consequently corresponding reaction of tunnel traffic control has to come very quick (conventional fire detecting systems don´t match quite good in this case, because of missing heat)

Smoke detection per sucking off equipments:

Such systems should match for detection of smouldering fires. Not a lot of experience is available yet.

Carbon monoxide and opacity:

These two measurements are responsible for the operational control of air quality and controlling the ventilation system in normal operation. But in case of fire, they are not suitable ventilation control.

1.2. Control system

In normal operation the ventilation system is controlled by measurement of CO and opacity as well as by traffic amount.
In case of fire those parameters are not further suitable. The ventilation system is controlled in dependence of the fire location and the air flow, so that it reacts consequently in subsequent matters :

- sucking off smoke with flow rate
- minimizing longitudinal flow (in case of transverse ventilation with exhaust air dampers zero speed at location of open damper)
- reducing longitudinal flow – slow flow with little turbulence is the aim
- preventing overflow into the adjoining tube
- preventing recirculation into the adjoining tube, when smoke is leaving the portal
- guaranteeing free escape and emergency routes

these aims are realized by

- fire or smoke detection devices (for recognizing the point of the fire-source)
- flow measuring equipment (for controlling the motion of smoke)

2. PRACTICAL REALIZATION OF A FIRE TEST

2.1. Test arrangement

The fire source should be placed at a point with extraordinary conditions regarding to the demands on ventilation system.

- at the end of a ventilation section – adversest point because oft the farest distance towards the exhaust air engine, highest loss of pressure through the exhaust air channel (transverse ventilation).
- near cross-passages or escape-exits for proofing the defense of smoke
- in case of tunnels with 2 tubes,– motion of smog downwords (against buoyancy)

All the installed measurement equipment, the transmission-equipment and the central electronic-network has to be in regular state.

Additional portable measurement-equipment is also advisable for adjusting and comparing with the regular “installed” equipment on the one hand, and on the other hand for measuring at several points of particular relevance for the test.

Operational TV-equipment, as well as video-detection and video-recording have to be ready, for verifying their correct function in connection with the fire fighting procedures first, and second to record the processing on-site optimally for making it reproducible anytime.
Special situations in the tunnels have to be recorded separate, e.g. for documentation the flow of smoke for subsequent analyses.

2.2. Topics to be tested

The following topics should be tested
Response time of fire detection

Response time of fire fighting procedures regarding
    traffic control equipment
    ventilation system
    automatic video recording
    further self-acting processes

Smoke flow
    along the tunnel
    at the escape doors
    at the cross-passages-
    at the exit-portal

2.3. Initial situation

A situation near reality has to be provided inside the whole tunnel. This concerns mainly the air flow as it should mimic a situation during real traffic and a sudden accident immediately followed by fire. Using the ventilation a longitudinal flow may be forced. In case of cross-ventilation this may happen using mobile jets placing at the entrance of the tunnel. All the passages between the test-tube an its neighbour-tube have to be closed. For the security of visitors and observers measures have to be provided.

2.4. Documentation:

The following documentation has to be provided

- Test protocol and a map containing the location of the fire and the monitoring equipment
- time schedule in the order of the test events
  - time of fire detection
  - digital messages of tunnel surveillance
  - switching operations of tunnel ventilation etc.
- records of measurement data
- diagrams of measurement data
- video records by the installed fixed units
- video records by special mobile devices

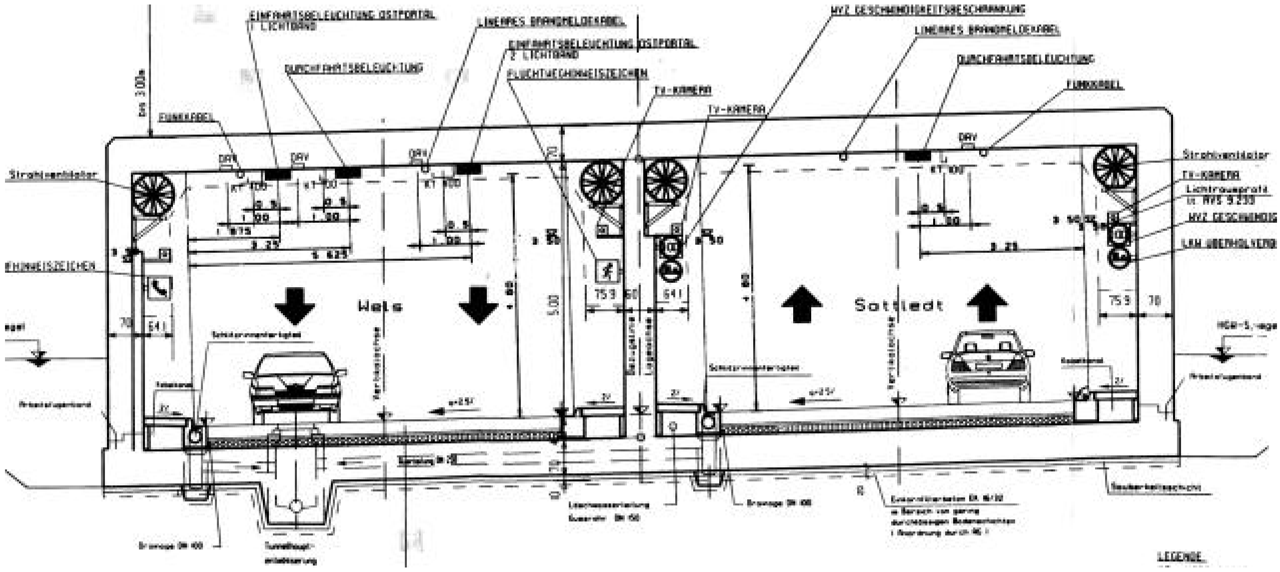
3. FIRE TESTS

In the year 2003 the author was engaged as project manager for electromechanical equipment at two tunnel-projects in Austria. Especially two cut and cover tunnels along the A8 near Wels in Oberösterreich and a further project, the 2nd tube of Gräbern tunnel along the A2 between Graz and Klagenfurt had to be realised. Shortly before opening the tunnels to regular traffic fire tests were performed. Both tunnels consist of two tubes with unidirectional traffic but differ in profile and cross-section.

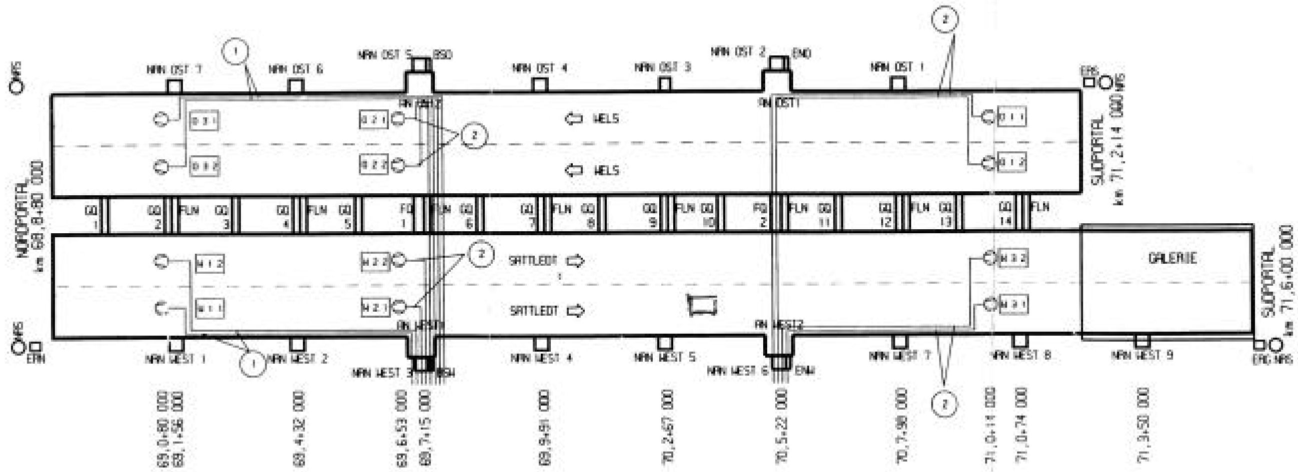
3.1 A8 - tunnels Steinhaus und Noitzmühle

Both tunnels were built cut and cover, have a rectangular profile and a clearance of 4.70 m
The fans are mounted at left and right upper edge, above the sidewalks
The tubes are separated by a concrete wall with a thickness of 0.6 m.
The distance between cross passages is : 125 m
The cross passages can be used for vehicles. The clearance of the sliding door is 4.20 m, the width is 5 m.

The fire tests were performed successfully at the end of July 2003 and their opening for traffic took place on August 25, 2003. The tests were triggered and controlled by the fire response software. Only minor adjustments to the software were necessary.



Picture 1: Cross section of Tunnel Steinhaus



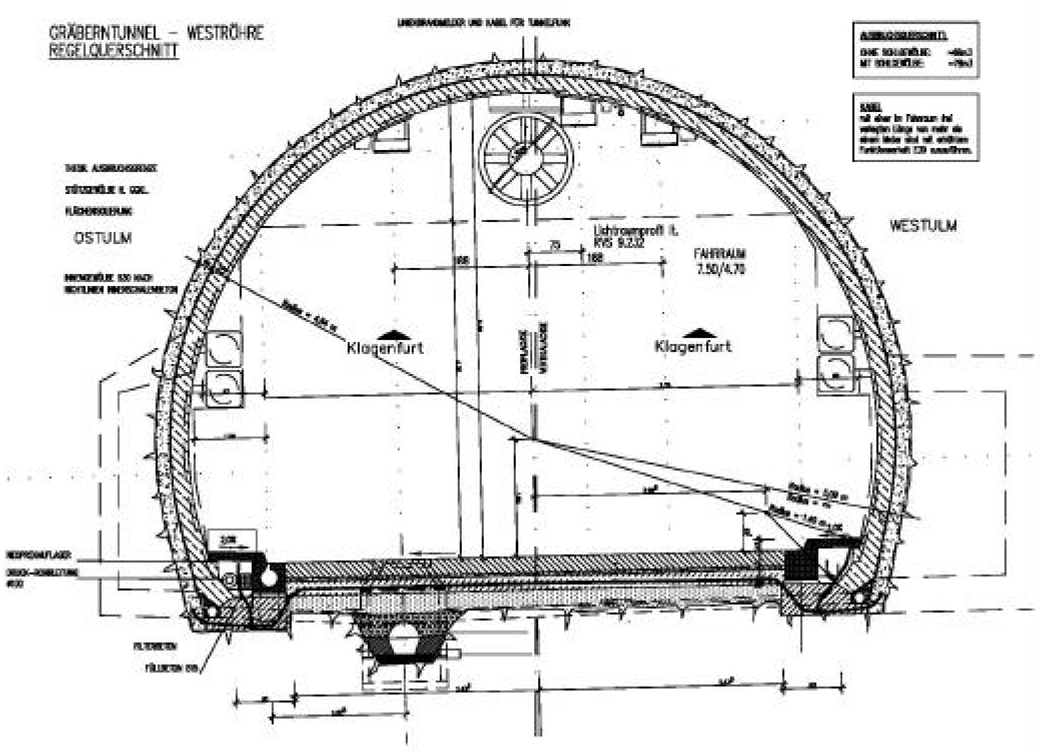
Picture 2: Longitudinal section of tunnel Steinhaus

3.2 . A2 – Gräberntunnel – 2nd tube

The 2nd tube (western-tube) was constructed by blasting method with the usual "horseshoe" profile. Thus the jets can be placed over the traffic room. Both tubes will be connected by 3 cross passages tubes with a length from 60 up to 100 m. The distance between these cross-passages is some 500 m at a longitudinal distance of nearly 500 m.

For the time being the traffic operation is bi-directional as the "old tube" undergoes currently a refurbishment.

The fire tests were performed for the tube currently in operation. The main tests including both tubes are scheduled as soon as the upgrading of the first bore is finished.



Picture 2: Crosssection of Gräbern Tunnel 2nd tube

3.3. Relevant results of these tests

Longitudinal ventilation and unidirectional traffic

- Sucking operation of the fans in the fire tube:
  The fans at the end of the tube are operated in direction of traffic. The result is underpressure inside the tube.
- Counter-flow operation in the parallel tube:
  The ventilators at the exit of the parallel tube are working against the traffic direction, that is to say against the moving pile of air. The result is an overpressure in this tube. After a few minutes the flow will change direction and air will flow back out of the entrance portal. This results in an overpressure in the safe parallel tube at each location inside the tunnel, especially there, where smoke is moving along. Consequently, no smoke enters the parallel tube in case of open escape doors, not even at those high cross passages doors.
- No backflow at the entrance portal of parallel tube:
  Especially at the cut and cover construction type the risk of a recirculation is very high because of the small distance between the tubes at portals. After changing the flow direction by counter pressure, no smoke is able to enter the clean parallel tube at the portal.

SAFETY MEASURES FOR ROAD TUNNELS – NEWEST DEVELOPMENTS FOR THE PLABUTSCHTUNNEL, AUSTRIA

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Abstract.

Compared to other federal regions in Austria, Styria has the densest tunnel network. By the end of 2005 more than 100 km will be in operation. The Plabutsch tunnel – with a length of 10 km – has just recently been equipped with the most up to date safety installations. This paper deals with the safety features and fire tests designed to test the effectiveness of the risk management system.

Road tunnels in Styria

The federal region of Styria has currently some 100 tunnel-km in operation. In the 10 km long Plabutsch-tunnel the second bore was been opened in January 2004. The first one is currently closed for maintenance and will be reopened at the end of 2004. It will then be the longest unidirectional road tunnel in Europe. The Plabutsch-tunnel is a very good example for the state of the art in tunnel safety in Austria.

The Plabutsch tunnel was opened in 1987 as a single bore tunnel with bi – directional traffic. The permanent increase in traffic forced the construction of a second bore. When opened in 1987, an average 10,000 vehicles per day passed through the tunnel. By 2003 the average daily traffic volume already amounted to some 23,000 vehicles, reaching a maximum of 32,000 per day and 3,000 per hour. Figure 1 shows the development of traffic volume since the tunnel was opened.

The increased safety for the tunnel users was one of the main objectives in the creation of the new bore. The costs of the safety installations in both bores amounted to some 33 M€, while the upgrading of the ventilation system called for an additional 20 M€.

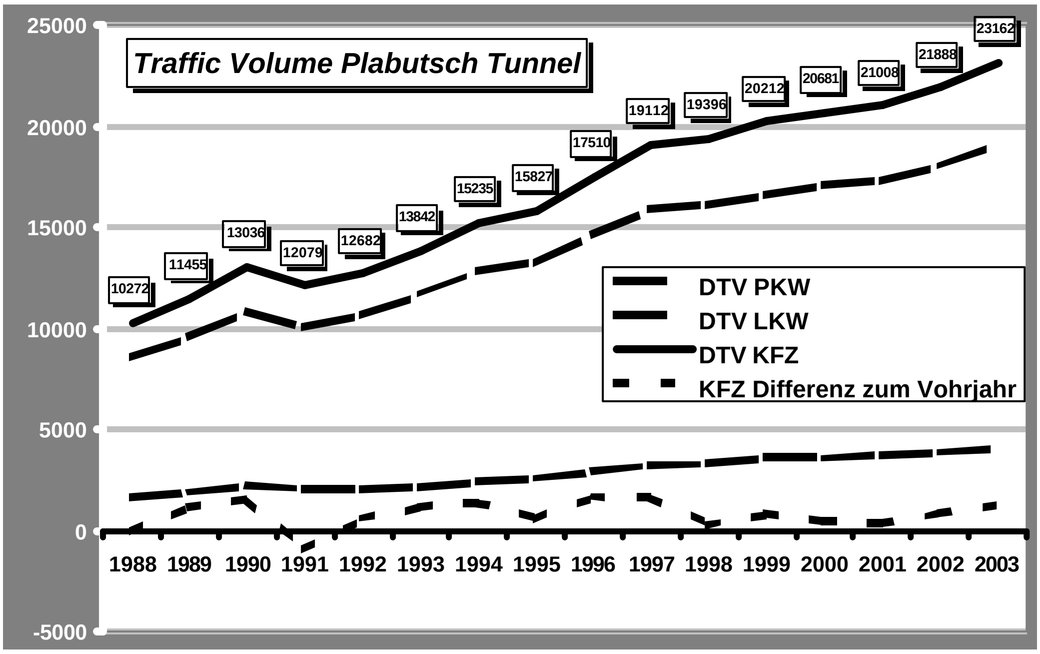

Figure 1: Development of the traffic volume in the Plabutsch tunnel

Developments in tunnel Safety

The safety of tunnel users was always a focal point for the department of road infrastructure and tunneling. Hence, Styria was very often a pioneer in introducing safety features. The following table shows the main topics implemented for the first time in Austrian road tunnels.

1979	Usage of the traffic channel with decoder signals transmitted from the tunnel control room.
1980	Fire resistant cabling (E90) for fans and emergency lights as well as usage of stainless steel for constructions inside the traffic room.
1983	Fully redundant data transmission systems
1984	Start of the first fiber-optic cable installation
1985	Control of ventilation and lighting dependent on actual traffic volume
1987	Tunnel lamps in stainless steel (VA4) and introduction of special effects to reduce the monotony in long tunnels. Frequency control for ventilation
2000	First NO_x controlled ventilation system for city tunnel
2000	Fully redundant data transmission network
2002	450 KW fan engines tested for operation at a temperature of 400°C over two hours
2003	First emergency call system base on “basic voice over IP”, introduction of a fully redundant control room
2003	Fire detection based on smoke analyses

On going improvements are being made in supply sections (max. distance 250 m), traffic control with CCTV, direction dependent switch able guidance lamps, etc.

Tunnel lighting

An increase in the efficiency of the lighting has been reached due to improved glass shields (8%) and a change in the distance of the reflector (3%). With newly developed mirrors it was possible to reach an efficiency of 80 % and an increase of illumination density from 200 cd/m to 260 cd/m, keeping the energy consumption constant. A side effect of these improvements was the lower operating temperature, and hence a longer lamplife.

A further effect concerned the control of the lighting, where convenient simplifications were replaced by empirically gained parameters.

Temperature requirements for cabling and lighting

Great emphasis has been place on increased fire resistance for all equipment within the traffic room of a tunnel. The cabling has to be E 90 resistant. For the lighting the following test protocol was required.

1) The lamp has to be placed in an oven at a heat of 250°C. It has to be in operation and the orientation has to be the same as in the tunnel.
2) A temperature sensor has to be mounted on each individual part.
3) The lamp has to operate over a period of one hour.
4) The values of temperature, voltage and electrical current have to be monitored and recorded.

Ventilation system and fire detection

Risk management in the case of a fire is based on proper ventilation strategy, as smoke free escape routes are a pre-requisite for self-rescue and rescue-operations.

In such cases a quick and accurate detection and location of the fire is very important. Fire detection is based on a fibrolaser®-system. In addition to this a unique smoke detection system based on gas analyses has been developed and installed. It is thus possible to locate the fire source within 30 m.

The exhaust air fans have been upgraded with improved heat resistant motors (400°C over 2 hours). For accurate smoke extraction, adjustable dampers with a cross-section of 12 m² were installed. As an extra safety feature, it is possible to connect the ends of two adjacent exhaust air ducts via a moveable vertical damper, in case one of the exhaust fans fails.

The Plabutsch tunnel has a transverse ventilation system, consisting of 5 ventilation sections. The ventilation of the south end is provided by jet fans. The reason for this is that due to environmental protection issues no polluted air may be exchanged via the portal. Figure 2 shows a sketch of the ventilation system.

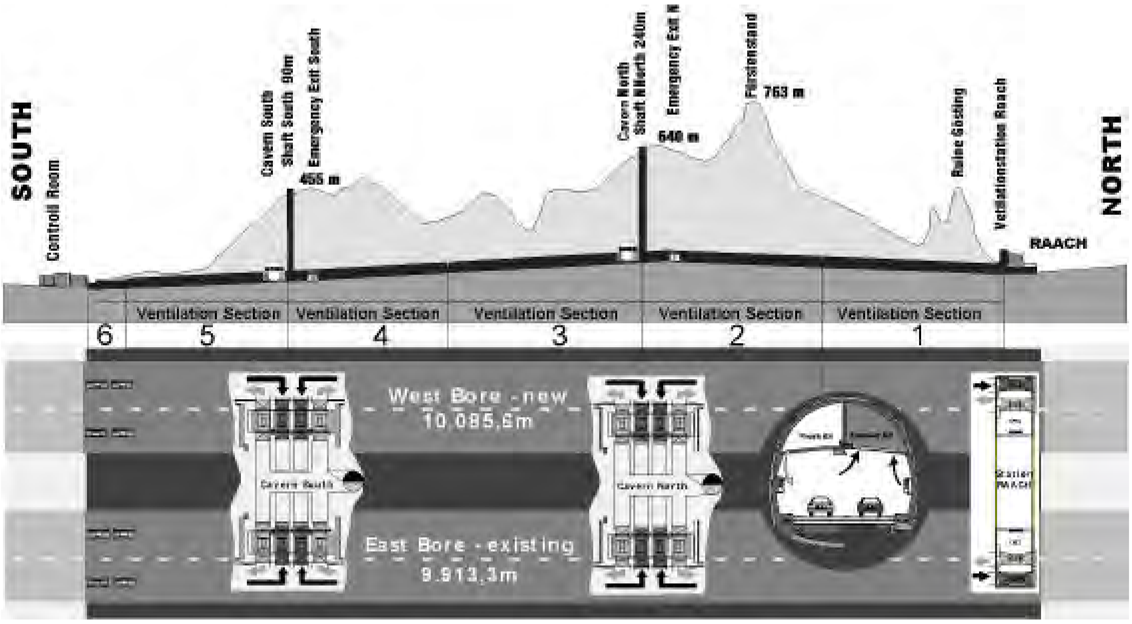

Figure 2: Ventilation scheme of the Plabutsch tunnel

Section 1 is ventilated via the portal fans at Raach. The remaining sections are ventilated via vertical stacks, sections 2 and 3 use the north shaft and sections 4 and 5 the south shaft. In this unique situation one stack supplies 4 ventilation sections, two in each bore. The operation and control of the fans can thus results in fairly complex procedures.

Control of the longitudinal air flow inside the Plabutsch tunnel

Even in a tunnel with a fully transverse ventilation a longitudinal flow of the air inside the tunnel occurs. During bi-directional traffic the wind speed will be low (dependent on the share of traffic in one direction and on meteorological conditions). During uni-directional traffic wind speeds up to 6 to 8 m/s can be expected.

However, in the case of fire, the wind speed must be controlled and should not exceed a certain threshold value. The ventilation of the tunnel is designed to suck off at least 120 m³/s at the location of the open damper. In order to gain an air (smoke) movement from both sides to the open damper, the velocity inside the tunnel must not exceed 1,5 – 2 m/s. The automatic ventilation control software steers the system towards this goal. This is done by operating the individual fans (exhaust and fresh air) in such a way that pressure is built up or reduced in the individual sections, and hence a longitudinal flow within the proposed velocity limits is imposed. At the same time an overpressure has to be built up in the second bore, in order to prevent an overflow of smoke through open doors in the cross-passages.

This unique software for ventilation control in the case of fire, was developed at the Graz University of Technology, and was adapted and improved during the fire tests (see next section) in co-operation with the company SAT.

Fire tests

In order to check the risk management procedure and the effectiveness of the ventilation system in cases of fire, the Austrian standard RVS 9.261 makes fire tests compulsory. Multiple tests were performed to check the procedure. The first set of the tests concerned aerodynamics. These tests were made without smoke. The fire alarm was triggered manually and the air flow inside the tunnel monitored with flow meters (sonic instruments) and reached visible by means of cold smoke. Some 10 different locations were tested and a couple of malfunctions were found. It became clear during the testing that the whole ventilation procedure is very sensitive to establishing correct readings of the air velocity in the ventilation section under consideration.

In accordance with standard RVS 9.261, these tests were followed by hot smoke tests. Two pool fires (1m² each) each consisting of 20 l of diesel and 5 l of gasoline were ignited. That fire tests were performed without any problem in the middle of section 3. A second set of tests was made exactly at the boundary between ventilation section 3 and 4. In this case the exhaust fans are almost 2 km away, and hence the pressure drop reaches a maximum and the exhaust air volume a minimum for this section. This location is one of the most critical locations inside the tunnel.

The fire was ignited in section 3 but due to a wind velocity of some 2 m/s inside the tunnel, detection occurred in section 4. Hence, the nearest damper in section 4 was opened.

Figure 3 shows a sketch of the fire location.

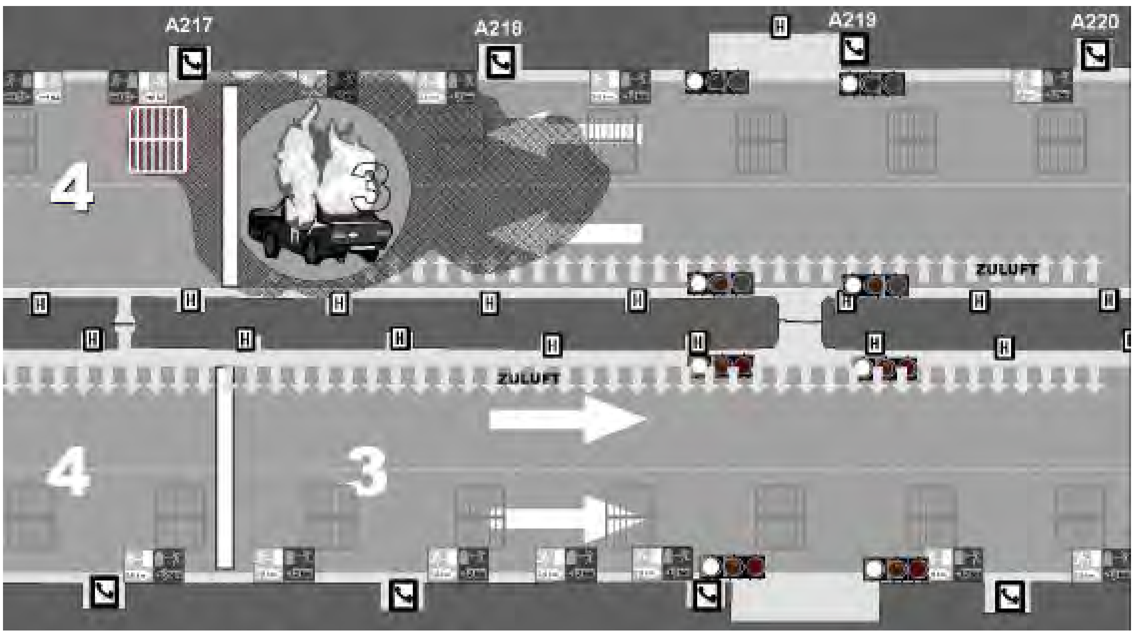

Figure 3: Location of the fire test

Having the detection of the fire in section 4 results in the following actions:

- ➢ full power exhaust ventilation in section 4 (100%)
- ➢ no fresh air supply in section 4 (0%)
- ➢ the remaining fans (section 1,2,3,5) are used for steering the longitudinal velocity inside the tunnel
- ➢ opening of the damper closest to the fire
- ➢ using the air velocity information from a velocity sensor in section 4

Figure 4 shows the velocity of the air flow south and north of the fire source. One line depicts the fixed velocity sensor (A210), while the other shows the mobile sensor (mobile 2). The fixed sensor is used for ventilation control The mobile one is a high quality sensor with a very high accuracy and was used to check the results. The other two lines represent the velocity measurements north of the fire source. A224 represents the fixed sensor and mobile 1 the movable sensor for quality control.

In the case of fire at this location, the software tries to steer the ventilation towards a velocity between 1.0 and 2.0 m. As can be seen from Figure 4, the fixed sensor (A210) showed totally incorrect values. While the software tried to reach the proposed velocity, the real velocity was already much too high. This resulted in smoke being driven back. For a certain period the smoke was even pushed behind the open damper. During this period only fresh air was sucked in and a large section north of the fire (in section 3) was totally filled with smoke (some 600 m).

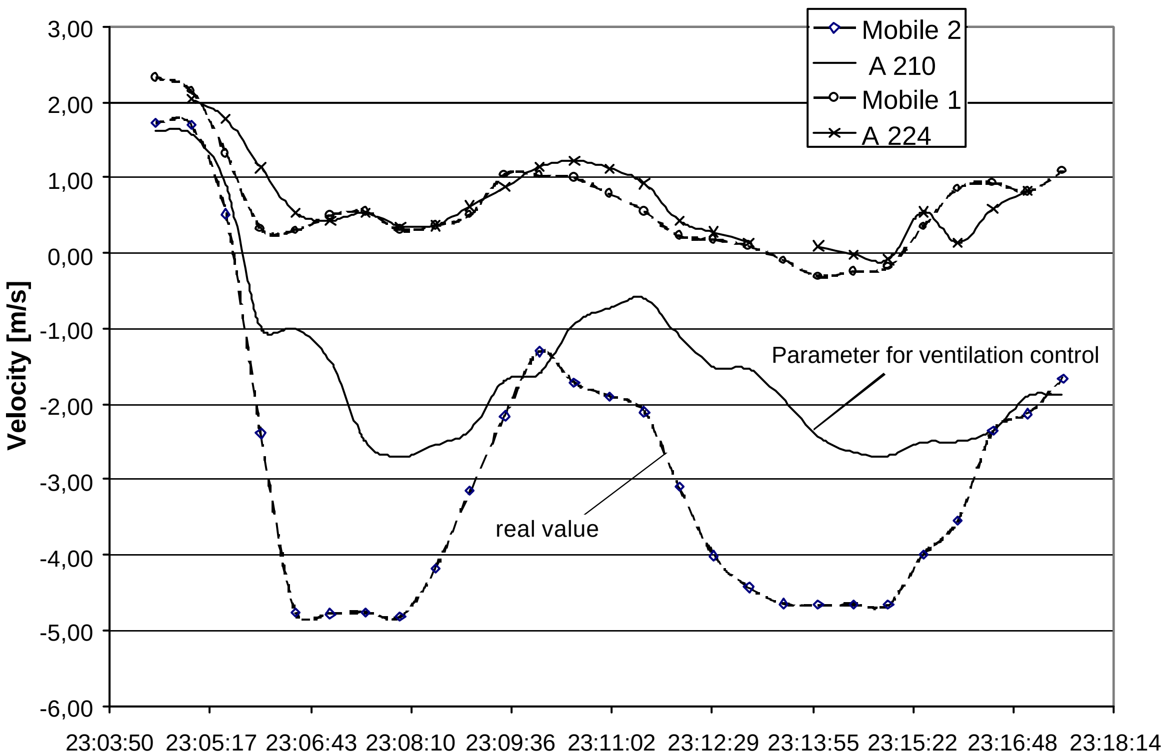

Figure 4: Wind speed inside the tunnel during fire test (uncorrected sensor).

Due to the malfunction of the velocity sensor a velocity of -5 m/s was produced with the ventilation system instead of (–1) to (-2) m/s. The malfunction was mainly due to an incorrect calibration of the sensor and the sensor location, which was influenced by traffic signs, traffic signals and a niche.

The result of this malfunction can be seen in Figure 5, where the "upstream" location is depicted. The test started with a flow in southerly direction. Shortly after the ignition a back layering was built up (upper two pictures), followed by a change in wind direction, due to an "overshooting" of the control software. Hence, the smoke was driven in direction of the people, who where initially at the "save" side of the tunnel.

Figure 5: Back layering at the fire site during the first malfunctioning fire test

Re-siting and proper calibration of the sensor solved the problem. A repetition of the fire test was performed and no problems were found. As can be seen from Figure 6, the readings from the fixed and mobile sensors matched well.

During the aerodynamic and fire tests the parameters of the implemented PID-controller were optimized, and as a fall back position, software for ventilation control, with fixed values for the fans – dependent on the fire location – was implemented.

The normal operation of the ventilation system is based on the measurements concerning the in-tunnel air quality and the traffic-density. In addition, the control software is able to cope with a breakdown of one fan. In such cases the neighboring fans impose a longitudinal flow in the ventilation section affected. This method has already been used successfully, e.g. during the refurbishment of the first bore when some fans are not in operation for certain periods.

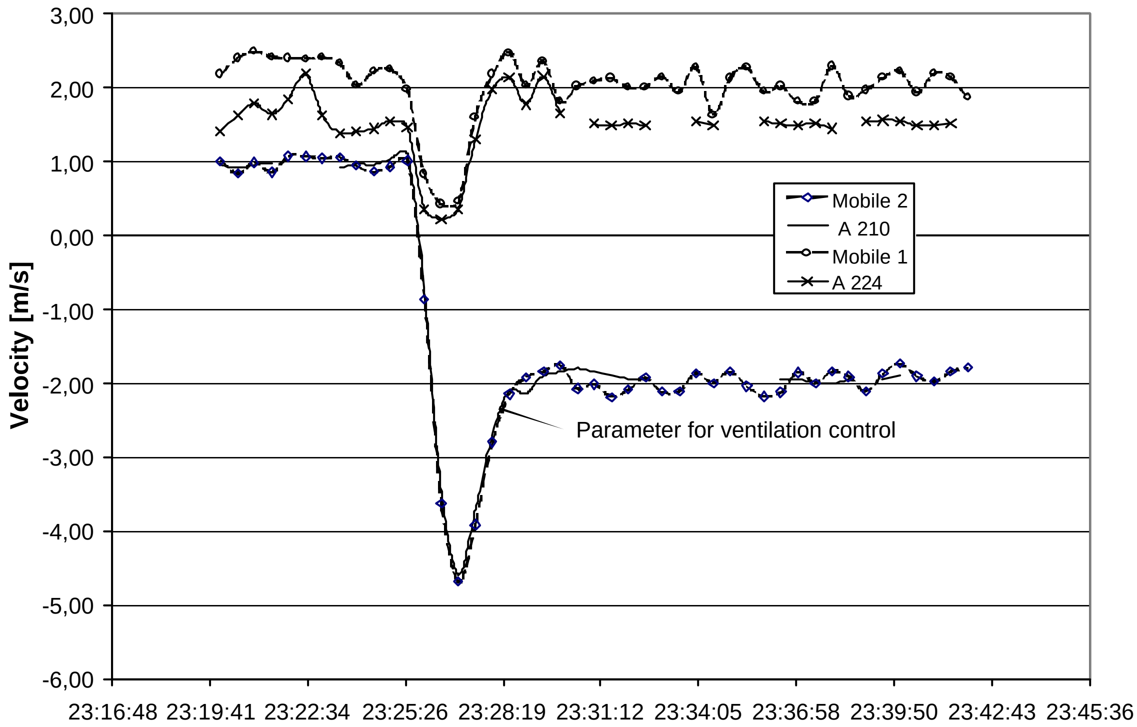

Figure 6: Wind speed inside the tunnel during fire test (corrected sensor)

<u>Control system and data transmission</u>

A main safety feature is the centrally managed data transmission and control. A flat structure and decentralized automatic steering devices are essential for tunnel safety techniques. A serial data transmission to stand-by PCs is not sufficient to have control of single malfunctions of equipment or sensors. Hence, one of the most important conditions for redundancy is parallel data transmission and processing in order to have a smooth changeover in case of a malfunction. Soft SPS-solutions have to be rejected, even for minor steering tasks, due to their rapid absolescence and their valuerability to virus attacks. Thus, no PC-solutions were adopted in the Plabutsch tunnel.

Instead of the former point to point data transmission the Ethernet is now the tool for data transfer and remote control of equipment. It is important to have enough capacity for data transmission and – again – to have a back-up net in order to ensure the necessary data transfer in case of an incident. The rough tunnel atmosphere is an additional parameter which has to be considered. For data transfer multiple local 100 Mbit LAN's are connected to a back-up GBIT LAN. Even emergency calls are transmitted via these LAN's. The only exception is the video system. For quality reasons and owing to uncertainties in transmission and the need for centralized image processing, analog transmission is still used for the video system.

Emergency exits

A main feature of safety in a road tunnel is the clear marking of the emergency exits. The signaling has to be simple and full of contrast. Decision making aids should be present to help indivuduals to find the right emergency exit, especially if unexpected situations block the nearest one. The marking of only one exit – which in an actual emergency can not be used – may result in panic.

A big help for people fleeing would be an indication of the direction they should take. As in most cases direction of the smoke movement is determined by the ventilation, direction signaling could be done automatically as a function of fire location and smoke movement.

Conclusion

The second bore of the Plabutsch tunnel was opened in January 2004. More than 50 M€ were spent on safety installations and upgrading of the ventilation systems. Currently the first bore is closed for refurbishment. When it is opened again at the end of 2004, the Plabutsch will be the longest road tunnel in Europe with two bores operating with uni-directional traffic. For the sake of the users, the tunnel has been equipped with the most up to date safety equipment.

In the case of fire smoke is extracted via large (120 m²) adjustable dampers. In order to force the smoke to the open damper ventilation control software has been installed which utilizes all available fans in order to build up or reduce pressure in the tunnel and hence impose a longitudinal flow from both sides to the open damper. The Plabutsch is the first transverse ventilated tunnel with such a ventilation control system.

Further improvements in tunnel safety were carried out in incident detection with video and gas analyses, data transmission, use of electronic equipment, control room installations, lighting, etc. Most of the systems are fully redundant.

SCALE MODEL EXPERIMENT FOR THE VENTILATED AIR INTERFERENCE AT INTERMITTENT TUNNELS

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ABSTRACT

New East Coast Freeway construction project is under planning on the route of east coast of Taiwan area. This freeway will be constructed in the very difficult terrain, such as severe land slide, typhoon and earth quake etc,, Due to this topographical conditions, 6 long tunnels (over than 4km long) and other 4 short tunnels will be planned in this section (section length 80Km approx). Especially, two long tunnels will be located in each other with connecting short bridge structure (approx, 60m long). In addition, semi-shelter structure will be constructed on this bridge with following reasons.

* For the prevention of big difference between two tunnels and short open section, such as, "visual environment by strong sun light on the short bridge section", "natural wind force of lateral direction at open section", and "wet, dry pavement conditions in the rain."
* However, effects of air interference of ventilated air to down stream tunnel must be minimized for the reduction of all tunnel ventilation systems and power consumption.

Based on these backgrounds and concepts, several types of semi-shelter structure were proposed and implemented by the scale model with vehicle running apparatus on the tunnel ventilation testing apparatus.
As a results, two very important design factors to be obtained.
* Rate of air interference between two tunnels and unit respiration air volume at opening part.
* Aerodynamic coefficient at tunnel entrance with semi shelter.

Key words: tunnels, ventilation, scale model experiment, air interference

1. PROJECT DESCRIPTION

Taiwan is located at west end of the pacific ocean surrounded by east china sea, south china sea and facing to mainland china putting with Taiwan straight.
Land area of Taiwan is 36.000Km^2 with 22million habitants (approx).
Especially, topographical and geological conditions at the pacific ocean side (at eastside) of Taiwan are very difficult terrain for the traffic routes construction
New expressway will be constructed through this terrain built with 4 short tunnels and 5 long tunnels and bridges.

2. OBJECTS OF THIS STUDY

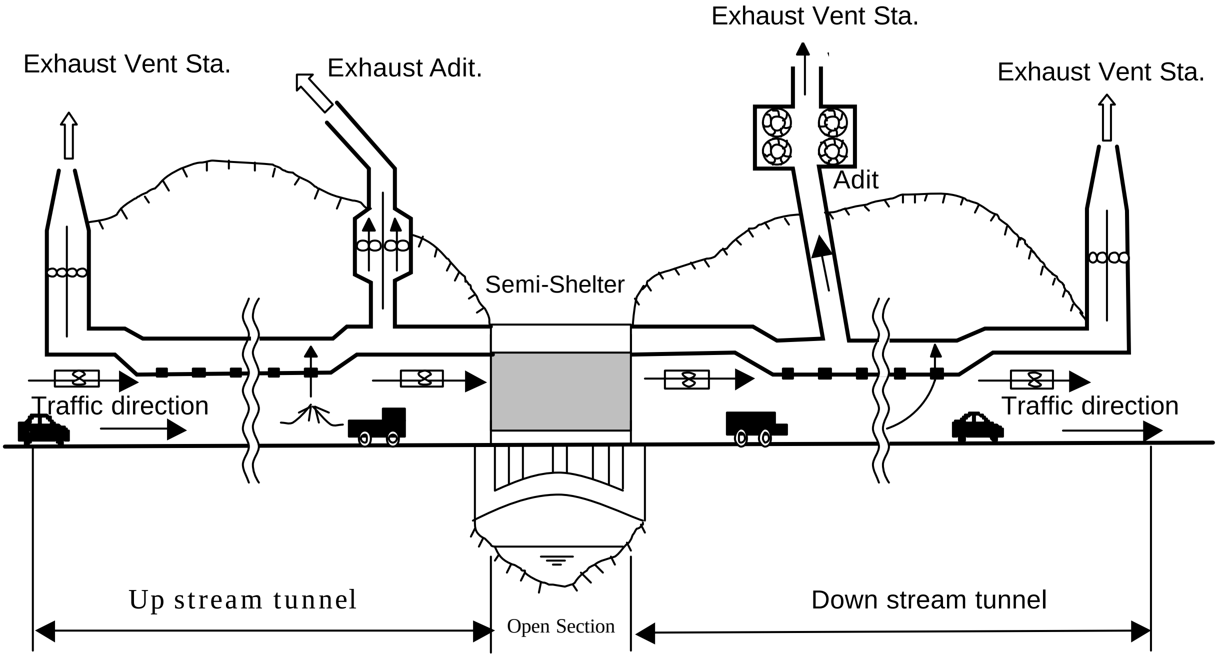
Especially, No6 Tunnel (length will be 7600m Approx) and No7 Tunnel (length will be 4600m) are connecting with 60m short bridges in the deep valley (Gooing bridge) on the route of Eastern Express way
On the point of view of traffic safety, structure of semi-shelter will be constructed on the bridge with following reasons.
1) For the avoidance of remarkable difference between two tunnels and open section
   * Remarkable difference of visual environment of luminance level at open section by strong sun light (tunnel - open - tunnel).
   * Avoidance of strong crosswind at open section (In the case of typhoon)

* Avoidance of pavement condition, dry - wet- dry (in the rain)
* Avoidance of falling goods on the carriageway from mountainside (in the case of natural disaster)

On the other hand,

2) Air interference to down stream tunnel must be minimized for the purpose of reduction of all of tunnel and ventilation systems.

As a results, we discussed about possibility of semi shelter structure installation.
In the case of semi-shelter installed on the bridge section, some of polluted ventilated air will be re-entered to the down stream tunnel due to the traffic conditions with ventilation control strategies. This phenomenon is very serious and significant problems for the increment of all of ventilation systems, operation costs and related structures to down stream tunnels.
However, relevant technical information for this question for the tunnel ventilation design are still insufficient in the past. Therefore, we decided to implement the scale model experiment for acquisition of basic technical information for these structures.
Fortunately, we possess the very sophisticated and very unique tunnel ventilation testing apparatus in CECI laboratories at Kaohsiung Taiwan, which testing apparatus was employed for this study.
Figure 1 presents the schematic configuration of tunnel structure and ventilation systems.



.**Figure 1 Schematic configuration of tunnel structure and ventilation system**

3. EXPERIMENT METHODOLOGY

Nomenclature

C1	:	Tracer gas density at upstream side tunnel	(%)
C2	:	Tracer gas density at down stream side tunnel	(%)
q	:	Unit respiration volume	(m^3/s?m^2)
A_r	:	Cross section area of tunnel	(m^2)
V_r	:	Mean air velocity between two tunnel section	(m/s)
A_s	:	Area of opening part	(m^2)
qn	:	Non dimensioned respiration air volume	(q/Vr)
V1	:	Air flow velocity at up stream tunnel	(m/s)
V2	:	Air flow velocity at down stream tunnel	(m/s)

Vr	:	Mean velocity at tunnel section(V1+V2)/2	(m/s)
$\mathbf{Q_r}$	:	Air flow rate at tunnel section	(m^3/s)
$\mathbf{q_{co2}}$	:	Tracer gas flow rate	(m^3/s)
$\mathbf{C_{co2}}$	:	Tracer gas concentration	(%)
$\mathbf{C_r}$	:	Tracer gas concentration in tunnel space	(%)
$\mathbf{C_o}$	:	CO_2 gas concentration in the back ground air	(%)
G1	:	CO_2 amount at upstream tunnel	(m^3/s)
G2	:	CO_2 amount at down stream tunnel	(m^3/s)

3.1. Out line of experiment

1/150 scale tunnel ventilation model was installed on the running apparatus. Two type of vehicle (HGV and passenger cars) with rectangular shape should be moved on the running apparatus by belt drive. The traffic conditions such as, traffic volume, HGV vehicle mixing ratio and traffic velocity should be simulated with real (design) conditions.
Natural wind conditions were settled in calm condition at indoor laboratories.
In addition, aerodynamic coefficient of tunnel entrance loss for tunnel ventilation calculation to be measured.
The following experimental parameters to be set up,

1) Structural conditions at opening part, shape of louver
2) Air flow rate at tunnel portals and exits of two tunnels

Based on above conditions, the relationship between air flow rate and gas concentration distribution to be cleared.

3.2. Testing apparatus for running vehicle

For the experiment, a running apparatus (Figure 2) with effective length of 18m is used. Table 1 gives details of the running apparatus. Figure 3 presents the Whole view of testing apparatus.

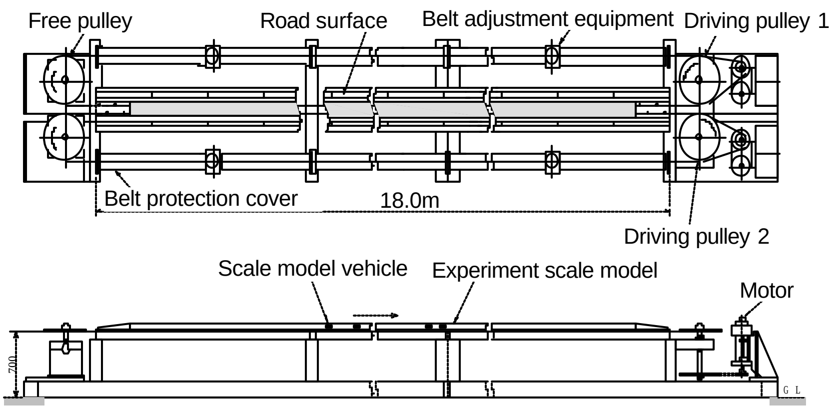


Figure 2 Configuration of Running Apparatus

Figure 3 Whole view of testing apparatus

Table 1 Specification of the running apparatus

Vehicle velocity	Any velocity in a range of 10 – 60 km/h
Velocity measurement	Line speed meter
Driving power	3f × 200V × 4P × 3.7kW, 2 units variable velocity type
Effective length for measurement	18,000 mm
Running belt	Height : 30 mm thickness : 3 mm Polyamide
Tracer gas release equipment	Located in the middle of the road or at both road sides at 10mm intervals, the tracer gas is released in equivalent concentrations in the direction of the road surface (over all length is 18.0m)

3.3. Scale model of vehicle

Figure 4 presents the dimension of scale model of vehicle for this experiment. The scale model vehicle was divided into two categories. Passenger car was simulated to 2000cc class and HGV was simulated 7.75tons cargo truck. The shape of vehicles were simulated by rectangular shape with sharp edge due to the different of aerodynamics drag in the low Reynolds number region. This shape of vehicle for the experiment has been high reliability of aerodynamic drag in compared with real situation. Therefore, this testing methodologies also have high reliability on the point of view of aerodynamics and tunnel ventilation aspects.

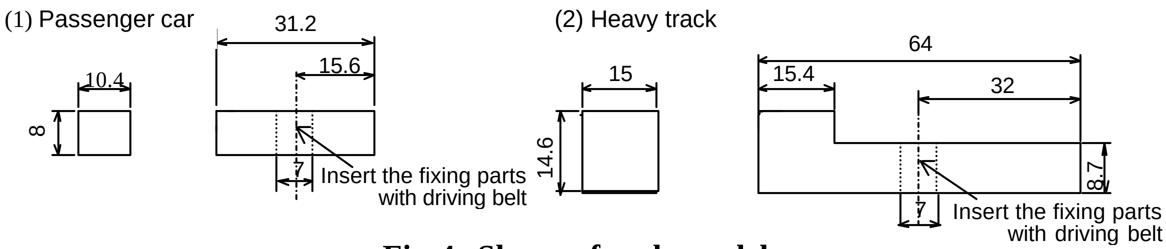


Fig 4 Shape of scale model

3.4. Measuring for CO_2 gas concentration and static pressure at tunnel section

CO_2 gas concentration was measured by CO_2 analyzer with multiple scanning valve throughout the sampling holes which are locating at both side walls and ceiling.
Figure 5 presents the gas concentration and static pressure measuring system.

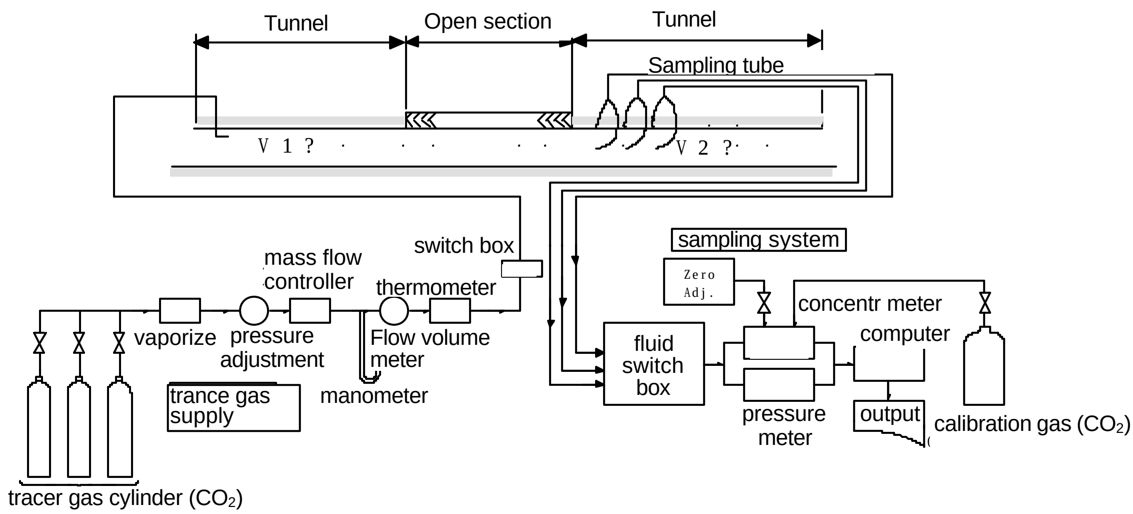


Figure 5 Chart of CO_2 gas concentration measuring system

Genuine CO_2 gas was employed for the experiment, which density is similar to ambient air. This CO_2 gas was charged to tracer gas nozzle at ceiling of upstream tunnel entrance throughout the CO_2 gas cylinder to evaporator to pressure adjuster and gas flow meter.
CO_2 gas flow rate was controlled by mass flow controller.
Back ground air concentration was measured at the upstream side of tracer gas injection point in each tunnels. Effects of natural wind to gaseous concentration distribution to tunnel and open section are not take into account.

3.5. Traffic conditions

Table 2 presents the traffic conditions for this experiment. Based on the actual traffic conditions, the head to head distance were simulated with 1/150 ratio. The mixture rate of HGV, number of lanes and traffic velocity to be realized to real situation.

Table 2 Traffic condition in real situation

	Traffic condition with two lanes
Traffic volume	1143 veh/h. 2 lanes
Traffic velocity	60 Km/h
Head to head distance	52.5 m
HGV content	15.0 %
Number of lanes	2 lanes

Vehicle velocity on the scale model experiment was controlled and detected by the digital meter, which are installed at main axis of driving pulley.

3.6. Tunnel Structural Model

Figure 6 presents the schematic structure of tunnel ventilation system for experiment.
This scale model was made by transparent plastics with 1/150 scale.
Tunnel structure was modified to rectangular cross section with point extraction and jet fans for air flow rate control.

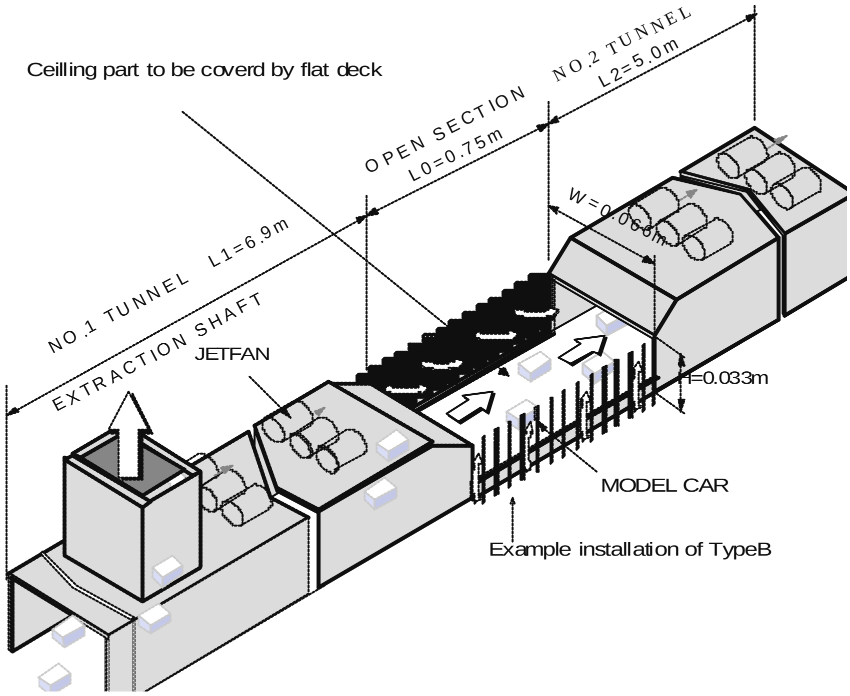
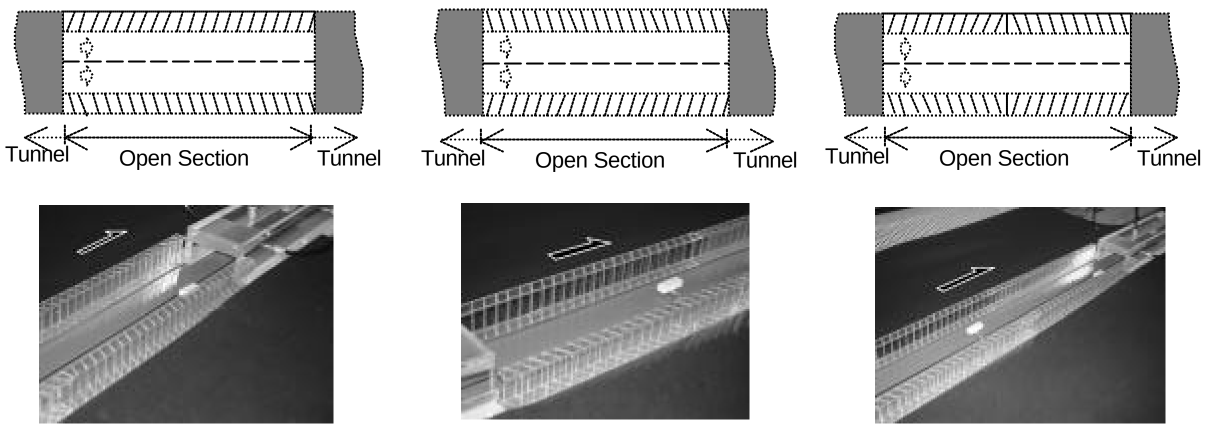


Fig 6 Schematic structure of tunnel ventilation system

3.7. Louver model

Figure 7 presents the vertical blade arrangement of louver model, scale ratio of louver will be 1/60 with made by transparent plastics due to the gain of Reynolds number for turbulence air flow.



a)Type A b)Type B c)Type C

Figure 7 Several type of Louver model

4. MEASURED DATE ARRANGEMENT AND ANALYSIS

4.1. Air flow rate at tunnel section

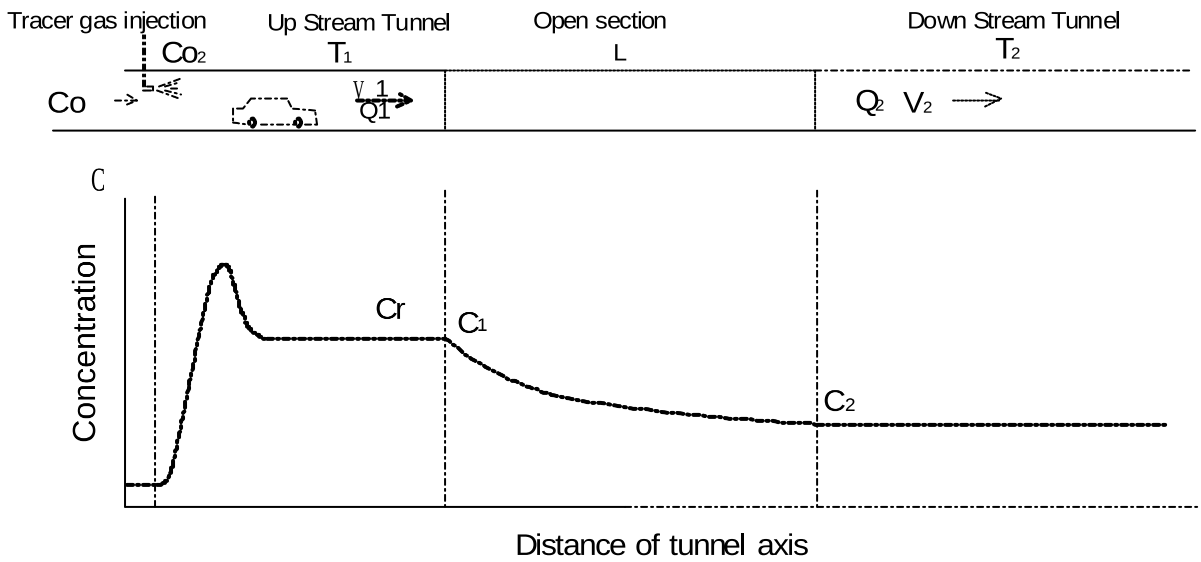


Figure 8 Example of gas concentration distribution

Figure 8 presents the tracer gas measuring method for the prediction of air flow rate in each tunnel section.

Air flow rate at tunnel section could be calculated by the tracer gas flow rate and measured data at down stream section. Formula (1) presents the relation ship between mass balance of tracer gas and air flow rate at tunnel section.

$$Q_r = q_{co2} \frac{(C_{co2} - C_o)}{(C_r - C_o)} \qquad \text{..................................(1)}$$

4.2. Interference ratio Ip

Ip could be confirmed by following equations for the purpose of clearly of air interference between two tunnels.

$$Ip = G2/G1 \qquad \text{.....} (2)$$

In this case, tracer gas concentration at up stream tunnel exit $C_{1,}$ and assumption of structural condition at open section is constant. C_1 will be deteriorated at open section then change to C_2 of down stream tunnel CO_2 gas concentration.
In this case, unit respiration air volume (q) can be expressed by following equations,

$$q=(A_r?V1/A_s)?In(C_1/C_2) \qquad \text{.....} (3)$$

This unit respiration air volume possess the dimension of m/s.
Non-dimensioned respiration volume can be calculated from unit respiration air volume divided by air velocity.

$$q_n=q/V_r \qquad \text{.....} (4)$$

4.3. Results of experiment for interference ratio

figure 9 presents of the tracer gas concentration distribution and air interference ratio to down stream tunnel.

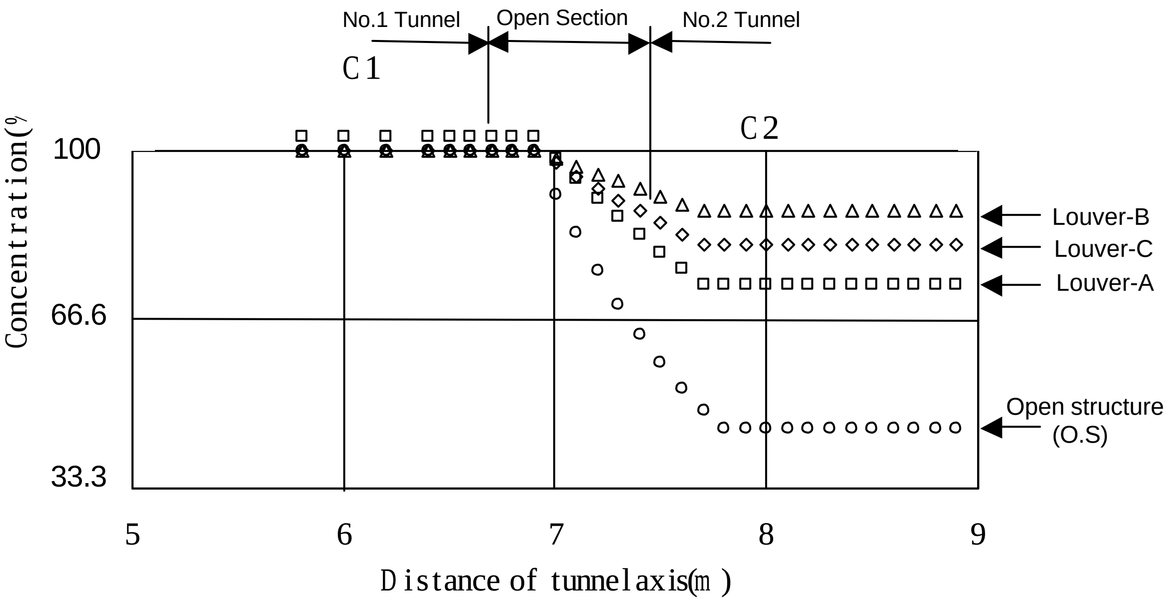


Fig 9 Tracer gas concentration distribution and air interference ratio to down stream tunnel.

4.4. Loss of aerodynamic coefficient at tunnel entrance

Tunnel entrance aero dynamic coefficient loss can be identified by following equation.

$$?in = \frac{?Pin}{(\frac{?}{2}Vr_2)^2} - 1 \qquad \text{.....} (5)$$

herewith ? Pin : Pressure drop at down stream tunnel entrance
Vr_2 : Air velocity in down stream tunnel

Table 3 presents the results of aerodynamic coefficient loss of tunnel entrance (? in)

Table 3 Aerodynamic coefficient loss of tunnel entrance (? in)

	Open structure	Type A	Type B	Type C
Tunnel entrance coefficient loss ? in	0.63	0.94	0.51	0.59

5. CONCLUSION AND REMAINING QUESTIONS

Based on this basic study, following issues to be concluded.

1) In the case of 100 long for full open section (1m height sidewall was installed) with 8m/s air velocity approximately under the normal traffic condition, 48%of polluted air will be re-entered to down stream tunnel.
2) In the case of semi-shelter installed, more than 70% polluted air will be re-entered to down stream tunnel.
3) Louver type A (outlet type of polluted air from upstream tunnel) of air interference to down stream tunnel is better than the other type. However, aerodynamic loss at down stream tunnel entrance is biggest in comparing with the other cases. Because of inlet air at downstream tunnel should be two times bended like S curve.
   But this is not serious problem, because of traffic piston always supporting to the induced airflow to down stream tunnel without in the case of low speed traffic.
4) More appropriate semi shelter structure must be investigated, however, it will not be able to find the better than open structure.
5) In the case of natural wind blowing, the air interference will be decreased. However, this factor might be reserved for the redundancy of ventilation capacities.

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APPROACHES OF APPLICATION OF VENTILATION SYSTEMS IN DIFFERENT TUNNELS: SOLUTIONS ADOPTED AND WORKING OPERATIVE.

José María Maya
Manuel Alberto Abella Suárez

ABSTRACT

The present article, tries to valuate the solutions adopted in the ventilation of an urban tunnel, located in the Circumvallation of Las Palmas, divided in two diferent parts to constructive effects, and two diferent profile traverse; that took advantage to endow to the same tunnel of two systems different from ventilation: A stretch by a longitudinal ventilation, and its continuation by two couples fan extractors; the tunnels of the Circumvallation of Las Palmas, in the island of Las Palmas of Gran Canaria, tunnel of clearly urban character, designed for traffics of 60.000 vehic/day.

The ventilation by extractor fans is applied, also in the case of a freeway tunnel, submerged partly, built in an artificial way, in which the scarce clearance did not allow the employment under conditions of good yield, of jet fans.

The two mentioned tunnels are in service, and the operation is correct, without until the moment incidents have taken place, thanks to an operative of exploitation that combines the information to the user, with the employment of the ventilation and signaling system.

The second ones are the Tunnels of Villaviciosa, in Asturias, North of Spain, in the A-8, when this comes under the Ria (small fiord) of Villaviciosa, designed for traffics of 20.000 vehic/day.

1. PARAMETERS OF DESIGN OF THE TUNNELS.

The conditions of the environment, together to the economic readiness and the use forecasts, are who mark the general characteristics of design of the tunnels: layout, section, equipment, and in last term, the way of exploitation.

Referred to the object tunnels of the present exhibition, they think about two, maybe better to say three, different conditions:

The first tunnel that will be exposed, is without any doubt the most simple, and with better conditions, it is the Tunel de la Ría of Villaviciosa.

Located in the Railcar A-8, in ace vicinities of the town of Villaviciosa, it is a tunnel carried out in covered trench. Their construction is due to avoid the visual and environmental impact in a natural environment.

The singularity of this tunnel, is that goes under the Ria, and that transforms it into a tunnel submerged partly under a bed of water subjected to the influence of the tides.

The adverse constructive situations, and the conditions of maintaining the phreatic levels, limited, in great measure, the geometric characteristics of the tunnel.

On the other hand, the security for the facilities and users were considered high-priority from the first moment, and influenced notably in the adoption of the traverse section of the group, and of the different elements of the equipment of the group.

The final section belongs together with the figure:

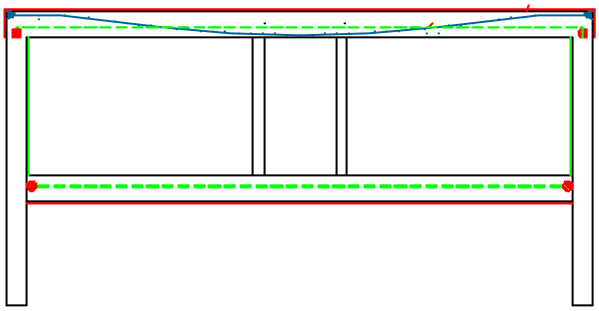


Figure 1: Outline of the traverse section.

It is made up of two tubes, one for each rail, separated by a central cell that is used like on the way to escape in the case of a serious incident, at the same time that it houses different services.

From each tube you consents to the central cell through fire resistant doors separated about 70 meters to each other, so traveling for the users in the event of necessity is of about 40 meters maximum.

Each tube is equipped also, with a complete system of security and aposyo to the user:

- Each 70 meters in the side of the central cell, it is equipped with a fire extinguisher system, provided of hose of water to pressure, and extinguisher.
- Each 70 meters in the side of the lateral wall, it is equipped with a fire extinguisher system, provided of hose of water to pressure, and extinguisher, besides a system of aid posts that allows the communication with the Control Center.
- Located in the high part of the tunnel, they are the illumination apparatuses.
- Each 400 m. approximately they have settled signaling panels with variable messages, and cross/arrow signs.
- Each 400 m. approximately they have settled traffic lights.
- Along the tunnel, each 20 m has settled emergency lights, with autonomy of one hour, in absence of net light.

The general outline belongs together with the following figure:

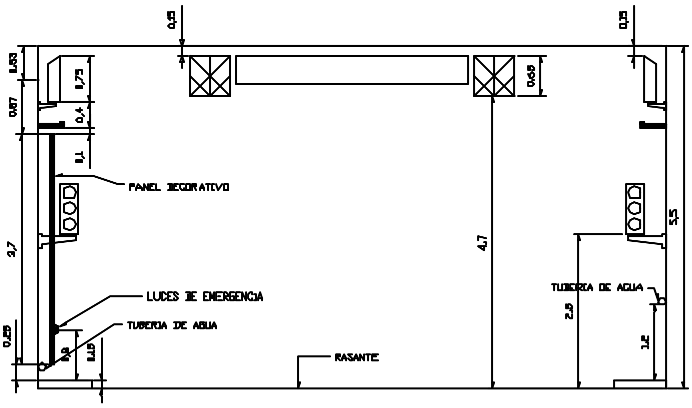


Figure 2: Outline of facilities

The volume of foreseen traffic is from about 20.000 vehicles to day, of which 15% will be trucks. I’ts not previewed problems of retentions, and the collision risk inside the tunnel is not specially high, when reflecting for him a flowing traffic.

Due to the scarce available height inside a strict traverse section, the solution of a longitudinal ventilation, by means of jet. fans, forces to that these plows of very small diameter, and it presents, among other, the following inconveniences:

- Bigger number of apparatuses to achieve an adapted ventilation.
- A very high sound level inside the tunnel, and in their bordering.
- Bigger investment in apparatuses and in their maintenance.
- Bigger investment in having wired.
- Bigger risk of crash of heavy vehicles, and limitation of the use of the tunnel in the event of special transports.

Among the studied solutions, it was thought of using the central cell, applying a system of ventilation traverse semi then. Nevertheless the biggest inconvenience was not to be able to use like on the way to escape and quick intervention the central cell. Therefore the elected system was a ventilation by means of extractors, that is to say to place a fan aspiring the air of the interior of each tube, entering the fresh air for the mouths.

In normal situation, with flowing traffic, with a half speed of the vehicles above 35 Km/h, the tunnel it's self ventilated.

Only in the event of congestion, or a serious incidence, like fire for example, it is necessary to use the extractors.

In the case of fire we take advantage the tendency of the hot smoke of ascending to maintain the low area free of smoke when being aspired this from the roof; this low area assures the escape possibility of those affected.

The used fans, one for each tube, they have a power of 75 Kw, with an interior diameter of 2.500 mm. The resistance to the fire is of 250 ºC during two hours, and its extraction capacity is of 240 m3/s, enough to finish a truck fire.

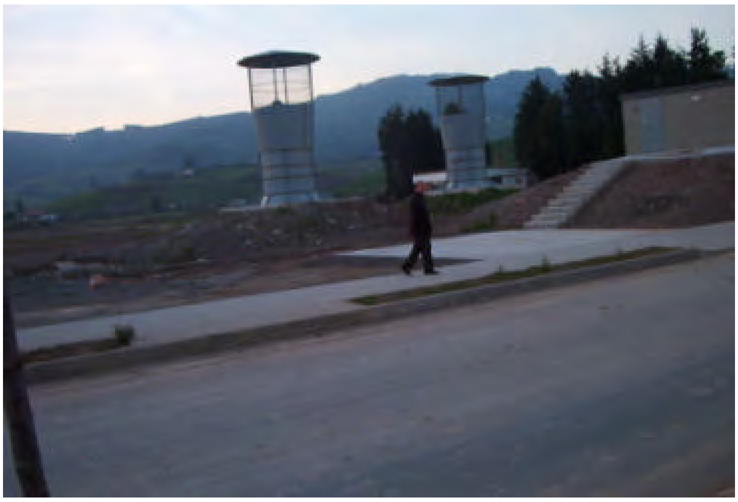
The operative of operation of the Center of Control has been studied thoroughly, especially the formation of the operators, and in the software of the control computer, automatic sequences have been implemented, that once worked by the operator, they take charge of closing the tunnel, to activate the fans, to manage the signaling, etc.

In the following pictures the final state of the tunnel is appreciated

Picture 1: Seen of the portal of the tunnel.

Picture 2: Seen of the interior of the tunnel

The aspect of the fans in the exterior is appreciated in the following picture:



Picture 3: Fans in the exterior of the tunnel

The following design, of this report, corresponds to a much more complex situation: it is the solution adopted in San José Tunnel, in the ring of circumvallation of Las Palmas of Gran Canaria.

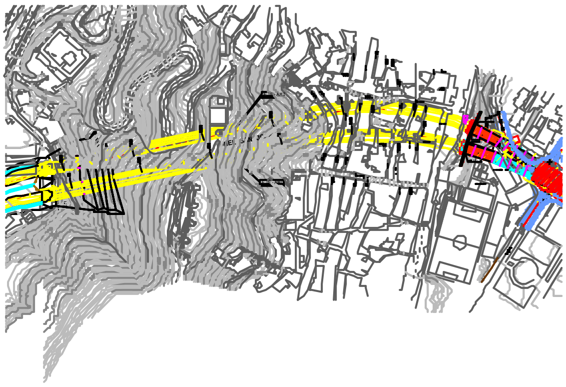


Figure 3: General schem of the tunnels.

This road of great capacity is foreseen for a great traffic demand. It is considered a half intensity of traffic of about 90.000 vehicles day. it presents in their layout the singularity of San José Tunnels and San Cristóbal that united without solution of continuity for the user, if they present clear differences:

- The section of San José tunnel is arched, while San Cristóbal is a section in drawer.
- San José tunnel has a tube for each address, while San Cristóbal houses the two addresses in the same drawer, separated by a barrier New Jersey, and the support piles to the board that he closes the flagstone.
- San José tunnel is a structure closed in its longitude, while San Cristóbal has holes (practiced in the rounds and the relationship with San José that communicate it with the outside).
- Regarding the ventilation San José tunnel is of the unidirectional type, while San Cristóbal is bidirectional.

In the following ones you imagine they show the different sections:

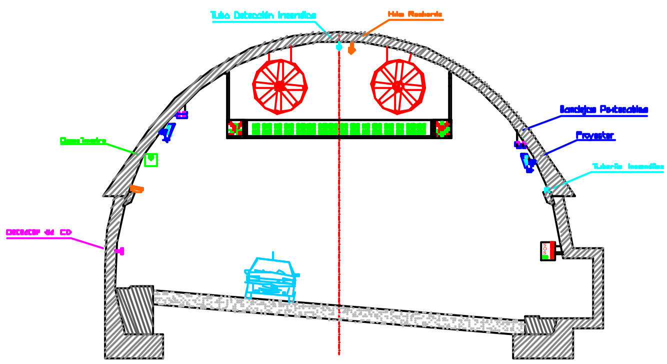


Figure 4: Transversal section of San Jose Tunnel.

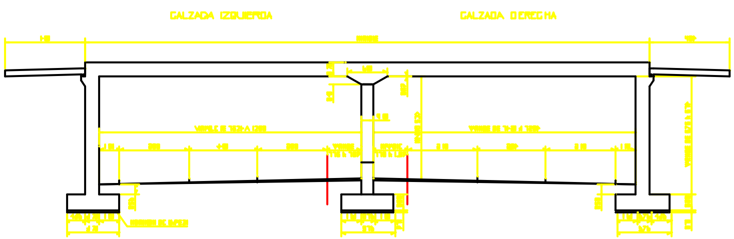


Figure 5: traverse Section of the tunnel of San Critobal.

To the effects of the ventilation, these differences have been the conditions for a treatment different from each tunnel, establishing a separation among both, so a tunnel has a ventilation solution different from the other one. This way the ventilation chosen for San José tunnels, is the Longitudinal Ventilation with accelerators of Reversible type for the following reasons:

- It is safe. It allows to maintain the tunnel under appropriate environmental conditions.
- The realization of wells, reinforcement roof, etc is avoided, necessary for another ventilation type.
- It is cheap. They are necessary few fans.
- Their placement is very simple, and its weight is not specially significant, locating you between the 900 and the 1.500 kgs. according to the elected pattern.
- The maintenance is extremely simple.
- It allows a good control of the energy consumption, when pulling up only the necessary fans.
- It is the most economic solution, and their reliability for the longitude of the tunnels it is more than proven.

The calculations of necessary fresh air, and the performance considerations in the event of fire show that one needs a push of about 8.046 Newton to extract the smoke in the event of fire, supposing the case but unfavorable that means an occupation of the tunnel in their entirety, that is to say the tunnel with an occupation of 100% of vehicles.

The maximum necessity in the case of dilution of gases and smoke, without considering the fire, settles down in the calculation in about 4.600 Newton, clearly inferior to the necessity for fire. The result is the installation of six axial fans, reversible of 55 Kw of unitary power, and 2.100 Newton of unitary push.

In San Cristóbal Tunnel, however, the relative inconveniences to the realization of the wells don't exist when being a covered trench, in which can be carried out how many openings they are necessary: it doesn't exist a shortage therefore for this concept.
On the other hand, San Cristóbal tunnel presents a remarkable difference regarding San José tunnel: Its traffic, to ventilation effects it is bidirectional. The solution of longitudinal ventilation, with fans subject to the roof of the tunnel is not the but adapted by the following reasons:

- It would force to a high number of apparatuses, with a great consumption of power.
- The daily operation with highly alternative dominant traffics, demands bigger quantity of hours of operation of the apparatuses, what implies bigger consumptions, but you wear away and bigger investment in maintenance and repair.
- The strict available space would force to place the fans in not very appropriate spaces regarding its yield, like they can be the superior corners of the mark, or the central area, among the piles.
- The characteristic of urban tunnel, with possibility of frequent traffic congestion the risk of incidents increases in its interior.

Keeping in mind these inconveniences, a ventilation has been chosen by means of extractors that it presents the advantages enumerated in the case of the ventilation of the Tunel de la Ria of Villaviciosa. When being an urban tunnel, with a density of much more traffic, the ventilation necessities refer to the capacity of extraction of air and smoke for the wells.

Establishing a capacity of extraction of smoke of 70 m3/s for each well, equivalent to the fire of a medium vehicle (bus or slight truck), the speed of air has settled down inside the tunnel, and the lost of load, being deduced the capacity of the necessary machine. The result is the installation of four fans in its respective wells, of 75 KW of unitary power.

The separation to effects of the ventilation among the tract of the tunnel in mine, of the tract of covered trench is gotten by a round open of about 40 m. diameter; in the following picture can see this separation.

Picture 3: Space opened between San José and San Cristóbal

This way, it not only breaks the continuity of the tunnel, a pleasant transition is also achieved between the semicircular section and the rectangular one of each one of the tracts.

In the following pictures it is appreciated this transition clearly:

Picture 4: Transition between San José and San Cristóbal

The location of the fans extractors in the urban environment, generates an annoying level of noises, at the same time that its visual impact is unpleasant, to avoid it they lodge in a structure that avoids the noises, it protects to the machines of possible vandal acts, and it favors the maintenance. In the following one there is an outline:

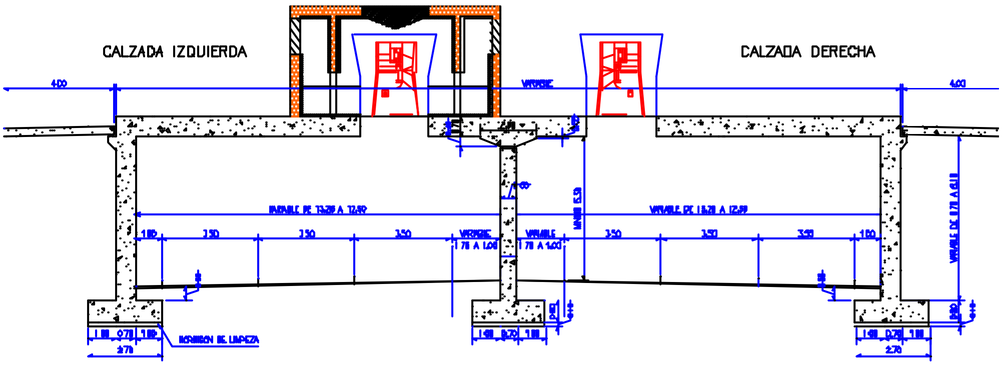
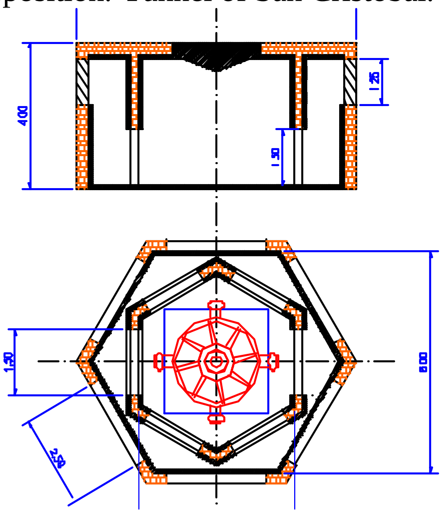


Figura 6: Fan Disposition. Tunnel of San Cristóbal.



It figures 7: Details of the structure anti noise

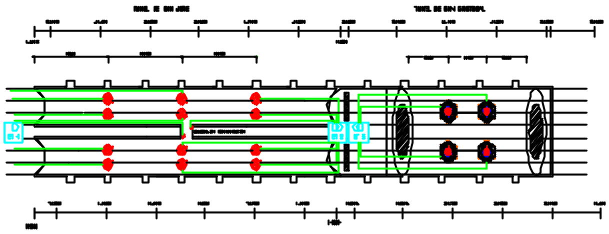


Figure 8 : Placing of the fans in each tunnel.

2. CONCLUSIONS

The ventilation of the tunnels is a fundamental aspect in the security, and together with the own stability of the excavation they conform the aspects more delicate: The geotecnical aspects and of maintenance of the excavation, they offer a durable, stable and sure structure along the time.

The ventilation and elements associated to it, as the detectors of CO, the opacimeters, the fire detectors, and the control systems, allow a comfortable and sure traffic of the vehicles, maintaining an use flexibility, and a means of fight against the smoke in the case of fire.

Without losing of view these aspects, the election of a certain ventilation system, we understand that it should be made enlarging the horizons from the possibilities of adaptation to the environment, the disposition of the machines for their good yield, the execution easiness, and the possibility of minimizing the derived nuisances of the forced maintenance.

In the cases of sections strict, and scarce height, as those enumerated in this report, we understand that the solutions like those adopted are the most appropriate to allow a good operative.

VENTILATION OF PROTECTED AREAS IN ROAD TUNNELS

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ABSTRACT

During the past few years big efforts have been undertaken to improve the safety of the tunnel users. Even though signalisation, ventilation, detection, alarming as well as the education of the users have been examined and enhanced certain risks remain. Normal truck loads can initiate tunnel fires that are overwhelming for all technical equipment designed for a limited size of incident. Under this aspect the ventilation of the protected areas, which can be summarised as being the path between the escape doors and the environment, gets an important role for the safety of the tunnel users as well as for the rescue personnel.

Key words: tunnel, ventilation, design, protected areas, escape way, emergency exit, lock, safety

1. INTRODUCTION

The fatal fire disasters in the years 1999 and 2000 have influenced the public discussions in a way that new and more stringent requirements for tunnel ventilations had to be established. In Switzerland the general design rules of 1983 are replaced by the requirements of the guideline Ventilation of Road Tunnels. The guideline includes indications for the maximal distance between the emergency exits. The Federal Road Administration (FEDRO) plans to set up a separate guideline for the ventilation of the escape ways this year. The aim is to set a standard for sufficient protection and for rigid systems with low energy consumption during the permanent operation. The paper here presented is based on the provisional version GR 2003 which was mandated by the Civil Engineering Department Canton Grisons. Presently in the canton Grisons several long safety galleries are planned or are under construction.

2. EMERGENCY EXITS

2.1. General remarks

Emergency exits as part of the safety concept have to be adjusted to the ventilation system in the tunnel itself. Therefore the concept of emergency exits and escape ways is integrated in the Swiss guideline for Tunnel Ventilation. A second reason for the integration of escape ways in the mentioned document is a possible interaction of its ventilation systems with the one of the tunnel itself.

2.2. Maximal distance of emergency exits

The requirements in the former guideline of 1983 allowed the construction of single bore tunnels with smoke extraction over the full tunnel length without emergency exit. One of the lessons that had to be learned from the recent fatal tunnel fires were that

- the detection systems are too slow to give an acceptable chance for the tunnel users to escape
- the smoke layering in a real case is less ideal than assumed
- the extraction density in $m^3/s,m$ of the conventional ventilation systems is far too small to prevent a large tunnel length to be filled with smoke

Even though the FEDRO-guideline 2003 prescribes for long tunnels the installation of a locally forced extraction capacity by means of controllable dampers, maximal distances between emergency exits for all road tunnels types have be defined as well.

For dual bore tunnels the distance of the cross connections remains 300 m. Every third cross connection has to be sized for the passage of large equipment of the fire brigade. In accordance with the European directive on Minimum Safety Requirements for Tunnels in the Trans-European Road Network the maximal distance between emergency exits in single bore tunnels is generally set to 500 m. In the Swiss guideline FEDRO 2003 the distances are specified according to the fact whether there is natural or mechanical ventilation of the tunnel and according to the tunnel slope. The basic assumptions for the determination are

- a reaction time of the tunnel users of 3 minutes
- a reasonable time to reach the next emergency exit of 3 to 5 minutes depending on the ventilation system
- a walking speed of 2.4 m/s in slopes up to 2 % and of 1.2 m/s at a slope of 8 % with a linear interpolation at slopes in between.

The resulting maximal distances are shown in Figure 1.

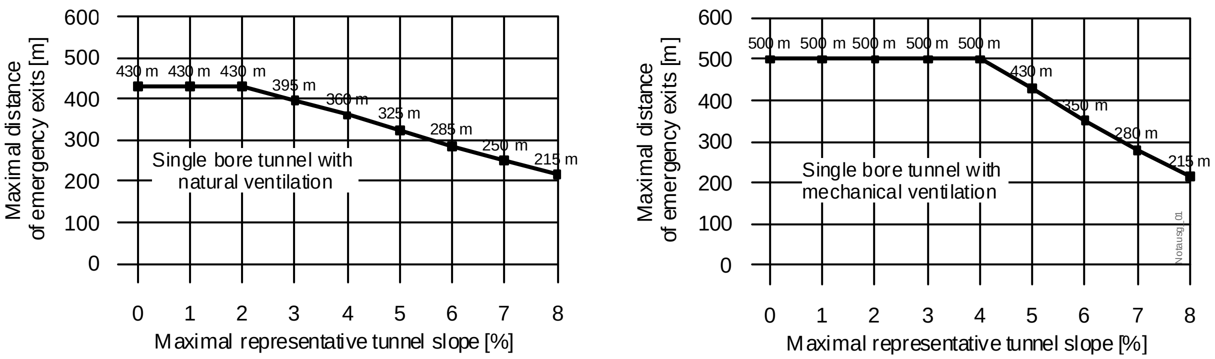

Figure 1: Maximal distance of emergency exits in single bore road tunnels

The values in Figure 1 apply as well for unidirectional tunnels without a parallel tube. The construction of new tunnels with slopes higher than 5 % should be avoided. Nevertheless tunnels with higher slopes already exist especially in the alpine region and it is questionable if steep tunnels can always be avoided in future.

3. DEFINITIONS

For a proper understanding of the following chapters it is necessary to define some special terms:

Area with primary risk	Area with the incident. In this zone all emergency exits are opened presumably. For the design of the ventilation of the protected area in this paper it is assumed that the length of the zone with primary risk is 600 m for tunnels with smoke extraction, for tunnels with other ventilation systems it is the tunnel length but not more than 1'200 m.
Protected area	Area between the escape door at the tube with the incident and the open. In a dual bore tunnel the non-incident bore is part of the protected area.
Escape door	Door marked as emergency exit between the area with primary risk and the protected area. It must be possible to open escape doors easily at any time. The escape door can be integrated in a larger gate for vehicle passage.

Intermediate door	Door which can be opened at any time within the protected area. An intermediate door is not a part of a lock.
Safety gallery	A tunnel leading from the road tunnel to the open. A parallel safety gallery is connected with the road tunnel by connecting tunnels and leads at its two ends to the open. A safety gallery leading directly to the open has only one exit to the open.
Connecting tunnel	Connection between the road tunnel and the safety gallery
Cross connection	Connection between two parallel tubes
Lock	Passage space with two interlocked doors. A lock allows a continuously controlled overpressure.
Normal operation	State of the ventilation without special incident
Emergency operation	State of the ventilation during an incident during which the emergency exits might be used

4. ARRANGEMENTS OF ESCAPE WAYS

For the design of the ventilation of the escape ways four different arrangements have to be regarded. Figures 2 and 3 related to one bore tubes - mainly tunnels with bidirectional traffic - figures 4 and 5 show double bore tunnels with unidirectional traffic.

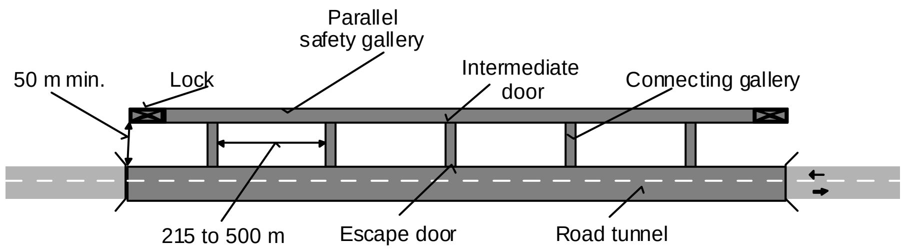

Figure 2: Arrangement with a parallel safety gallery

Two exits to the open equipped with locks characterises the arrangement of the escape ways in figure 2. Depending on the design of the aerodynamic system intermediate doors can reduce the necessary installed power.

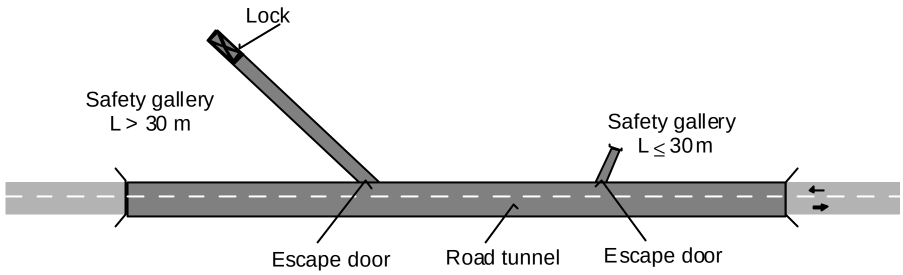

Figure 3: Arrangement with safety galleries leading directly to the open

The necessity of a controlled overpressure with a lock in safety galleries leading directly to the open depends on its length and its slope. A length over 30 m or a difference of height over +3 m were chosen as criteria.

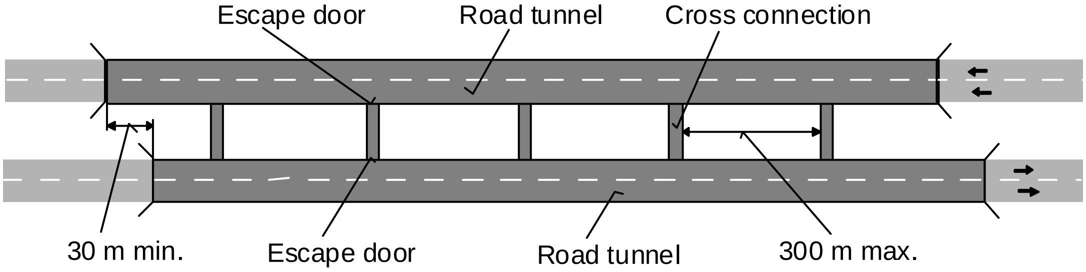

Figure 4: Arrangement with cross connections between two tubes

In drilled two bore tunnels the non-incident tube represents the escape way. The distance between the bores is big enough to allow two escape doors on either side of each cross connection. Instead of shifting the exit portal by 30 m a dividing wall of at least 30 m length can be built (see figure 5) in order to prevent a recirculation of smoke.

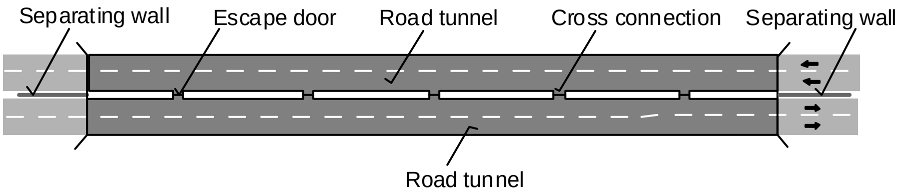

Figure 5: Arrangement with cross connections between two tubes of a cut and cover tunnel

Usually a simple wall divides the two tubes of a cut and cover tunnel. As a consequence only one escape door per cross connection is possible. The portals of such tunnels are closely adjacent. Additionally to active means with the tunnel ventilation separating walls or shifted portals (see figure 4) have to guarantee a sufficient protection against recirculation of smoke or other harmful gases from one tube to the other. (Further indications are given in FEDRO 2003, ch. 7.2.6)

5. VENTILATION

5.1. Goals

The design goals for the ventilation of the protected areas are

In normal operation:	Reduce the intrusion of pollution (A small transmission of pollutants is acceptable.) The slight overpressure gives at the same time a certain protection against smoke transmission even before the emergency operation is functional. Minimise the energy consumption of the permanently running system.
In emergency operation:	Keep the protected area sufficiently clear of smoke and other harmful gases.

5.2. Basic requirements

For arrangements with safety galleries the basic requirements for pressure, air speed, volume flow and fan redundancies are tabulated in figure 6.

Type of operation and fan failure	Type of requirement Setting	Arrangements with parallel safety gallery (fig. 2)	Arrangements with safety gallery directly to the open (fig. 3)
Normal operation	Δp at closed escape doors Air flow per closed escape door	50 Pa 0.2 m^3/s	50 Pa 0.5 m^3/s
Emergency operation, all fans available	- 1 single escape door open - 3 adjacent escape doors open - 2 escape doors in unfavourable position open	3.0 m/s 1.5 m/s 1.5 m/s	3.0 m/s
Emergency operation, failure of a single fan	- 1 single escape door open - 3 adjacent escape doors open - 2 escape doors in unfavourable position open	2.0 m/s 1.0 m/s 1.0 m/s	2.0 m/s
Emergency operation, total failure of a fan station	- 1 single escape door open - 3 adjacent escape doors open - 2 escape doors in unfavourable position open	1.6 m/s 0.8 m/s 0.8 m/s	No requirement Only 1 fan station

Figure 6: Basic requirements for the ventilation of safety galleries of single tube tunnels

The installed system has to meet the requirements in figure 6 including adverse effect from the tunnel ventilation in an emergency case as well as unfavourable thermostatic and barometric conditions.

For arrangements without a safety gallery the tunnel users have to escape through a tunnel tube and a portal. In tunnels with two tubes the cross connections and the non-incident tube have to be kept sufficiently clear of smoke and harmful gases by one of the following concepts:

a) Normal case for two bore tunnels with two escape doors per cross connections (figure 4): The design of the escape doors minimises the cross flow: The second hinged door must close by the air flow or supported by a closing mechanism. Sliding doors must be equipped with closing mechanism.
b) Normal case for cut and cover tunnels:
Cross connections are equipped with sliding doors with closing mechanism.
c) Special case: In rare cases - depending on length and slope of the cross connection - a mechanical ventilation can be necessary. As a rule to define a special case a height difference of more than 3 m between the two escape doors of the cross connection can be used.

The cross connections in the concepts a) and b) are not mechanically ventilated. In normal operation the ventilation of concept c) must be chosen individually in order that a comparable safety standard as with the arrangement for concepts a) and b) is reached. In emergency operation with concept c) the corresponding requirements in columns 3 or 4 of figure 6 must be fulfilled. The force of sliding doors that are self-closing must not endanger fleeing tunnel users.

5.3. Special requirements and standard values

Doors and gates:

Typical Dimensions

Door for person passage only: W x H = 1.25 m x 2.10 m

Gate for small personnel cars and service cars: W x H = 2.60 m x 2.30 m

with integrated door: W = 1.25 m

Gate for large rescue vehicles: W x H = 4.50 m x 4.50 m

with integrated door: W = 1.25 m

Gates for large rescue vehicles are required in two bore tunnels at intervals of 900 m.

- Fire resistance
  The fire resistance of the escape doors is 30 minutes (T30). A higher fire resistance of escape doors leading to an escape tunnel under overpressure is presently discussed (T90). For intermediate doors no special requirement concerning fire resistance is set.
- Force to open
  The maximum allowable force to open the doors must not exceed 80 N. For the design of doors with "crash-bars" the force to open the doors has to be assumed in the middle of the bar.
- Opening concept
  The opening concept can be hinged doors or sliding doors. All escape doors in a tunnel must be of the same type. Mechanical opening aids should be avoided. In any case such aids must not block the door.

Detection in the protected area:

- The intake for fresh air of the protected area must be equipped with smoke detection.
- Detection of fire and smoke is not required neither in safety galleries nor in cross connections. A fire in technical equipment is reported by a technical alarm.

Periodical tests:

- Periodical tests must guarantee the functionality of the system. The results have to be documented.

Initialisation of emergency operation:

- Fire alarm in the tunnel
- Pre-alarm in the tunnel (e.g. alarm from fire extinguisher)
- Opening of escape door
- In a safety gallery: Drop of overpressure of more than 50 % during 30 seconds
- Manual initialisation

5.4. Resulting systems

The above described requirements lead to ventilation systems for safety galleries with the following characteristic values:

Installed power: 10 kW/km
Used power 200 W/km in normal operation with energy costs of €400/km, year

6. OUTLOOK AND ONGOING WORK

The publication of the guideline for the ventilation of road tunnels and a guideline for the ventilation of protected areas is planed this year. Presently a guideline for doors in road tunnels is established. The Swiss Road Administration coordinates the work for the different guidelines.

ACKNOWLEDGEMENT

We thank the Civil Engineering Department Canton Grisons for funding the described work.

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ON LONGITUDINAL VENTILATION AND CONGESTED TRAFFIC

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ABSTRACT

During the past few years, emission regulations have resulted in a shift of the emphasis of ventilation design. While the main goal of the ventilation system was to provide fresh air for the dilution of pollutants, it is now smoke control during a tunnel fire. However, the reduction of vehicle emissions has also led to new and more stringent air-quality limits, e.g. the 50 ppm 30 min exposure limit for carbon monoxide CO, which is applied in new Australian tunnel projects. The exposure of drivers on their way through the tunnel has to be assessed in ventilation design and during operation. This is being done by examining the pollution concentration over the length of the tunnel.

Ventilation design is usually based on hourly average traffic and average emissions. For a longitudinal ventilation system, this gives a linear concentration profile along the tunnel section. The introduction of emission regulations for new vehicles has lead to very different emissions of individual vehicles. This paper deals with the variation of emission coefficients and the influence on the pollution profile along the tunnel. The pollution profile is being calculated using the simulation software RoadTun that allows the definition of individual vehicles with different emissions and travel speeds. While the influence is small during fluid traffic, it becomes more pronounced during congested traffic. Concentration peaks may lead to an increased exposure of individual drivers, although the peaks may remain undetected by the ventilation control system.

Key words: tunnel, ventilation, numerical simulation, individual vehicles, exposure

1. BACKGROUND

The CO exposure limit is a constraint for the new Australian road-tunnel projects. However, for this study, the tunnel geometry as well as traffic mix and emission data are not directly extracted from those projects.

Traditionally, the required fresh air for a given traffic scenario in the tunnel depends on the number of cars in the tunnel, the average emission per car in this traffic and the admissible peak concentration for this particular emission. The calculation methodology is described e.g. in PIARC (1995).

1.1. CO Exposure Limit

The ventilation design methodology as described in the PIARC reports is given for peak levels of carbon monoxide CO and turbidity. Carbon monoxide is taken as the leading gas for assessing the toxicity of the exhaust gases.

A new regulation has been applied to tunnel-ventilation design and operation in Australian tunnel projects. It defines a 50 ppm CO exposure limit for any 30 min period. The air-quality limit has been adopted from WHO goals for working environment. It is assumed that the CO level inside the vehicle is the same as in the tunnel air.

If the exposure limit was adopted only for the average tunnel user, allowing a design based on average vehicles and hourly average traffic, it would not determine the ventilation design. The typical time spend in a road tunnel is in the range of a few minutes. Therefore, the exposure limit would not be critical to the average tunnel user. However, as the exposure limit is made applicable to any individual in the tunnel, the behaviour of tunnel users has to be taken into account. The exposure of people involved in a traffic incident, such as a broken-down vehicle, or in an accident has to be examined. And – applying the exposure limit to any traffic situation and any tunnel user – the time and local variation of CO levels in the tunnel has to be examined as well.

In order to measure the exposure of individuals in a road tunnel, every tunnel user would have to be equipped with a CO meter before entering the tunnel. A close approximation could be made by examining CO meters and traffic loops that are installed at very short intervals in the tunnel. Both methods do not appear practicable. Because of the measurement technique involving a running average of the signal, it appears feasible only to assess an approximate, time average CO profile from a few CO meters in the tunnel.

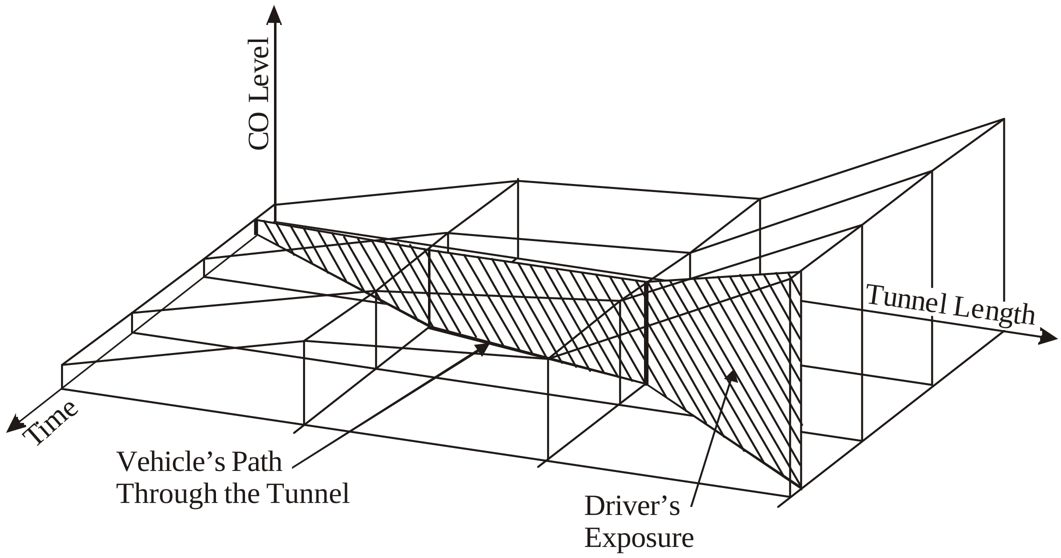

Figure 1: Assessment of a Driver's CO Exposure from Recorded Data of CO Profile and Travel Speed

Figure 1 indicates how the exposure of a driver can be assessed from recorded data of vehicle speed and CO concentration. The methodology may be used in order to estimate the remaining time until the exposure of a driver involved in an incident may exceed 50 ppm. The remaining time is equivalent to an acceptable response time for the tunnel operator to clear the incident or at least to evacuate the driver.

Although it is not feasible to measure the exposure of individual tunnel users, the local variation of CO levels in the tunnel can be examined by a numerical simulation.

1.2. Variation of Vehicle Emissions

The ventilation-design methodology as described in the PIARC reports is based on the emission of the average car in the traffic mix expected in a particular scenario.

However, looking at the introduction of new emission regulations in various countries, the question arises if the emissions of a series of average vehicles correctly represent the emission situation in a real tunnel. Assuming the introduction of new regulations within a couple of years may lead to the situation given in Table 1.

	Emission Regulation	Partition in the Traffic Mix	Relative CO Emission 2005
Cars (Petrol)	No Regulation	1 %	**8.3** *Average
	Reg. 1: 1982	2 %	2.5 *Average
	Reg. 2: 1985	33 %	1.9 *Average
	Reg. 3: 1997	64 %	0.4 *Average
HCV (Diesel)	No Regulation	20 %	**1.9** *Average
	Reg. 1: 1991	16 %	1.2 *Average
	Reg. 2: 1994	22 %	0.8 *Average
	Reg. 3: 1998	42 %	0.6 *Average

Table 1: Vehicle Classes, Partition and Relative Emission for Cars and Heavy Commercial Vehicles

As the CO emissions of the average heavy commercial vehicle HCV are only 2.3 times the emission of the average passenger car, the vehicles with the highest CO emission are the few very old passenger cars and not the HCV. Although these vehicles represent only 1% of the traffic mix, about 30 to 60 of these cars may be expected during a typical peak hour.

Furthermore, the relative emissions given in Table 1 still represent averages for a vehicle class. The emission variation within a vehicle class would be less than the variation in the total traffic mix. But still, an individual car could have several times the average emission of its class.

This paper concentrates on the variation of CO emissions for different vehicle classes. CO has been selected because of the application of the CO exposure criterion. It has to be noted, that for other pollutants, such as particles/turbidity or NO_X, the emission variation of different vehicle classes is much more pronounced.

2. ROADTUN

RoadTun (Vardy, 1976) is a computer program for the simulation of time-varying processes that are relevant for the ventilation of road tunnels. It uses the one-dimensional method of characteristics. It calculates the time variation of flow velocity, static pressure and pollution concentration in an entire tunnel system. RoadTun simulates the behaviour due to the time-varying traffic (volume, velocity, composition etc.), the ventilation and the inertia of the aerodynamic system. The tunnel configuration ranges from a single tube to very complex tunnel systems. Beyond the vehicle emissions and the natural ventilation, the influence of the ventilation system is calculated.

Thermal effects, such as the chimney effect due to hot smoke from a tunnel fire, can be modelled by prescribing an external pressure difference. In order to simulate the behaviour of various ventilation-control routines, measurement points are defined. The calculated values of concentration, velocity and pressure at the control points can be used as input data for the ventilation control.

RoadTun's most important feature for the subject of this paper is the traffic model. Vehicles classes and even individual vehicles can be defined applying different emission tables.

3. SIMULATION

3.1. Tunnel Geometry and Traffic

The simulations are done for a two-lane, unidirectional road tunnel of 3000 m length on level ground. The tunnel cross section is 50 m^2 and the air-flow rate is set to 250 $m^3\,s^{-1}$. This gives a constant air-flow velocity of 5 $m\,s^{-1}$ or 18 $km\,h^{-1}$ in traffic direction. Piston effect of vehicles is counterbalanced by an external pressure difference. The subject of this article is not the simulation of tunnel aerodynamics. The boundary conditions have been set in order to demonstrate the specific effect.

Nonetheless, the boundary conditions are not entirely unrealistic, as in countries such as Australia, jet fans are used in order to both accelerate and limit the longitudinal air flow. The air-flow rate in the tunnel is controlled in order to optimise the air extraction for the avoidance of portal emissions.

In these examples, the traffic consists of 2000 petrol driven passenger cars and 100 diesel driven HCV per hour. All vehicles travel at the same constant speed. Vehicles of the same vehicle class enter the tunnel at constant intervals. So there appears to be some statistic variation in the traffic flow. However, clusters of high emission vehicles, such as a series of HCV travelling in short succession, have not been included in the simulation.

3.2. Fluid Traffic at 60 km h^{-1}

Figure 2 shows the CO profile along the tunnel for a vehicle speed of 60 km h^{-1}. The air intake at the left hand portal starts with a CO level of 0, assuming no background concentration. The dashed line shows the result of the calculation following the PIARC methodology. The CO concentration increases linearly from the air intake to the exit portal (on the right).

The solid line gives a typical CO profile according to the numerical calculation. Except for small deviations e.g. at x = 600 m and 2700 m, the two graphs are in very close agreement.

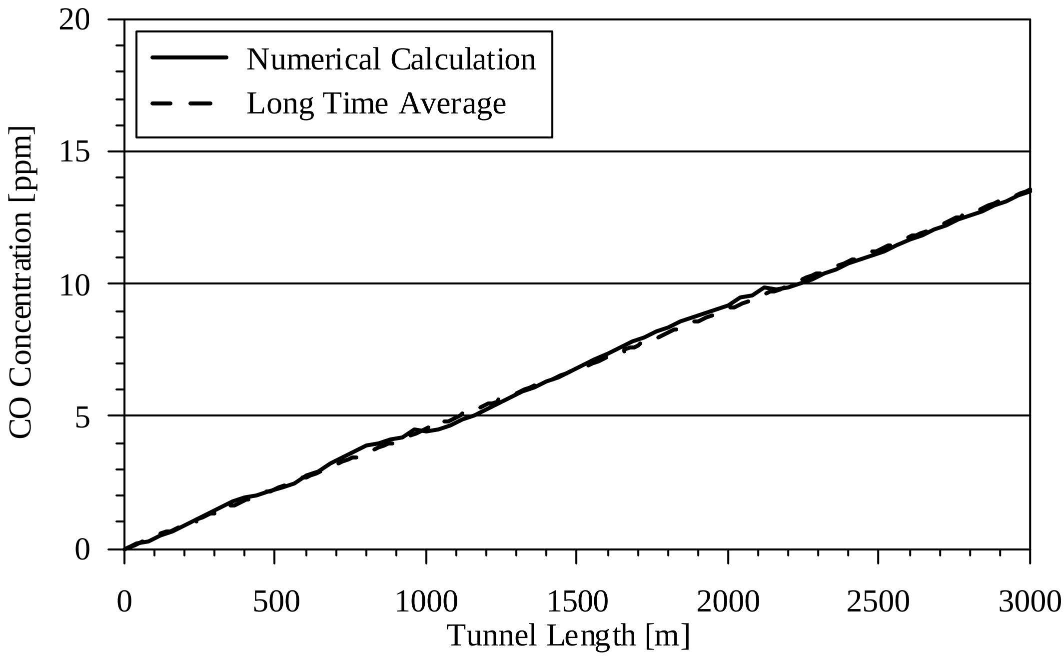

Figure 2: Calculated CO Level vs. Tunnel Length for Fluid Traffic

Of course, the peak CO level is by no means critical in terms of in-tunnel air quality limits. The CO exposure of any driver would not be critical either.

3.3. Congested Traffic at 18 km h^{-1}

Figure 3 shows the equivalent CO profile for a vehicle speed of 18 km h^{-1}, just matching the air-flow speed. As in Figure 2, the dashed line shows the result of the calculation following the PIARC methodology. The CO concentration increases linearly from the air intake (assuming no background concentration) on the left to the exit portal on the right.

The solid line gives a typical CO profile from the numerical simulation. For most part of the tunnel, the CO level is less than the linear profile. This is counterbalanced by a few distinct peaks distributed along the tunnel. Three peaks, at 700 m, 1600 m and 2500m, can be linked to passenger cars without emission regulation; the other peaks can be linked to HCVs without emission regulation.

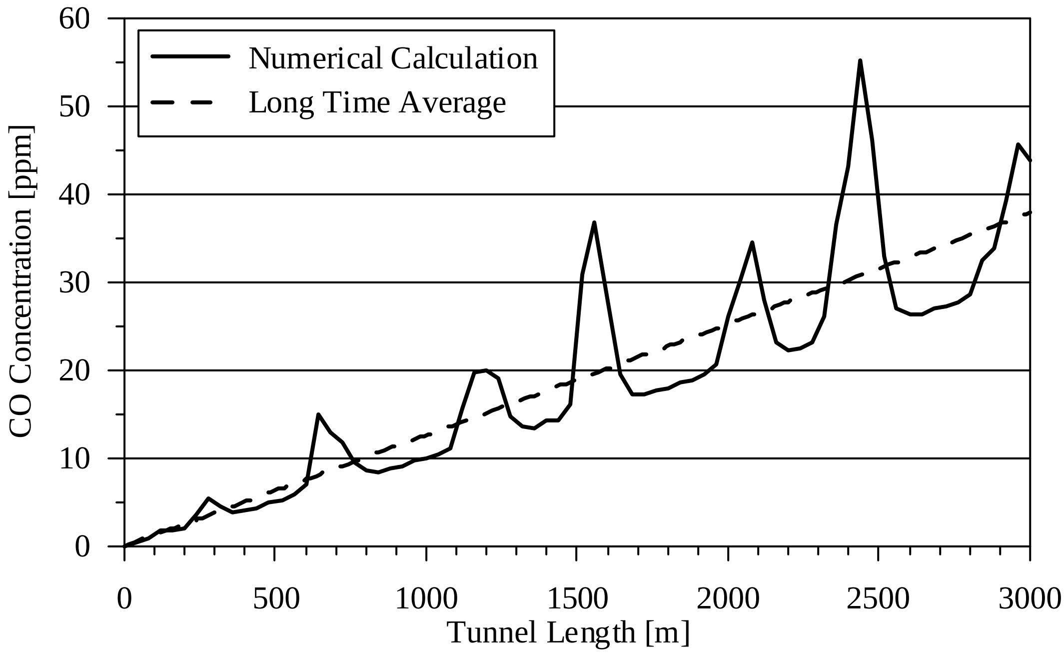

Figure 3: **Calculated CO Level vs. Tunnel Length for Congested Traffic**

As these peaks travel along the tunnel at the same speed as the traffic, the exposure of drivers travelling in such a peak is poorly approximated if calculated from the assumed linear CO profile.

3.4. Other Traffic Speeds

The height of the peaks can be measured by the ratio of peak concentration to average concentration. Peak heights for traffic speeds between 16 and 22 km h^{-1} are given in Figure 4. Peaks due to the variation of CO emissions of individual vehicles are only visible for a small range of traffic speeds. Once the difference of air flow and traffic speed is about 20%, the effect of individual vehicles on the pollution profile becomes negligible.

Figure 4 is not applicable as a general result. The travel-speed range and the peak height depend on a number of factors, such as emission variation and tunnel length.

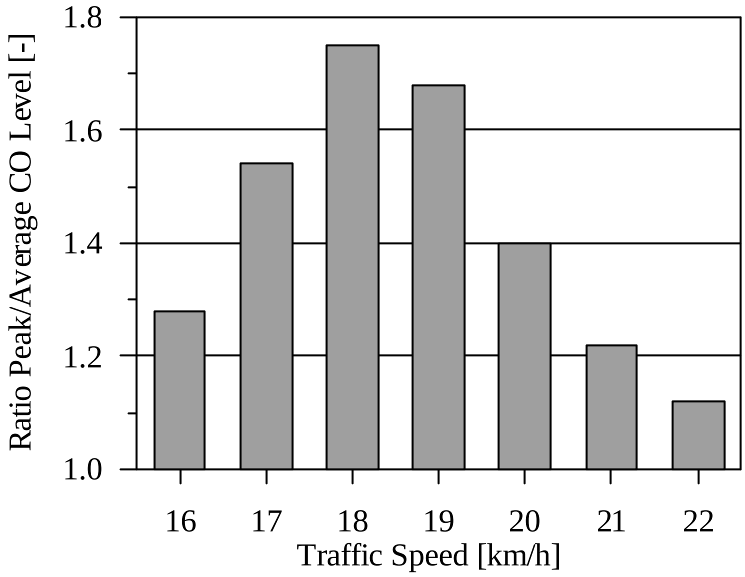

Figure 4: Relevance of Local Peak CO Levels vs. Traffic Speed (Simulation)

4. INTERPRETATION

4.1. What Happens?

Two schematic pictures demonstrate the effect of the relative speed of vehicles and tunnel air, see Figure 5.

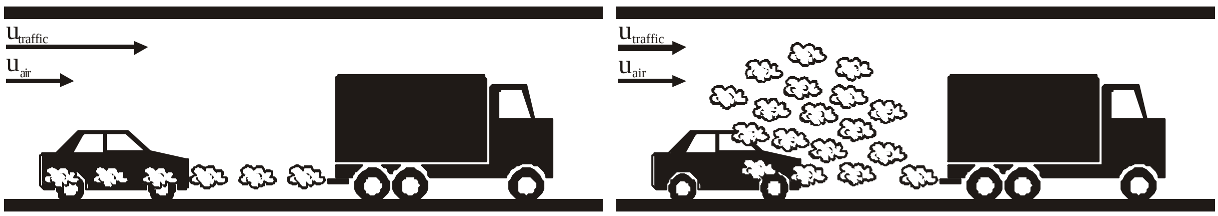

Figure 5: CO Dispersion Schematic for Fluid (Left) and Congested (Right) Traffic

During fluid traffic, the HCV's emission is trailing behind and mixing with the emission of the succeeding vehicles. This leads to a smooth CO profile along the tunnel, quite close to the CO profile that has been calculated from average emissions. The situation would be similar if the air-flow speed exceeds the vehicle speed, e.g. in standing traffic.

During congested traffic, when the air-flow speed is in the range of the vehicle speed, the HCV's emission remains close to the source, allowing the pollutant to accumulate with only minor dilution due to local turbulence or due to some relative movement between air and vehicle.

4.2. Is It a Real Phenomenon?

The peaks may be somewhat more pronounced in a numerical simulation. In real congested traffic, the vehicles do not move at exactly the same constant speed. Any variation of piston effect and ventilation adds to some relative movement between vehicles and tunnel air resulting in additional dilution. The numerical simulation, on the other hand, still applies only four emission classes for each vehicle type (cars and HCV). Real emissions of individual vehicles could be much higher than the emissions given for any vehicle class.

For this study, the variation of individual vehicle's emissions in real traffic has not been assessed. Therefore, no further quantification of the effect can be given. The CO peaks shown in Figure 3 may vary according to a series of parameters.

4.3. Are Short Term Peaks Detected by the Ventilation Control System?

As the readings of CO meters are usually processed as a running average for a time of 1 to 5 min, local peaks may not be visible during tunnel operation. Figure 6 shows a graph of the calculated CO concentration at the exit portal for the congested traffic scenario in Figure 3. Once the CO data are processed by a 1 min running average, the short term peaks are shifted and reduced. Applying a 3 min running average almost renders the variation of the CO concentration invisible.

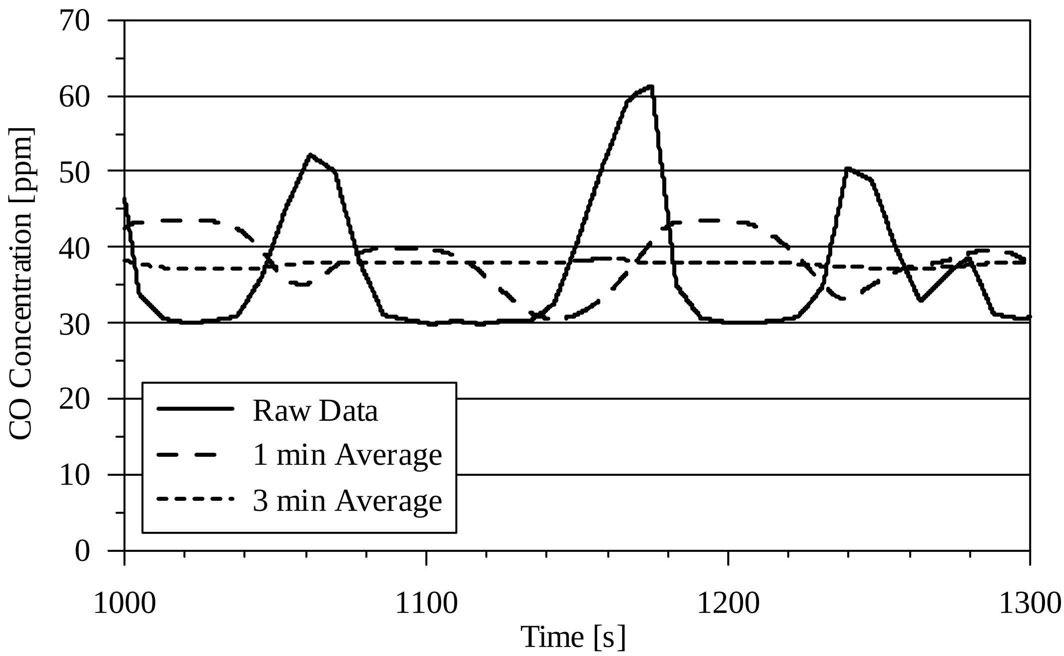

Figure 6: Calculated CO Level at the Exit Portal, Raw Data at 18 km h^{-1} and Running Average

5. CONCLUSIONS

The following conclusions can be drawn:

i. The PIARC methodology applying average vehicle emissions and assuming a linear CO profile per tunnel section appears entirely sufficient for all practical ventilation designs.

ii. For any tunnel equipped with longitudinal ventilation system, congested traffic moving at the same speed as the tunnel air should be avoided in order to avoid local peaks of pollution.

iii. As the CO exposure of individuals is impossible to examine in daily operation, it does not appear to be useful to apply such an air-quality limit to every individual. It appears beneficial for ventilation design and operation to introduce a more stringent air-quality limit that

   a) is applicable to the PIARC design methodology and

   b) can be tested.

   This air-quality limit could be a 50 ppm local peak CO level allowing for a time average of 5 min.

6. REFERENCE

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KNOWING THE USEFUL LIFE PERIOD OF TECHNICAL EQUIPMENT – A PREREQUISITE FOR SAFE TUNNEL OPERATIONS

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ABSTRACT

Today's tunnels have al large amount of technical equipment installed: for a new tunnel 15% of the cost has to be calculated. Once a tunnel is built and in operation, the yearly maintenance cost of the technical equipment can sum up to as much as 50% of the overall cost; i.e. the life cycle of systems and components is quite low. In a average span of 5…40 years the equipment has to be completely replaced and renewed, the average life period is below 20 years.

It is therefore essential to know the "useful life period" of the technical systems, in order to prevent system breakdowns with related safety hazards. It is further necessary to carefully monitor the condition of the different systems in order to minimize surprising system down-time.

The report shows typical tunnel system life cycles, outlines the related useful life period, and – draws conclusions on best behaviour.

1. INTRODUCTION

Today's tunnels have al large amount of technical equipment installed: for a new tunnel 15% of the cost has to be calculated. Once a tunnel is built and in operation, the yearly maintenance cost of the technical equipment can sum up to as much as 50% of the overall cost; i.e. the life cycle of systems and components is quite low. In an average span of 5…40 years the equipment has to be completely replaced and renewed, the average life period is below 20 years.

The overall goal of a tunnel authority shall be: safe and continuous operation of the technical equipment, minimized down-time of equipment and installations which jeopardize safety. To achieve this goal, a condition oriented maintenance system is mandatory, but, how shall the system conditions in a tunnel be reasonably tracked? Many concepts are available for the industrial field, but rather less data is accessible for system applications in tunnels.

It is necessary to know the life period of the technical systems to develop maintenance systems which help preventing break-downs and surprising down-times.

2. SOME BASICS

2.1. Down-time And Up-time

A speciality of technical systems is that their performance (or function) does normally not "slowly deteriorate" over the life time, it is the *reliability* of a system which changes slowly to lower values. (Not all technical systems behave like this, i.e. the light density of a lamp decreases continuously during aging. However, the majority of complex technical systems can be classified in "up-" or "down-condition".) Hence, knowing the failure rate and its development over time is the essential subject. These parameters are probabilistic values – and therein lays a major problem of finding the best-practice in maintenance of technical systems: these values cannot be measured within a reasonable time period, and, are normally not provided by manufacturers.

The MTTF (mean time to failure) is the quality figure of a system in operation, and it can be calculated over the life time of a system with the reliability function R(t) only:

$$MTTF = \int_0^\infty R(t)\delta t$$

Using the failure rate Lambda, the MTTF is:

$$MTTF = \frac{1}{\lambda}$$

If the failure rate is constant, i.e. there are no aging processes of the components (is during the useful life period normally the case), the probability of finding a system operating after a time period, is:

$$R(t) = e^{-(\lambda 1 + \lambda 2 + .. + \lambda n)t}$$

It has to be taken into account that every system is a collection of subsystems, having their own reliability functions. The MTTF of the overall system can be calculated only, if the reliability of the subsystems is known. Provided that all elements of a system are independent, the reliability of the system can be calculated as follows:

$$R(t) = \prod_{i=1}^{n} R_i(t)$$

Having these basic relations in mind, it is possible to describe the development of technical systems over the life span.

2.2. Bath Tub

It is common use to describe the behaviour of a technical system during life with traditional graphs. The following example was published years ago by a Swiss Facility Management Society:

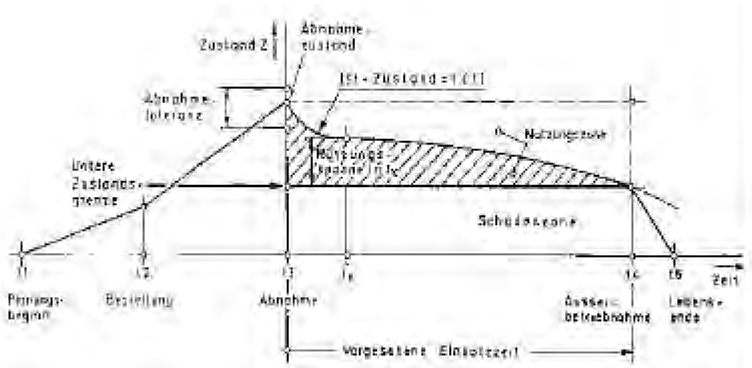

Fig. 1: Condition of a mechanical system

It is interesting to note that the y-axis is called "Zustand", i.e. the condition of a system.
The condition slowly decreases to a point, where the "damage zone" (Schadenszone) is reached. At that point, the system shall be "replaced". Fact is that non-mechanical systems do not slowly decrease in function, i.e. there is no sharp threshold where life time ends and damage starts.
Therefore, today's common curves are the bath-tub curves:

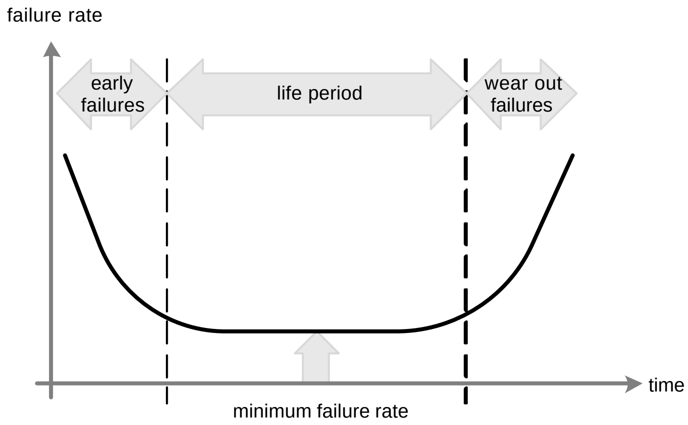

Fig. 2: Condition of a solid state system

This graph shows more correctly the condition of a system by the failure rate vs. time. The early failures take place in the "infant mortality period", whereas the late failures are the "wear out failures". Optimizing the operation of the systems means usually knowing the start of the wear out period, in order to react in time.

2.3. Useful Life Time

The useful life time of a system is normally shorter than the life time. The term "useful life time" expresses the period in which the system can reasonably be used, taking into account all extrinsic factors and boundary conditions. During the life time the failure rate falls to a minimum value which is system-specific and an intrinsic characteristic of the system element. Subsequently, this minimum value has to be accepted.

2.4. Maintenance Concepts

The maintenance concept has a remarkable influence upon the life time and the useful life period. By optimizing the maintenance strategies, it is possible to extend the respective periods. In this paper the maintenance theories shall not be discussed, however, one important fact shall be outlined:

The best-practice maintenance concept shall achieve low risk of failure, hence, a condition-based philosophy should be applied. This is feasible, if it is easy possible to recognize the condition of a system or to detect the gradual loss of function. Being able to detect the reliability of a system is now the key issue – and it will be shown that this is a time-consuming and difficult task.

If condition-based maintenance is not possible, the common-used time-based concept may be applied. This strategy bases on the assumption that repair work is possible and therefore the restoration of the initial performance or the reduction of the failure rates is achieved.

3. LIFE CYCLE ANALYSIS

3.1. Life Cycle Distribution in Tunnels

After having discussed more basic and theoretical aspects of the reliability and availability of technical systems, the focus shall be laid on experiences that originate from an existing tunnel and the equipment installed in this special environment.
The tunnel is located in Switzerland on a highway with remarkable traffic volume and a high percentage of HGV's (Heavy Goods Vehicles). The age is 30 years. The data on the life time of the equipment may not be taken as typical, however, comparisons to other tunnels showed a certain statistical value of the information.

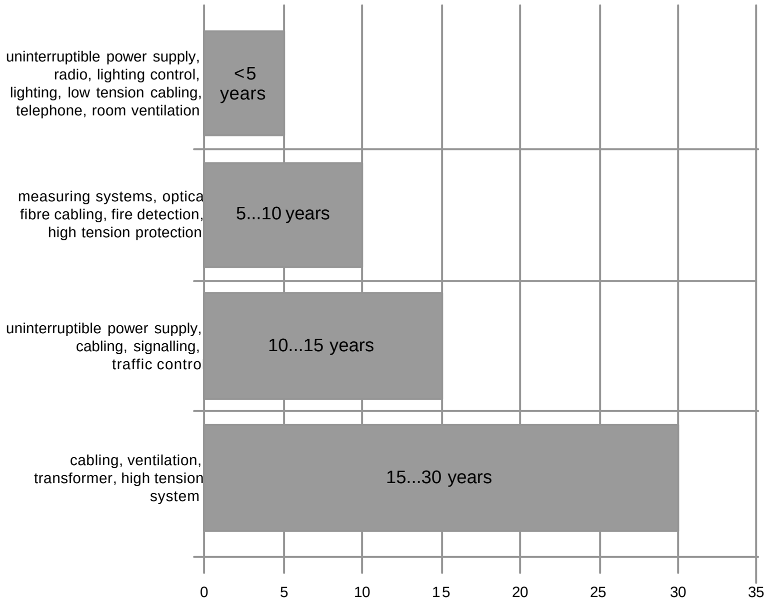

Fig.3: Life cycle distribution in a tunnel

It is shown that the energy systems and the ventilation system have not been replaced since the tunnel opening (cabling, high tension equipment, transformers, fans). Signalling equipment, traffic control, low tension equipment has been replaced after 15 years, and the rest of the systems are not older than 10 years.

Many other tunnels show a similar picture: Energy Systems and mechanical equipment have life spans of 20 years and higher; controls, low voltage systems, electronic equipment have very low life expectancies. There are no new outcomes, however, the fact that up to $^2/_3$ of the equipment will be replaced within 15 years is astonishing. We conclude that the focus shall be laid on these systems, having condition-based maintenance concepts in operation in order to avoid safety hazards due to surprising breakdowns.

3.2. Electronic Subsystems

As mentioned before, very few practical data on MTTF, MTBF (mean time between failures), failure rates and reliability of systems is provided by the manufacturers. The reasons are manifold, but it can be assumed that product liability and the respective legal consequences do not promote that kind of information.

Nonetheless, there are figures available: A UPS-unit (uninterruptible power supply) which was investigated showed the following values:

Failure rate λ: 1 / 250.000 hours (1 / 28.5 years)

The reliability function and the graph have the following form:

$$R(t) = e^{-0.0345t} \text{ ; t in years}$$

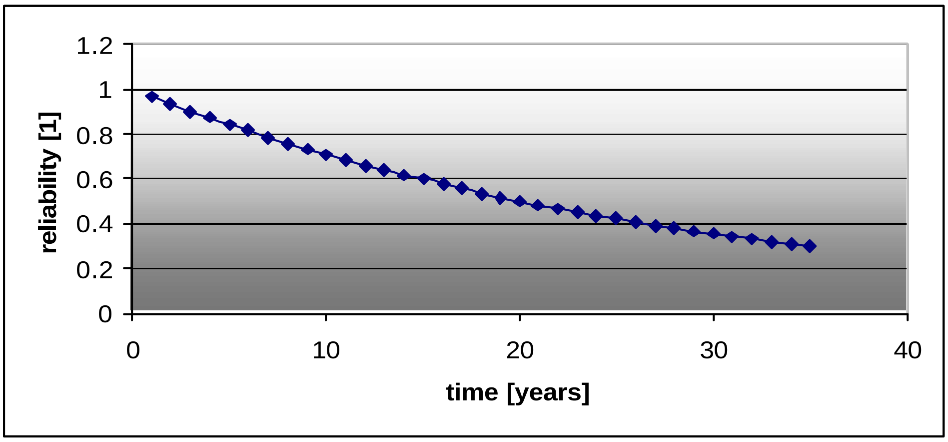

Fig. 4: reliability function of a uninterruptible power supply system

The unit exhibits after 5 years a reliability of 85 %, after 10 years of 70 %, i.e. 3 of 10 units fail within 10 (!) years, statistically regarded. The values do not appear as particularly high – or, simply not acceptable, bearing in mind that an UPS is a safety system. Hence, this system needs special maintenance, preferably time-based maintenance with regular renewal of certain components. The manufacturer recommends to replace the important parts as follows:

Capacitors	10 years
Fans	5 years
Backup battery	10 years
Batteries	3 … 15 years, depending on type

Other manufacturers present for power units MTBF-figures as high as 200 years, equals to 1.75 Mio hours (Ericsson).
If we compare the risk of failure within a period of 10 years between the two given examples, we find in general:

$$R(t) = e^{-t/MTBF}$$

For a MTBF of 28.5 years

$$R(10\text{ years}) = e^{-10/28.5} = 0.70 \quad (1)$$

For a MTBF of 200 years

$$R(10\text{ years}) = e^{-10/200} = 0.95 \quad (2)$$

The comparison shows that in example (2) the risk for failure is remarkably lower: The risk of failure within 10 years is 5 % compared to 30 % in example (1). (In all these considerations we assume that the ambient temperature is equal for the examples.)

We conclude that the selection of the system should consider the reliability function of the product, and, if available, the maintenance strategy has to be adapted to that basis. The "useful life period" for example (2) could therefore be defined with 10 years, if 5% failure rate is acceptable (no maintenance is made). If 5 % is not acceptable, the maintenance activities have to include regular spare part renewals.

3.3. Lamps

After having discussed the life cycle of a typical electronic/electric system (uninterruptible power system), we focus on another typical tunnel equipment product: the (fluorescent) lamp.

The illumination system is one of the important systems in tunnels; the safety and guiding aspect of lighting systems is beyond any doubts. But, it is not easy to determine the

useful life periods of lamps if we consider the main goal of such a system: to provide a sufficient lighting density during a prescribed time period.
The light density vs. time shows the following graph:

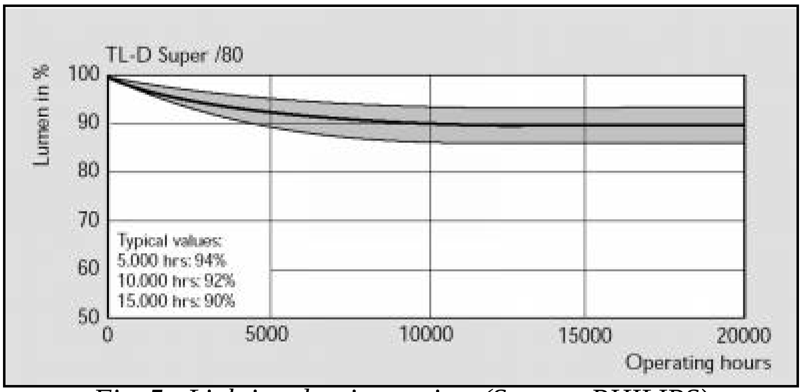

Fig. 5: Lighting density vs. time (Source: PHILIPS)

If we look to the survivals of the lamps vs. time, we find:

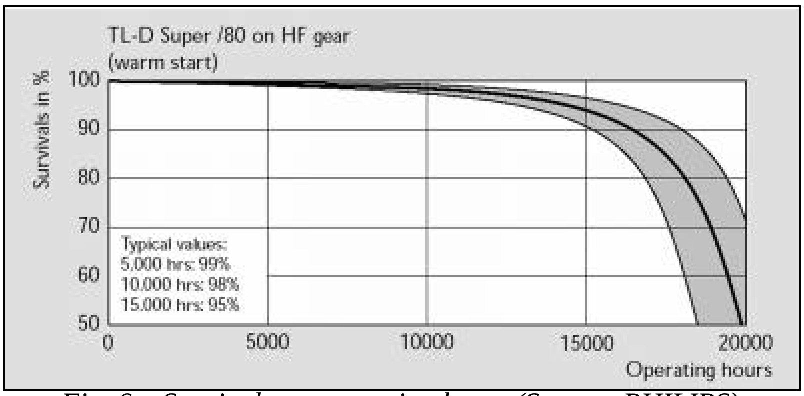

Fig. 6: Survivals vs. operating hours (Source: PHILIPS)

The above data is not directly applicable for tunnels because tunnel lamps are normally not switched and therefore have another life expectancy. Many experiences of tunnel operators show life periods up to 40.000 hours, however, there is no information on the luminous flux available at that time.

Obviously, fluorescent lamps have a life expectancy between 20.000 and 40.000 hours. We note that data sheet information is not sufficient as such, further data is necessary to discuss life cycles and the useful life period.

4. KEY CONDITION VALUES

4.1. General Remarks

The above discussion of typical life cycles has shown that every case has its own peculiarities, and no general rule for determining the life cycle can be given. However, by acknowledging the probabilistic behaviour of technical equipment, a successful approach is to know and monitor "key condition values" and to get acquainted with their impact on the useful life period.

4.2. Key Condition Values of Tunnel Equipment

It is necessary to identify these key condition values for every single system which has to be monitored (we assume that not every tunnel system has the same importance, a safety risk assessment shall be used to select the respective systems.)

Having identified these values, they have to be monitored in order to get acquainted with the system behaviour within the life cycle.

The following table gives some examples of key condition values.

Key Condition Values / Systems	Failure Rate [1]		Operating Hours t_B [s]		Contamination [high, mean, low]	Corrosion [high, mean, low]	Temperature [°C]	Vibration [m/s²]		Voltage [V]	Current [A]	Power [W]	Energy Consumption [kWh]		Light Density [Cd/m²]		Humidity [%]
Monitoring System	X																
Lighting	X				X										X		
Fire Detection					X												
Radio	X		X														
Communications	X		X														
High Tension							X			X	X	X	X				
Telephone System	X		X		X	X											
Climatization	X						X										X
CO/Opacity	X				X	X											
Uninterruptible Power Supply	X						X					X					
Ventilation			X		X	X		X			X						X
Video																	
Signalling	X																
Waste Water System	X		X								X	X					
Access System	X		X														

Fig. 7: Key condition values of typical systems

4.3. Useful Life Periods Step-By-Step

The diagram below illustrates a possible step-by-step approach to define useful life periods. It is recommended to apply such a procedure on limited systems only, for instance for systems with a high risk potential on the safe operation of a tunnel.

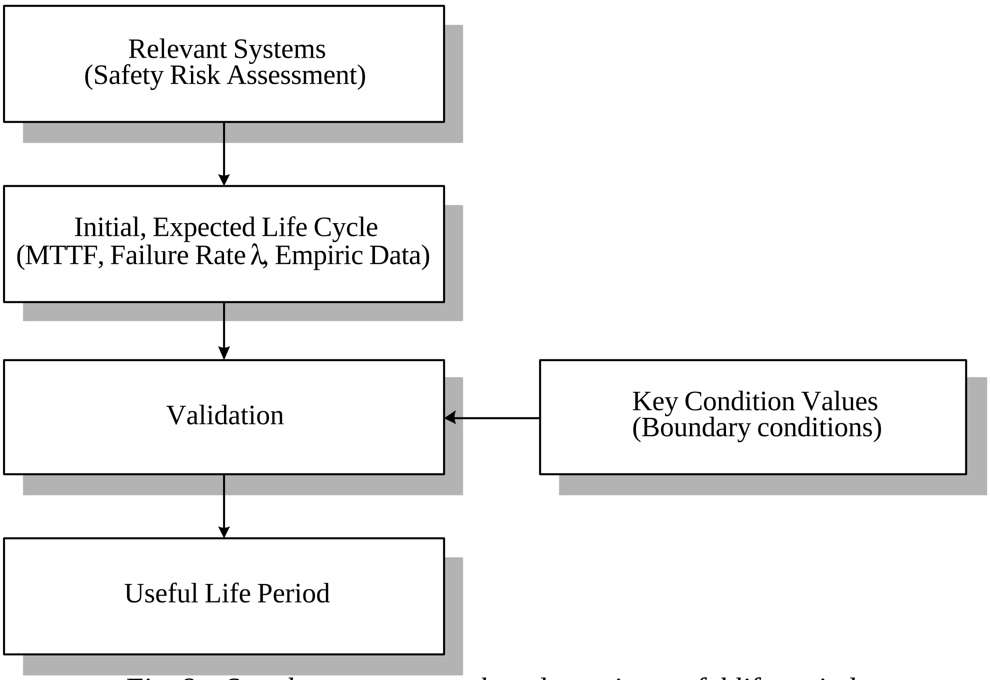

Fig. 8: Step-by-step approach to determine useful life periods

Once all systems have been evaluated with a method like the above, a summarized equipment chart can be worked out, comprising all data on the useful life periods and allowing a life-cycle-guided budget process. Having the useful life periods in mind during budgeting is finally the pre-condition for a system renewal just-in-time – and, thereby supporting safe tunnel operations.

5. CONCLUSION

The paper has outlined how a life cycle approach can be applied for tunnel systems. It was shown that most systems behave with up-time or down-time modes and do not follow continuous performance detoriation behaviour. Therefore, probabilistic values like failure rates and reliability functions have to be considered. The condition of the tunnel equipment can be monitored by applying so-called key condition values which express the extrinsic and intrinsic factors of the systems. Finally, a chart summarizing the useful life periods grants for renewals in time as well as for optimized maintenance concepts.

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TUNNEL SAFETY: WATER MIST FIRE SUPPRESSION SYSTEM IN AN AUSTRIAN ROAD TUNNEL

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ABSTRACT

The first road tunnel equipped with a water mist fire suppression system is operated in the city of Linz to increase the level of safety in terms of minimising the consequences after a potential tunnel fire. Prior to this first installation this innovative fire protection system was tested and certified by notified institutes of the European Community.

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

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

From these experiences the objective of a water mist system in tunnels were derived in co-operation with leading experts: Quick response to the outbreak of a fire by suppressing the fire in the earliest possible emerging stage in order to prevent temperature from rising to dangerous dimensions to protect persons and tunnel structure and to limit the development of smoke by preventing the spread of the fire. Additionally the water mist system provides a significant benefit to the fire brigade when entering the tunnel for extinguishing the source of the fire. The only way to comply with this objective is to install the water mist system directly within the tunnel.

Due to our philosophy of empirical evidence, we decided to demonstrate the specific properties of water mist, which in no way are comparable with the properties of sprinklers, in full scale tests. For that reason Aquasys contracted the erection of a 200 m tunnel in the size of a two lane motorway. In this tunnel a ceiling, a smoke exhaust system and the Aquaysys water mist system were installed, and a number of full scale fire tests with a fully loaded truck (HGV semi-trailer) mock-up were carried out there.

The official full scale test programme was then conducted by two notified bodies, the IBS (Institut für Brandschutztechnik und Sicherheitsforschung GmbH) Austria and the VdS GmbH (former: Verband der Schadenversicherer) Germany. The test programme comprised a series of full scale fire tests at different longitudinal wind speeds and was successfully passed! This validated and certified water mist system for suppression of tunnel fires was then applied to an Austrian road tunnel in the city of Linz.

Key words: water mist, tunnels, fire suppression, tunnel safety

1. WATER MIST IN ROAD TUNNELS

1.1. Basics of water mist

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

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

1.2. Safety in road tunnels

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

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

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

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

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

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

1.3. Configuration of the water mist system in the tunnel

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

- pumping units outside the tunnel (at the portal),
- a main line throughout the entire length of the tunnel,
- nozzle lines installed under the ceiling of the tunnel and a
- control unit, which also provides the interface to the detection system.

2. CERTIFICATION OF THE AQUASYS WATER MIST FOR TUNNELS

2.1. Certification Tests

Due to our philosophy of empirical evidence, we decided to demonstrate the specific properties of water mist which in no way are comparable with the properties of sprinklers, in full scale tests. For that reason Aquasys contracted the erection of a two lane motor way tunnel, meaning approximately 10 m with, nearly 5 m height of the ceiling and 200 m long. Additional to the water mist system this tunnel is also equipped with a smoke exhaust system to simulate conditions as applicable in a real operational tunnel.

In this tunnel a full scale HGV mock-up was placed, entirely loaded with timber pallets and 12,5 % shredded plastics. For monitoring the conditions in the tunnel during a full scale HGV fire an array of numerous temperature sensors were distributed in the tunnel. Additionally a certified fire detection was installed to simulate the fire alarm conditions in reality.

In the year 2001 a series of full scale fire tests with a fully loaded truck (HGV) mock-up were carried out in this test tunnel at different longitudinal wind speeds with the objection to prove the efficiency of water mist for fire protection of tunnels. This official full scale test programme was conducted by two notified bodies, the IBS (Institut für Brandschutztechnik und Sicherheitsforschung GmbH) Austria and the VdS GmbH (former: Verband der Schadenversicherer) Germany.

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

These criteria were:

- successful prevention of spread of the fire
- providing access to the scene for the fire brigade to finally extinguish the fire, which was the main problem of the tunnel fires in the past
- protecting the tunnel structure and prevent the concrete from spalling

By issue of the according certificates the notified bodies VdS Germany and IBS Austria documented that all criteria of the fire tests were successfully passed and that a water mist system is state of the art technology for fire protection in tunnels.

3. APPLICATION OF WATER MIST SYSTEMS IN TUNNELS

The validated and certified water mist system for the protection of road tunnels is already applied in an Austrian tunnel in the city of Linz. This tunnel is a two lanes bi-directional tunnel, one lane each direction and equipped with longitudinal ventilation without intermediate ceiling.

The water mist system consists of a machinery room outside the tunnel where the pump units and the control system are installed. Inside the tunnel the main-line is installed in order to transport the water throughout the entire length of the tunnel. At this mainline the section valves are located which activate the respective fire suppression section of the tunnel. These fire suppression sections cover an area of about 30 m each. Which section valve to be opened in case of a fire is controlled by the fire detection system.

With installation of the water mist fire protection system the safety level of this tunnel is considerably improved.

Beside the just presented application of water mist for protection of road tunnels, such system can also be used for fire protection inside a railway tunnel:

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

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

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

SENSORIC, MEASUREMENT, DETECTION AND VENTILATION CONTROL

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During optimisation of jet fan control in the Bømlafjordtunnel in Norway we found it necessary to change the way of thinking, and instrumentation of the tunnel was changed.
The Bømlafjordtunnel is a 7.8 km long sub sea tunnel. Low point at –264m below sea level.
Traffic approximately 2500 vehicles a day. With 8.5% decrease as maximum.
When fan control was based on measurement of CO and NO, the line of sight was often drastically reduced.
Earlier experience gave that measurement of dust or aerosols by line of sight would not work satisfactorily.
To gain the most effective control of jet fans we found it necessary to install 4 aerosol measurement units based on backward scatter.
By using aerosol measurement as main control the bill of electricity was reduced, and line of sight drastically improved.
Same principles are now implemented in other long tunnels. Main reason is the good accuracy also with low concentrations, which enables finer tuning of the ventilation control.
Logging measured values of CO, NO and aerosol in $\mu g/m^2$ has given us the opportunity to do some calculations of correlation between values.
Taking in to consideration that the equipment used for monitoring CO and NO has lower accuracy than preferred we still get a correlation due to repeatability.
It is today not possible to get a high concentration of CO without an alarm on aerosol concentration. Using standard tunnel measuring equipment we found a correlation between NO and aerosol >0.8. With ventilation control based on aerosols we never have high concentrations of CO, and very rarely of NO.
In city streets it has been shown a correlation >0.9 between aerosol and NO_2.(Wåhlin and Palmengren 1999).

1. BACKGROUND

The Bømlafjordtunnel opened for traffic around Christmas 2000. Shortly after, drivers started to complain about the air quality in the tunnel. Since the tunnel originally was equipped with a log, witch logged all analogue values once a minute; we could easily take out the log, after receiving complaints. The problem was that none of the CO or NO measurement points showed high values.
Our own maintenance people confirmed that we had a drastically reduced line of sight when complaints were received. Figure 1 shows the position of measuring stations in the tunnel. At this time only CO, NO and flow was installed.
Experience gives that from time to time we will have high humidity and congestion to fog inside a tunnel. But in this tunnel aerosol (soot) was the main suspect. To be able to decide what caused reduce sight we installed a lot of measurement positions of aerosol, humidity and temperature. The complete new measuring program is listed in table 1.

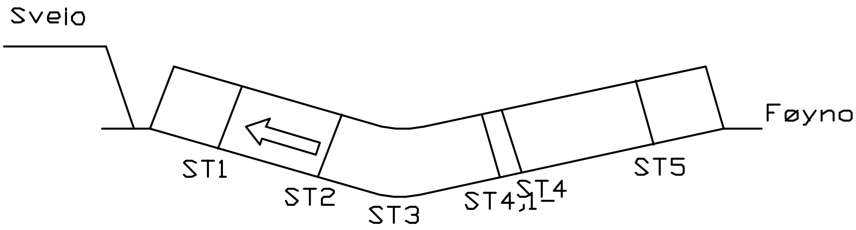


Figure 1

Measuring station	Placed	Euipment
Sveio	30m before the tunnel	Temperature and humidity
St1	970m from Portal Sveio	Temperature, humidity, CO, NO, Aerosol and flow
St2	2430m from Portal Sveio	Temperature, humidity, CO, NO, and Aerosol.
St3	3600 m from Portal Sveio, low point of tunnel	Temperature, humidity, CO, NO, Aerosol and flow
St4,1-	4680 m from Portal Sveio	Aerosol
St4	4980m from Portal Sveio	Temperature, humidity, CO, and NO
St5	6850m from Portal Sveio	Temperature, humidity, CO, NO, and Aerosol.
Føyno	130 m after portal Føyno	Temperature and humidity

Table 1

2. MEASURING TECHNIQUES

Why bother with aerosol measurement at all, why not just run the vetiltation by CO and NO measurement.

The trouble with this is the accuracy of electrochemical sensors, with respect to measured values.

The typical concentration of CO during drastically reduced line of sight was found to be 20-30ppm. A start criteria for the ventilation based on low concentrations of CO were not recommended, even by producer. The same problem will arise if you try to run the ventilation by NO measurement. Using NO_2 becomes impossible. Electrochemically measured NO_2 will, when you have detector adjusting for change in humidity, have accuracy around 0.45 ppm if calibrated very often. Unfortunately the electrician installing measurement equipment has now idea of how or what it is used for. He will give a guaranty that it is not necessary to calibrate more than once a year. Then accuracy will be reduced to approximately 3ppm for NO and 0,57ppm for NO_2.

Closing conditions in the middle of a tunnel are 0.75ppm. Using NO measurement as a measurement for NO_2 improves this some, but closing conditions in the middle of the tunnel is 6.75ppm and the accuracy is approximately 2.6ppm (For measuring NO compensation for change in relative humidity improves the result to approximately 2.2ppm)

You are then left with to options. This is Traffic counting and aerosol measurement. Aerpsol measurement by backward scatter has by parallel measurement by gravimetrical scientific equipment been shown to give an accuracy araound 6% of measured valuIe: (Wedberg 2000) Norway, we do feel that to run ventilation based on traffic counting will give more ventilation than necessary. That gives us measurement of pollution, and in this case measurement of aerosols, as a basis for ventilation control, when the tunnel not has enough CO

When we are measuring aerosols, we do prefer an answer in $\mu g\ m^{-3}$. This must not be confused with extinction or k-value that is mainly used in the rest of Europe. We do have a formal limit for pollution of dust (1.5mg m^{-3}). When we are measuring soot, this is too high.

A measured soot concentration on approximately 700-800 $\mu g\ m^{-3}$ will give a drastically reduced line of sight. Experience shows that in a tunnel with a long line of sight (>2km) people will complain already when the levels are around 400 $\mu g\ m^{-3}$.

How to measure aerosol levels of this magnitude with high accuracy.

If you use an instrument based on transmission, the best instruments, when new calibrated will give accuracy around ?k ˜0.9 * 10^{-3} when k-value are measured. This will in a tunnel, converted to $\mu g\ m^{-3}$, be around 300 $\mu g\ m^{-3}$. You will normally wish to avoid complaints by the public. It is then too easy to just start full ventilation manually. In Norway this is expensive due to partially payment by max effect used.

By installing aerosol (dust or soot) measurement based on backward scatter (main importance is scattered light) the accuracy can be drastically improved.

This enables a fine tuning of the fan control, which made it possible to create a steady airflow on an early time, using only a few jet fans. This has been confirmed in other tunnels using aerosol measurement.

The use of scatter light in Norwegian tunnels are increasing due to good experience when used. But still many people of influence remember dust measurement by transmission, and a situation where the produced CO was in high amounts, so that the easy and proper way to control the fans was by CO measurement.

When you consider this way of controlling the ventilation in a tunnel, give a thought to how you control our own ventilation. I know that traffic and time is used a lot. The ventilation is then turned to a position which normally gives what is felt like acceptable air quality. Do you have to adjust manually when un normal conditions arise ?

By using pollution the system will take care of the ventilation for you, also in then special conditions, like extreme truck traffic. In a high traffic tunnel, with one way traffic, it normally is very little need for artificial ventilation. Piston effect will often give 4-5 $m\ s^{-1}$. And this will be sufficient in most tunnels. (Fløyfjellstunnel, each tube 35000, nearly now ventilation needed, 4km)

The tunnels, which are expensive to ventilate, are the long two-way traffic tunnels, with high traffic, that we wished were highways instead.

Thus far we have not been speaking about the air velocity in the tunnel.

To keep an acceptable air quality inside a tunnel we do some calculations resulting in a needed air velocity. How to measure this air velocity?

In any road traffic tunnel you will have a highly turbulent airflow. To measure the velocity in one point close to the tunnel wall will not give you the information you need. In fact if you measure the airflow in a two way traffic tunnel on the tunnel wall on each side, they will temporarily show different directions, even with low traffic. The only way to measure air velocity inside a road traffic tunnel, and have any accuracy at all is by line integration from one side of the tunnel to the other. Even then, to be able to use the result for anything you will have to use a floating middle value for the last 5-10 minutes. Otherwise piston effect from vehicles will disturb the measurement to much.

3. RESULTS

During the process of optimizing the ventilation of the Bømlafjordtunnel we performed logging of all analogue values each minute for several months. At he same time we logged number of jet fans running. Checking this toward time of complaints from the public enabled us to improve the ventilation, without using too much ventilation.

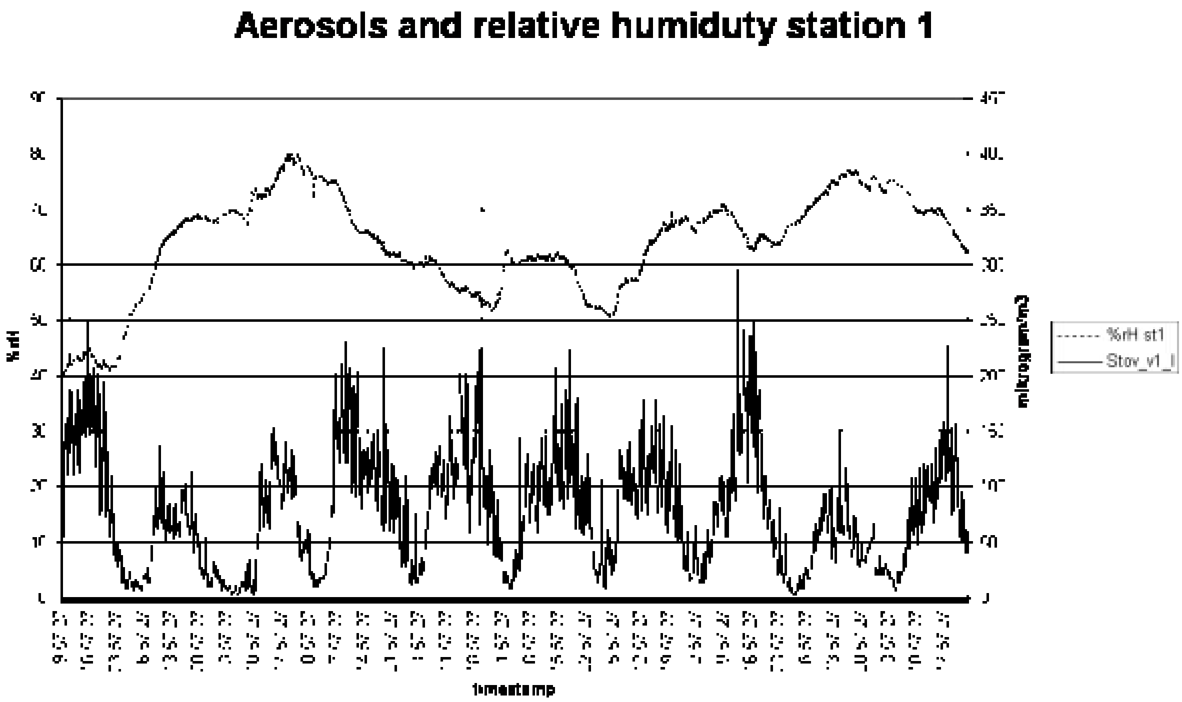


Figure 2

One of the surprising results we can find from this large amounts of data are the surprisingly large variation in rH. And that the measured aerosol concentration in the tunnel normally is completely independent of rH. This is shown in figure 2.

We did also detect abnormal conditions regarding aerosol concentrations. An example of this is shown in Figure 3 for 6 February 2002. The automatic responds to the increased pollution and increase the ventilation. That way it is only a short time with the high concentrations.

The special condition this day was that to have an air velocity in the area of 2-3 m s^{-1} we needed far more power than usual

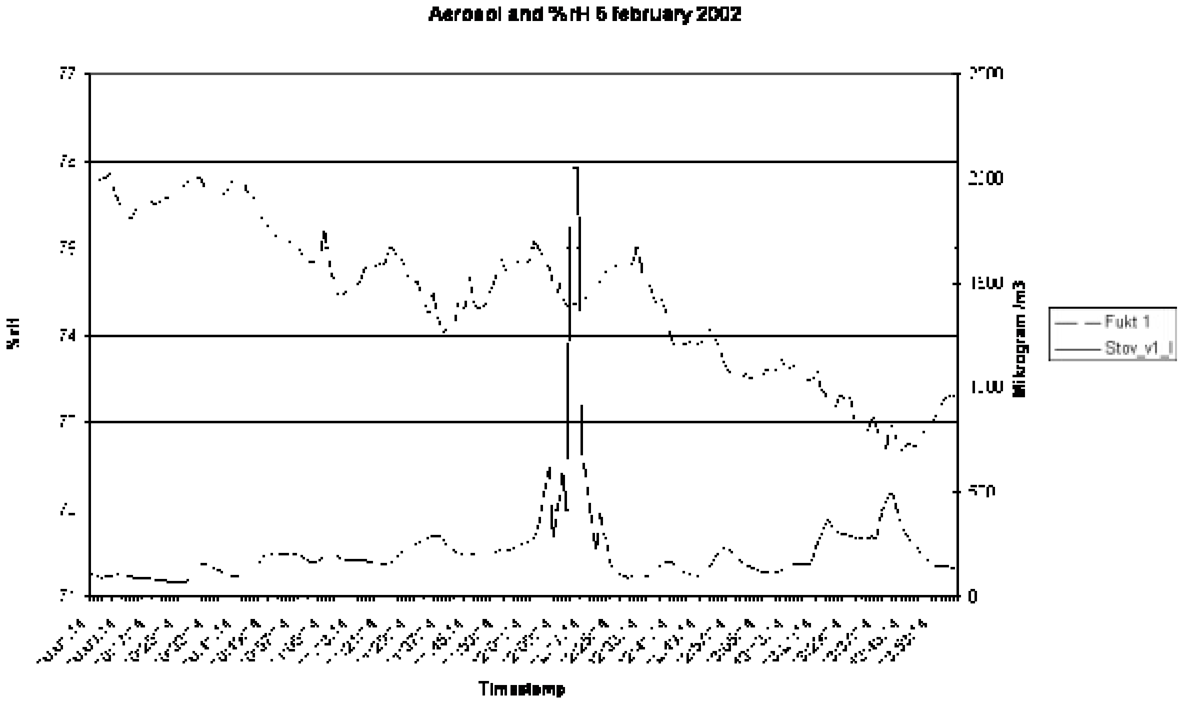
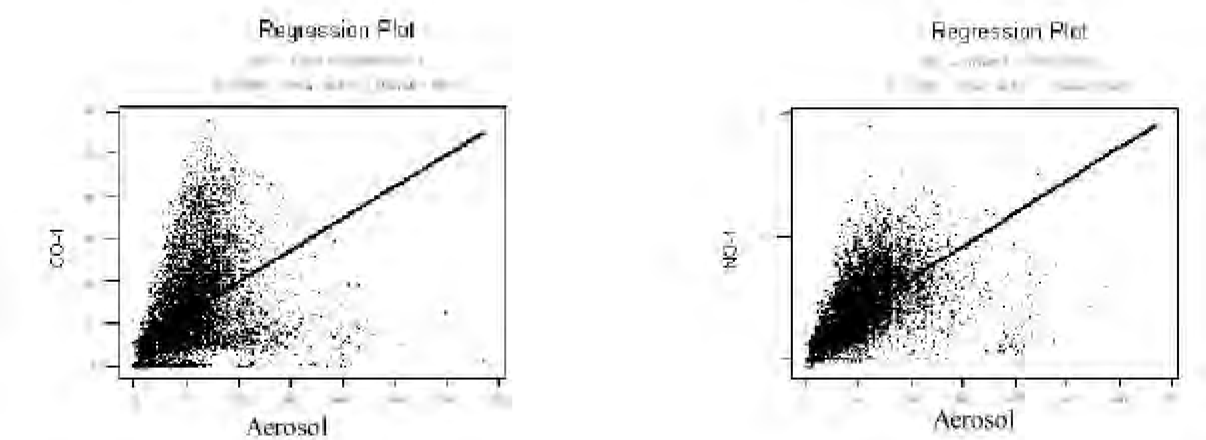


Figure 3

Where we will expect to fin a correlation is between the different compounds in exhaust.
Based on the equipment normally used for ventilation control it has been done a thorough analysis of correlations in the Bømlafjordtunnel by (Indrehus Aralt 2003)`), this work shows that CO and NO concentrations not are any problem. This has been confirmed in several investigations (Chan et al. 1996, Kirrchstetter et al. 1999, Kean et al. 2000, ChowChan 2003) Under abnormal conditions they still might be a problem, so it is not recommend to remove them.
From these examinations we can find some correlations that might be useful.
Figure 4 shows regression plot CO/Aerosol and NO / Aerosol



Figur e 4

The actual plots contains data for six weeks. It shows none linearity between CO and aerosols, but it is better when we are comparing NO and aerosols. Calculated correlation is

The reason for removing, or not using NO for ventilation control is shown in figure 5

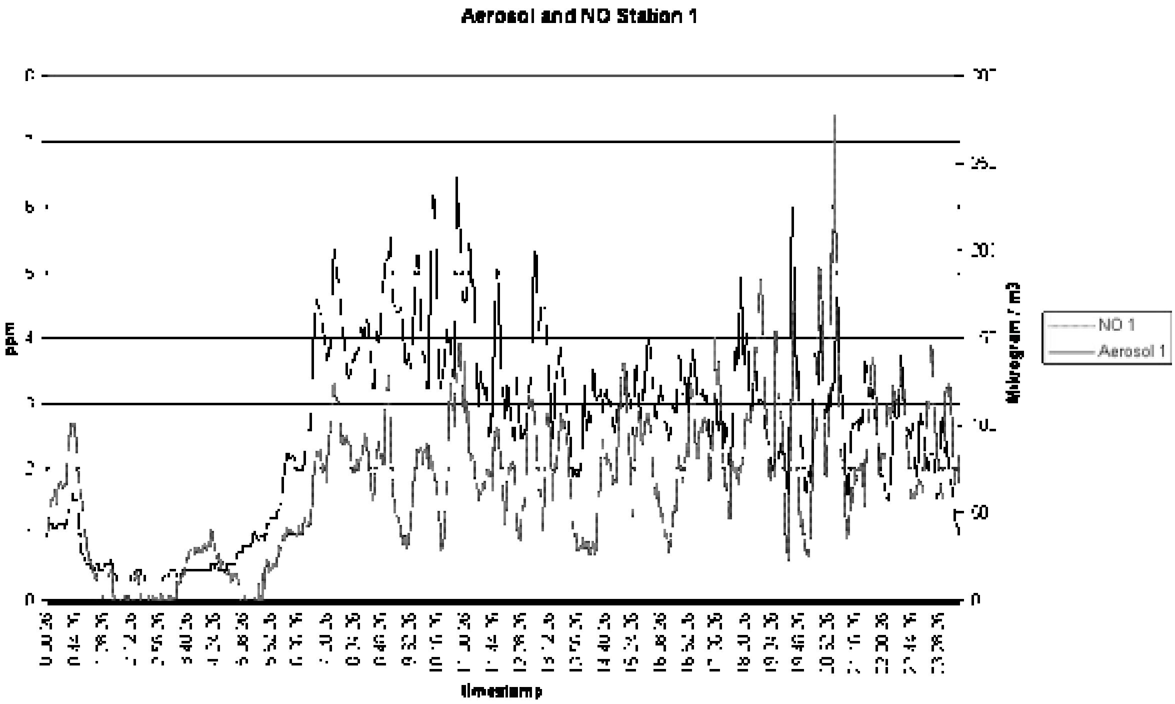


Figure 5: Concentrations near exit of tunnel. Calculated correlation 0.67

A closer inspection reveals that you nearly never have high concentration of NO, without a rise in aerosol. This will be confirmed by any calculation of pollution in a road traffic tunnel. The calculation shows you that it is the production of soot from heavy dusy traffic that will be the dimensional factor for the ventilation due to traffic. (Normally 20MW fire will be dimensional) The production of CO will be so low that it may be neglected unless you have problems wit congestion with very few diesel engines.

4. FIRE

We will here only look on the detectors for ventilation control and how these detector will respond in case of fire. The data used are from a fire drill in the Folgefonn tunnel (11km).
The drill was performed by placing an old car 2km inside the tunnel, and igniting it. This was done two times, 1 our between igniting the cars

What happened when the fire-gases reach a measuring station containing CO, NO and aerosol measurement.

Highest measured CO 101 ppm (short time peek)
Highest Measured NO 8 ppm (short time peek)
Highest measured aerosol above limit on 2000 microgram immediately, last for 40 minutes
Wind speed 3m s^{-1}

The fumes could be seen on every measuring station, when it arrived, due to aerosol measurement.
There were no dangerous CO consternations in the tunnel.

5. UNCERTAINTY'S IN EXAMINATION.

Standard industrial measurement equipment used for measuring all values
As shown the accuracy of gas detectors are low for scientific use. Examinations should be done with scientific equipment. Due to outdoor examination we could then expect a better correlation between NO and fine particles.

6. APPENDIX A

The approximately accuracy for electrochemical cells are based on
Measuring cells from Dräger,
40% change in relative humidity from calibration point
Variation of air flow 0-6m/s
Variation of temperature from calibration point 10 degrees Kelvin
And other vice as described in datasheet from Dräger

Calculation done by
$d_{Value}=(e1^2 + e2^2 + e3^2 + ... + 3n^2)^{0.5}$
Where d_{Value} total error
e1 error number one, e2 error number 2 etc.

Referees

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MEASUREMENTS OF AIR FLOW, TEMPERATURE DIFFERENCES AND PRESSURE DIFFERENCES IN ROAD TUNNELS

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ABSTRACT

Natural forces caused by buoyancy, wind and barometric pressure differences can strongly influence the design and operation of ventilation systems for road tunnels. The field measurements described in this paper indicate concrete values for these influences.

Key words: tunnel, ventilation, design, pressure difference, buoyancy, barometric pressure, temperature, field test

1. INTRODUCTION

The knowledge of natural forces in a road tunnel is an essential base for the design of the ventilation system. Relevant natural forces can be buoyancy, wind and barometric pressure differences between the portals. Buoyancy plays only a role when the two portals are not on the same level above sea (positive or negative grade), relevant barometric pressure differences only occur in long tunnels which connect different meteorological regions.

The natural forces can support or act against the desired direction of air flow in a tunnel. The Swiss guideline Ventilation of Road Tunnels (FEDRO 2003) requires that in addition to effects from the incident the ventilation is able to cope with an unfavourable yet realistic combination of the following pressure differences:

- Pressure differences caused by buoyancy: 95 %-value of the hourly values of a year
- Pressure differences caused by wind: Dynamic pressure of the average speed of winds directed to the portal
- Barometric pressure difference: 95 %-value of the hourly values of a year

The designer of a new tunnel has to assume values for the three effects. Whereas information about wind speed and direction is in most of the cases easily available, data about barometric pressure differences and buoyancy are more difficult to find. This paper describes the findings of measurement campaigns undertaken in two tunnels in Switzerland.

2. THEORETICAL BACKGROUND

2.1. Density of air

The density of air can be calculated as follows:

$$r = r_0 \cdot \frac{p \cdot T_0}{p_0 \cdot T}$$

?	Density in kg/m^3 at p and T
?$_0$	Density at normalised conditions = 1.293 kg/m^3
p	Barometric pressure in mbar
p_0	Barometric pressure at normalised conditions = 1’013.2 mbar
T	Temperature in K
T_0	Temperature at normalised conditions = 273 K

With the typical conditions in a road tunnel, the influence of the relative humidity to the density of air is less than 1 % and not relevant.

2.2. Pressure differences caused by buoyancy

The pressure difference in a tunnel caused by buoyancy can be approximated by

$$\Delta p \cong (r_e - r_i)\, g \cdot L_T \cdot LN/100$$

Δp	Pressure difference in Pa (+ = updraught, - = downdraught)
?e	Density of exterior air in kg/m^3
?i	Density of air inside the tunnel in kg/m^3
g	Gravity in m/s^2 (9.81)
L_T	Length of tunnel in m
LN	Gradient in %

2.3. Air flow in a tunnel

In a tunnel with constant cross section, no traffic and no mechanical ventilation the air flow is given by

$$\Delta p = (1 + \Sigma z + l \cdot \frac{L}{D}) \frac{r}{2} \cdot v^2 + r \cdot L \cdot \frac{dv}{dt}$$

Δp	Pressure difference in Pa
Sζ	Sum of resistances (related to v)
λ	Friction coefficient
L	Length of tunnel
D	Hydraulic diameter of tunnel cross section
?	Density of the air in the tunnel
v	Velocity of the air in the tunnel in m/s
t	Time in s

3. MEASUREMENTS IN THE GOTSCHNATUNNEL

3.1. Description of test site

The measurements in the Gotschnatunnel were made in the construction phase of the tunnel between December 2001 and October 2002. In this period the drift of the tunnel was already finished and the work on the tunnel lining was under way. The cross section of the tunnel varied according to the progress of work. In addition the varying installations and the need to protect the tunnel in winter time against low temperatures caused strongly varying obstacles for the air flow in the tunnel. During the whole measurement campaign the tunnel was ventilated naturally. The characteristic data of the Gotschnatunnel are:

Tunnel with two lanes in one tube
Bi-directional traffic

Height above sea level	1’155 m (mean value)
Total length	4’200 m
Grade, averaged	4.6 % (200 m vertical difference of portal height)
Cross section of finished tunnel	46.8 m^2 (under the false ceiling)
Hydraulic diameter	6.7 m

Semi-transverse ventilation system with smoke extraction in ducts above a false ceiling, extraction-dampers every 70 m in the ceiling, jet fans

3.2. Measurement of temperatures

The temperatures were measured with NTC-thermistors, the results were recorded with small loggers. For the measurement of the exterior temperature the device was protected against solar radiation. In the campaign we have placed 6 fixed probes in the tunnel and 2 probes in the environment close to the portals. In addition we measured several temperature profiles along the tunnel by hand for better understanding of the temperature distribution along the tunnel.

Figur 1: Setting of measuring device for temperature in the Gotschnatunnel

Figure 2: Setting measuring devices for air velocity in the Gotschnatunnel (see chapter 3.3)

The results of the temperature measurements in the Gotschnatunnel are summarized in figure 3. The campaign covered very cold as well as very warm situations in the range of -15°C to +30°C. In winter time the average tunnel temperature stayed in the range of 7 to 10°C. During 75 % of the time over a year, the air in the tunnel is warmer than in the environment, which causes an updraught. The rest of the time it is cooler in the tunnel, causing a downdraught.

Forces due to wind or to barometric pressure differences are not important at the Gotschnatunnel. It has to be noted, that the temperature inside the tunnel could change after the opening of the tunnel. We assume though that the average temperature will change only slightly compared with the results reported here.

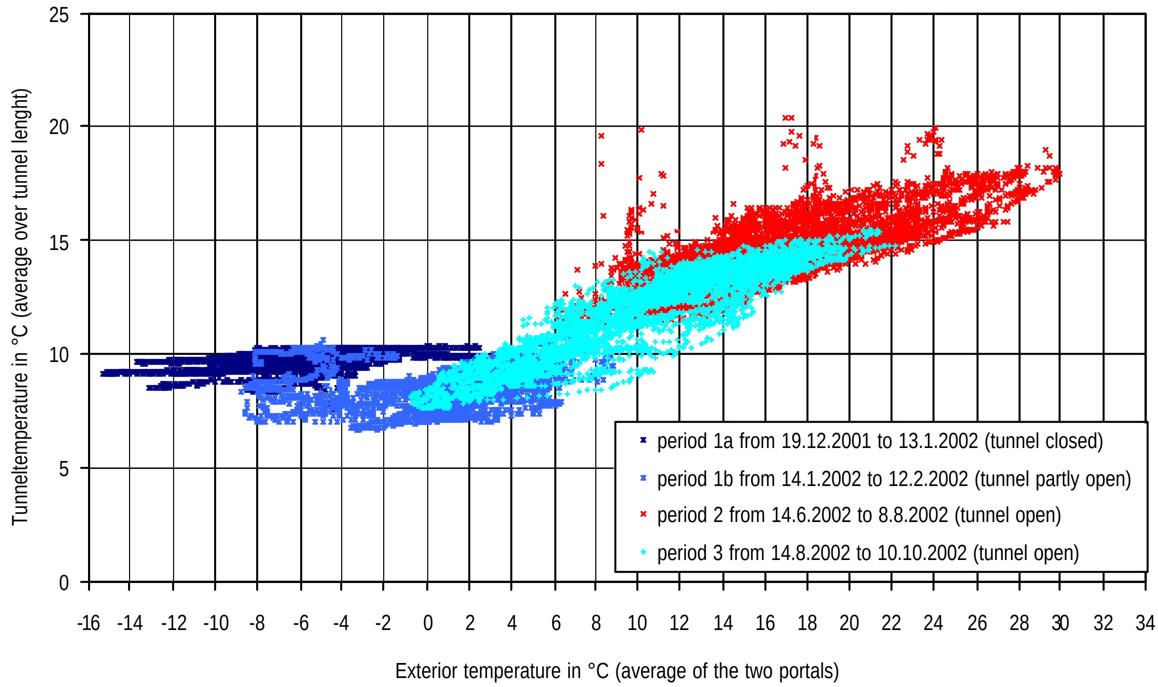

Figure 3: Relation between exterior temperature and average temperature through the Gotschnatunnel

From the temperatures in figure 3 the buoyancy-induced pressure differences acting on the tunnel air follow according to chapter 2.2. The result is given in figure 4.

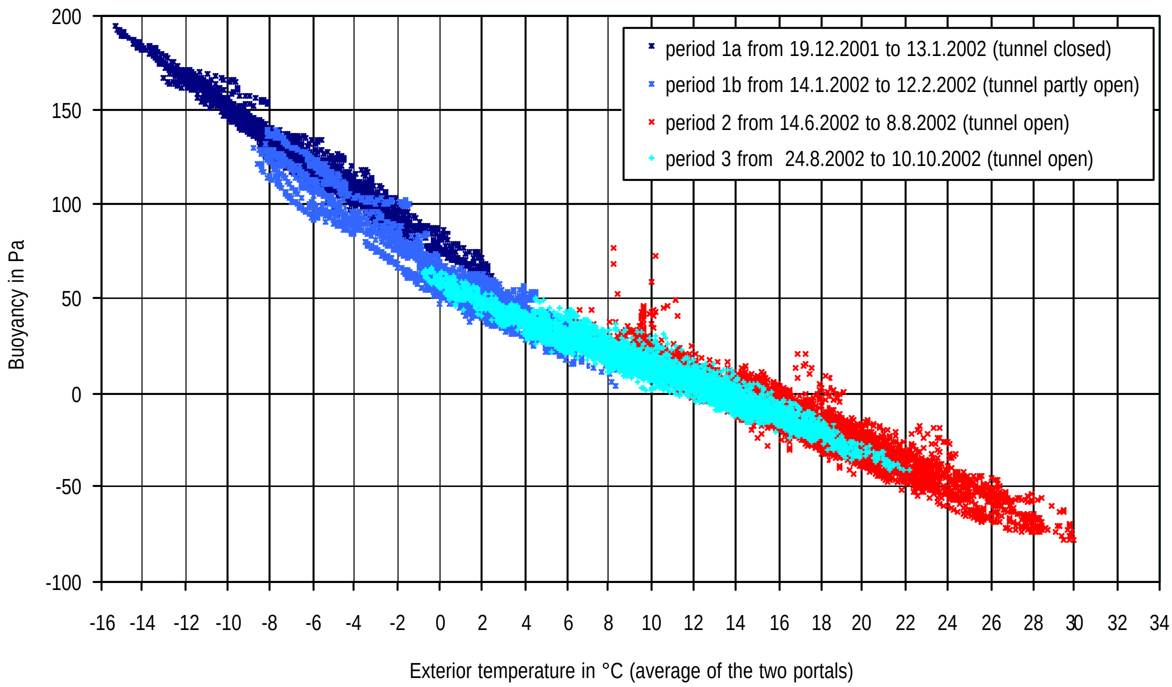

Figure 4: Relation between exterior temperature and buoyancy in the Gotschnatunnel

3.3. Measurement of air velocities

For the measurement of the air velocity in the Gotschnatunnel, we have used two pitot tubes from Schiltknecht which are designed for the use in road tunnels (Steinemann U. and Zumsteg F. 2002). These devices have produced good results in a comparison study in the Gotthard road tunnel. Due to the progress of work in the tunnel, it was only possible to measure the air velocity in the periods 2 and 3 from June 14, 2002 to October 10, 2002. The installation is shown in figure 2.

The results of the measurements of the air velocities in the Gotschnatunnel are displayed in figure 5.

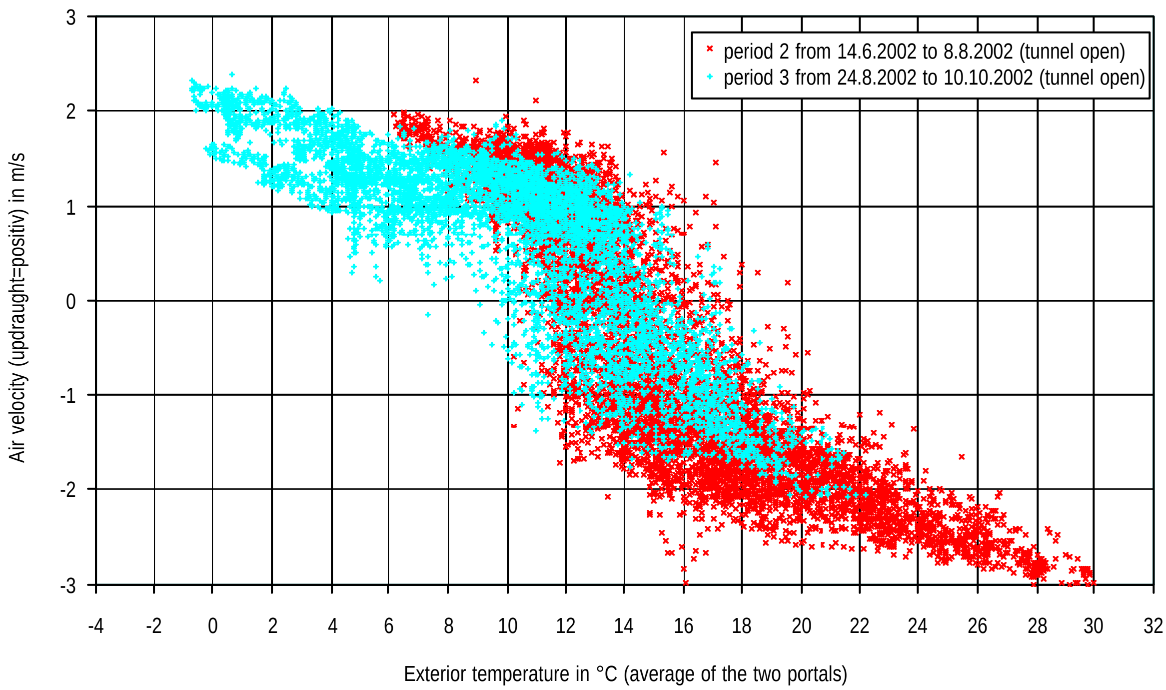

Figure 5: Relation between exterior temperature and air velocity in the Gotschnatunnel

3.4. Consequences

The results of the described measurements led to a re-design of the jet fan thrust in order to fulfill the requirements of the Swiss guideline described in chapter 1. The determinating case was found to be the combination of the exterior temperature of -11°C and the tunnel temperature of +10°C. To cope with the resulting buoyancy force, the Gotschnatunnel will be equipped with 24 uni-directional jet fans with a thrust of 640/270 N and an electrical power of 22 kW each. It is planned to open the tunnel for traffic in 2004.

4. MASUREMENTS IN THE GOTTHARD ROAD TUNNEL

4.1. Description of test site

The measurements of temperature and pressure at Gotthard road tunnel are made under normal operation with cross ventilation. The campaign is still ongoing. The characteristics of the Gotthard road tunnel are:

Tunnel with two lanes in one tube
Bi-directional traffic

Height above sea level	1’120 m (mean value)
Total length	16’872 m incl. cut and cover section north of 550 m
Grade, averaged	0.4 % (60 m vertical difference of portal height)
Cross section of the tunnel	40.5 m^2 (under the false ceiling)
Hydraulic diameter	6.0 m

Fully transverse ventilation system with fresh air and exhaust air in ducts above an intermediate ceiling, extraction-dampers every 96 m in the ceiling

4.2. Measurement of temperatures

On February 4, 2004 we measured the temperature distribution along the tunnel by driving four times through the tunnel with a constant speed of 70 km/h and gathering the temperature data in time steps with a fast responding NTC-thermistor. The results are shown in figure 6. All four passages led to very similar results and show an average temperature in the Gotthard road tunnel of 23.2°C (incl. cut and cover section north). The temperature-valleys are caused by the vertical shafts, through which the ventilation system brings cold air into the tunnel. The exterior temperature in Göschenen (north portal) was around 8°C, in Airolo (south portal) around 12°C.

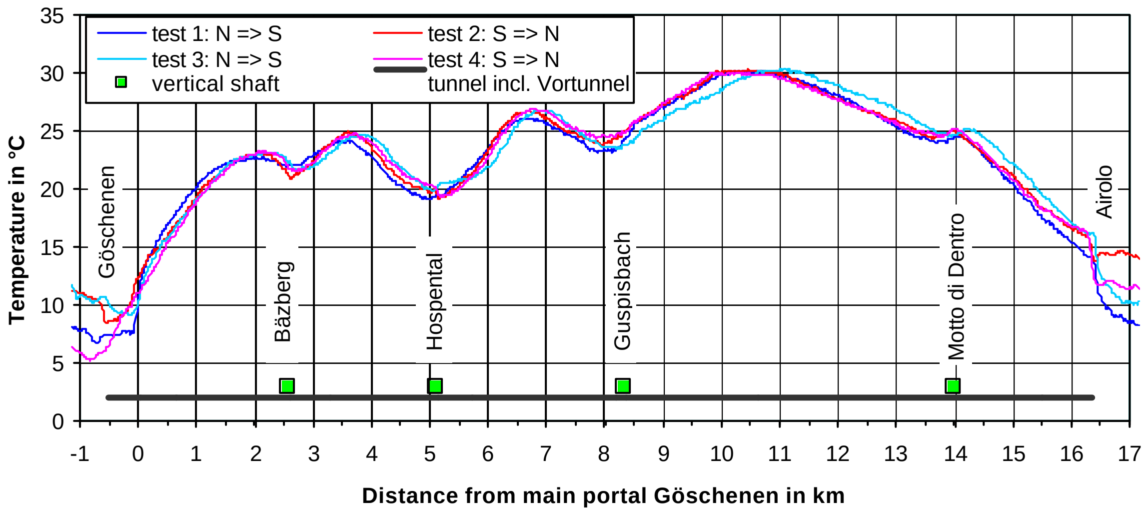

Figure 6: Temperature distribution in the Gotthard road tunnel on February 4, 2004

4.3. Measurement of pressure differences between portals

The Gotthard road tunnel crosses the Alps, which can lead to significant differences of the barometric pressure between the two portals. To measure the relevant pressure difference is demanding, because it is the difference of two high absolute values which is relatively small. However, with extremely high performance measuring devices and after a long period with device adjustments the pressure measurements are reliable.

The measurements of the pressure differences between the two portals have started on July 24, 2003 and will last for one year at least. Until now the most relevant pressure differences have been measured in the period from December 22 to 26, 2003. The effective 1-hour pressure difference corrected with the height reached a maximum value of 3’700 Pa.

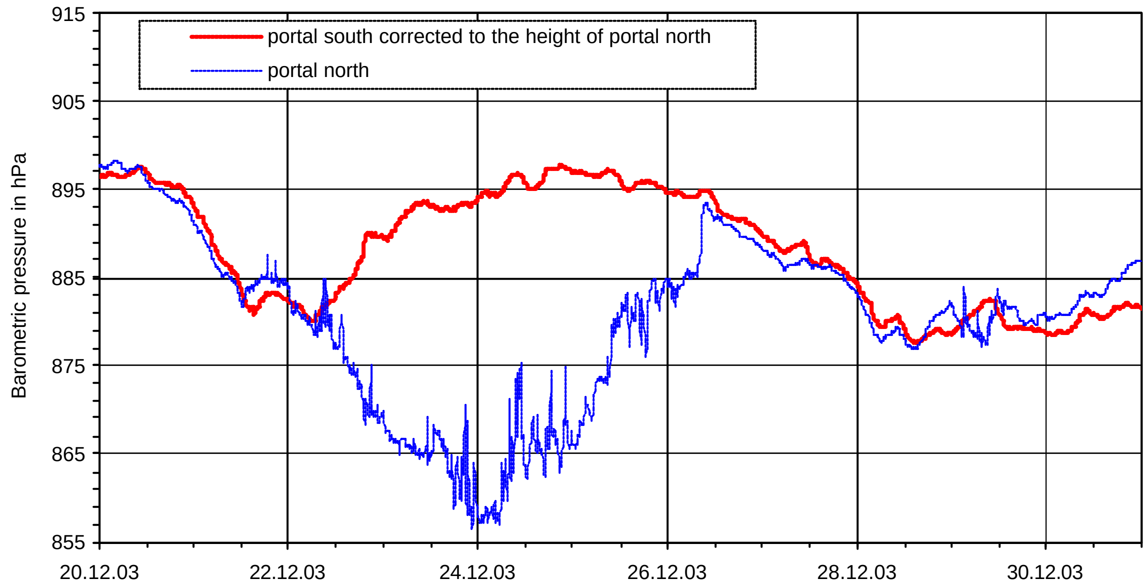

Figure 7: Period with extreme barometric pressure differences between the portals of the Gotthard road tunnel during the presently running campaign

4.4. Consequences and ongoing work

The measurements show, that the buoyancy and the barometric pressure differences can cause significant pressure differences between the portals of the Gotthard road tunnel. The resulting longitudinal flow needs to be controlled, especially in case of a fire in the tunnel. The work is going on to define and implement proper strategies to early detect such conditions and control their consequences rapidly in the case of an incident.

ACKNOWLEDGEMENT

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PRACTICAL EXPERIENCE IN VENTILATION DESIGN FOR LONGITUDINAL AND SEMI TRANSVERSE VENTILATION SYSTEMS

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ABSTRACT

The design of tunnel ventilation systems is in theory described in many documents and papers. But as it is often the case, theory and practice do have small differences. Today a lot of different tools are offered to calculate air demands, fan layout or the necessary number of fans. Using a one dimensional time dependent model you will reach good results in calculating the air flow and pressure conditions inside a tunnel. But these programs and aids are only as good as the necessary data's are, you are using. You also can find a lot of parameters and coefficients for your calculations within a wide range of literature. If you do not have enough information's, especially with new systems or at tunnel locations with no basic layout data's, you need to evaluate your design during the start up and test phase.

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

1. LONGITUDINAL VENTILATION SYSTEM

Within this chapter I would like to describe my experience at the design of the ventilation control system for the 1.9 km long by-directional Kohat Tunnel in Pakistan. The tunnel is longitudinal ventilated and within the first stage equipped with 10 fully reversible jet fans (thrust 1250 N, power 37 kW). In a second phase 6 additional jet fans will be installed. All fans will be installed in pairs.

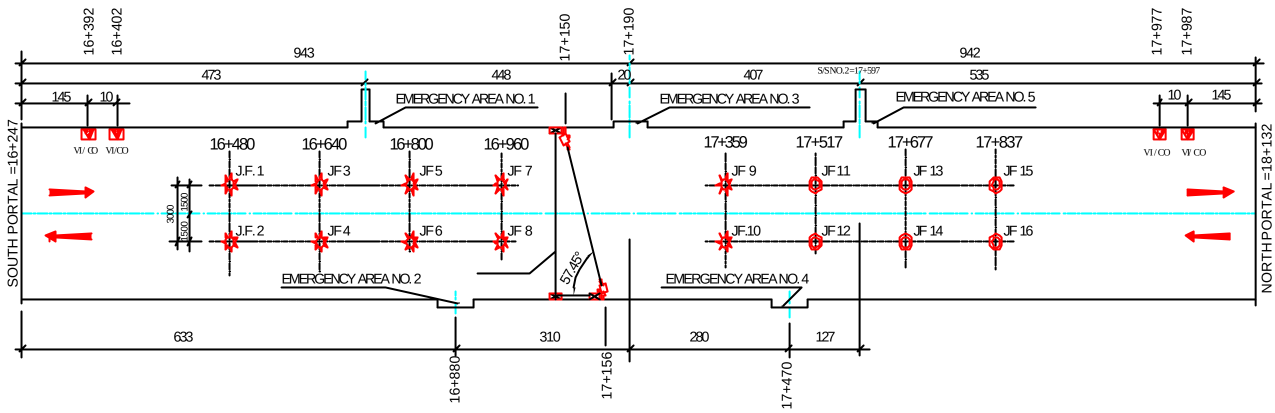

Fig. 1: Equipment arrangement inside the Kohat tunnel

The ventilation system shall automatically be controlled as a function of the following parameters:

(1) 2 CO meter units (150 m after the portals)
(2) 2 visibility/turbidity meter units (150 m after the portals)
(3) 1 longitudinal air velocity and airflow direction meter (in the middle of the tunnel)
(4) 43 manual fire alarm call points, divided into 10 zones

The following operation modes have to be foreseen:
(a) program control
(b) manual control (controlled by operator)
(c) automatic control (controlled by VI, CO, air speed levels)
(d) full notch control (controlled by maximum level of air quality meter)
(e) smoke exhaust control (controlled by fire alarm program)

The block diagram below indicates the interplay of the different parameters and operation modes.

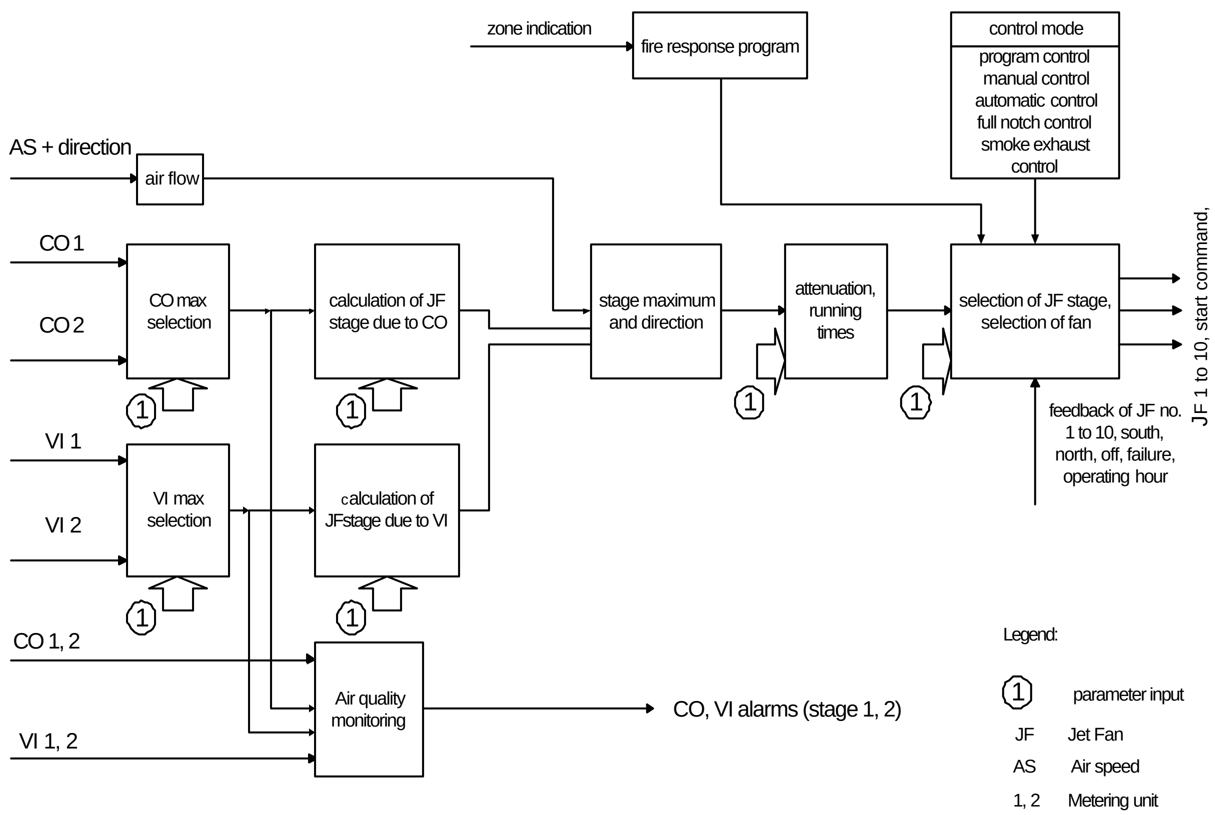

Fig. 2: Block diagram for the ventilation control

1.1. Approach

A one dimensional time dependent simulation model was used, because this leads to a minimum calculating time with reasonable and convincing results. The goal was to create different ventilation stages and strategies for different conditions (traffic and meteorological). As the pressure gradients are small, it was assumed that the density is almost constant, therefore the model have been linearized.

The result of the simulation was the ventilation control procedure for normal and fire operation. Under normal operation, depending on the actual CO and turbidity, different fan stages will be activated.

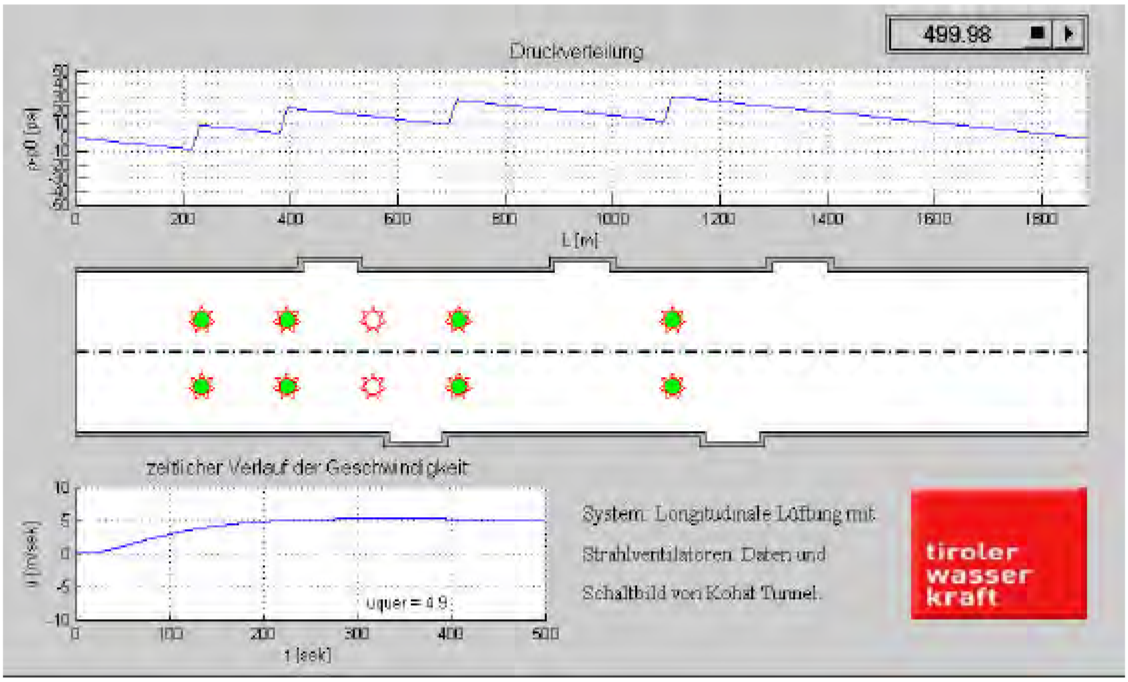

Fig. 3: Simulation interface

The main goal of the fire response programs was to reduce the spreading of smoke to a minimum. During the evacuation phase the air flow velocity should not exceed a value of more than 1.5 to 2 m/s in order to maintain stratification of the hot smoke. This will help to enable evacuation of people trapped in the tunnel on both sides of the fire.

For each of the 10 zones a fire response program have been created. The selection of the respective fire-response program depends on the tunnel section in which the fire alarm has been initiated. The rotating direction of the jet fans was chosen in such a way that the smoke extraction direction of the respective fire-response program was supported.

air velocity	JF1	JF2	JF3	JF4	JF5	JF6	JF7	JF8	JF9	JF10	air flow
> 2.5	off	off	off	off	off	off	on south	on south	on south	on south	direction north
1.5 - 2.5	off	off	off	off	off	off	off	off	off	on south	
0.5 - 1.5	off	off	off	off	off	off	off	off	off	off	
0.0 - 0.5	off	off	off	off	off	off	off	off	on south	on south	
0.5 - 0.0	off	off	off	off	off	off	off	off	on south	on south	direction south
1.5 - 0.5	off	off	off	off	off	off	off	off	off	off	
2.5 - 1.5	off	off	off	off	off	off	off	off	off	on north	
5.0 - 2.5	off	off	off	off	off	off	on north	on north	on north	on north	
> 5.0	off	off	off	off	on north	on north	on north	on north	on north	on north	

Fig. 4: Fire response program for zone 1 and 2

The marked jet fans (JF) are located in the affected zone and not allowed to be started.

1.2. Test procedures

To verify all these results, measurements and tests on site have been necessary.
For checking the ventilation control software for normal operation the following tests procedures have been performed:

- measuring of the basic air flow without any jet fans in operation
- testing of the different fan stages by simulating the output signal of the CO/VI meter at the first clamp (using a calibrator)
- checking the time frames for starting and stopping of the jet fans
- measuring of the air velocities achieving with the different fan stages
- measuring of the air flow rise

The air velocity was measured using a air velocity transducer. To get the average air velocity within the tunnel profile, a grid of several different points (16) was used. For one fan stage all points have been measured under stable conditions. Using these results a correction factor was calculated for a reference point. This reference point was used to get the results for all other stages. The tests has been performed at different natural air flow levels (0.8, 3.2 and 4.5 m/s). During the tests the air flow direction. To achieve a low air speed, it was necessary that the north portal partially have been covered using tarpaulins. This results that the air speed drops down to 0.8 m/s.

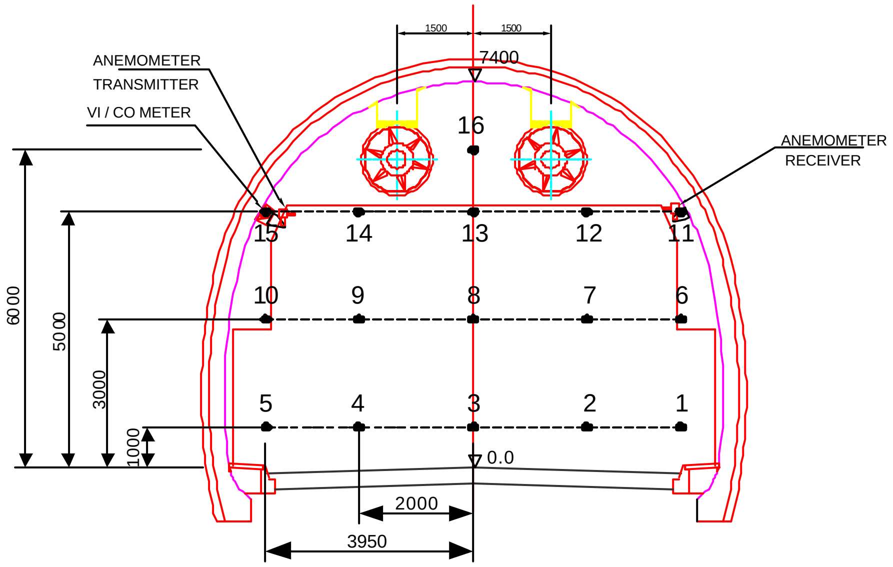

Fig. 5: Tunnel cross section with metering points

The main result given by these tests have been that the difference between the average air flow speed installed in the tunnel cross section and the one measured with the air flow meter is about 40 %. There are only minor deviations within the different air speed levels.

To collect information's and data on the achieved air flow inside the tunnel caused by the use of the jet fans, various tests have been done. The jet fans have been started single and in pairs to see the influence in the air flow increase as well as in the air flow decrease. These effects have been simulated by operating the fans first in and second opposite the existing air flow direction. All tests have been carried out using a minimum of 10 minutes time between each test to reach always the natural air flow.

Summarizing these test results it was found out, that by operation in air flow direction the use of one jet fan accelerates the air about 1.5 m/s. The increase of the jet fan number leads always to a rise of about 1 m/s.

All these results have been used to check the simulation conclusions. The comparison for one scenario is depicted in the next figure.

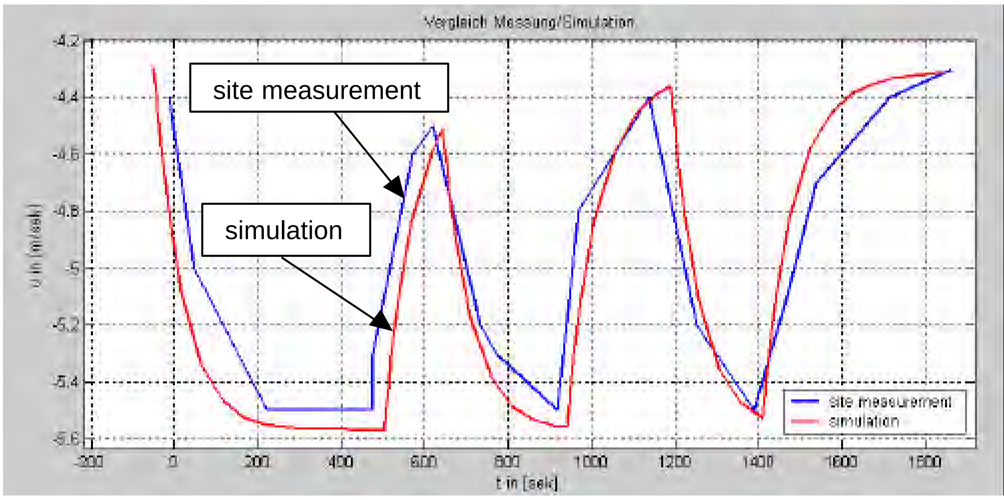

Fig. 6: Comparison of the site measurement and simulation results

The course of the fire response program have been checked, starting the program using the respective button on the SCADA system in the control room. This was in accordance with the normal operation, as the fire response program always will be released manually. The fire alarm will be activated by pressing the manual fire buttons inside the tunnel which leads to an alarm in the control room. The operator will check the fire zone using the CCTV installation and start the program manually.

To verify if the recommended course of the jet fan operation, given in the fire response matrix leads to the desired result, keeping the air flow in between 1 and 2 m/s to guarantee optimal conditions for a smoke stratification, tests have been made using the natural air flow as starting condition. As the meteorological conditions most of the time caused air flow velocities between 2 and 5 m/s, these tests have been done under realistic operation conditions. In tunnels used with bi-directional traffic the air flow velocities are very seldom higher, in the majority of cases the air speed should be within this range.

The first tests done showed that in some cases the given jet fan operation parameters did not fulfil this criterion. Therefore the fire response matrix have been adjusted to the local conditions. The first issue of the fire response matrix includes 10 different types. After the changes the types and steps have been reduced to 5. The reason why a further reduction was not possible is the arrangement of the jet fans. The jet fans arranged in the concerned zone or close to this zone are not operated due to the turbulences produced by them.

During all tests carried out after the adaptation the automatic control system was able to reduce the starting velocity within 1 to 2.5 minutes and settled the air flow velocity in a range between 1 and 2 m/s. The duration of all these tests have been more then 10 minutes.
No change of the predominated air flow direction or turbulences have been observed inside the tunnel.

The next figure depicts the printout of the SCADA system for the test of the fire response program in zone 9.

Fig. 7: Result of the fire response program test in zone 9

2. SEMI TRANSVERSE VENTILATION SYSTEM

For tunnel of a length between 3 and 5 kilometres a semi transverse ventilation system often have been applied. The usual way for a semi transverse ventilation system is blowing fresh air via an air duct and continuous openings into the traffic area. Most of theses systems have been designed as reverse operation system, which means that in case of a fire the fan could be operated in reverse mode and suck air out of the tunnel. This system is efficient and proper for normal operation but in case of a fire it is no more corresponding with the increasing philosophy of safety. The time to reverse the air flow and reach the maximum exhaust capacity often needs more than 3 to 4 minutes. This leads to the decision within Austria, that older systems of this type should be changed to exhaust systems. Therefore in the year 2001 the Austrian tunnel ventilation guideline RVS 9.261 have been changed. It was defined that semi transverse system are only allowed as exhaust system.

Below you can see the scheme of a fresh air supply system under normal operation, including the characteristics of the air flow speed u. The fresh air is blown into the traffic area via regular openings, therefore the air speed in the duct will be reduced linear. The exhaust air will be blown out through the portals, based on the pressure increase in the traffic area.

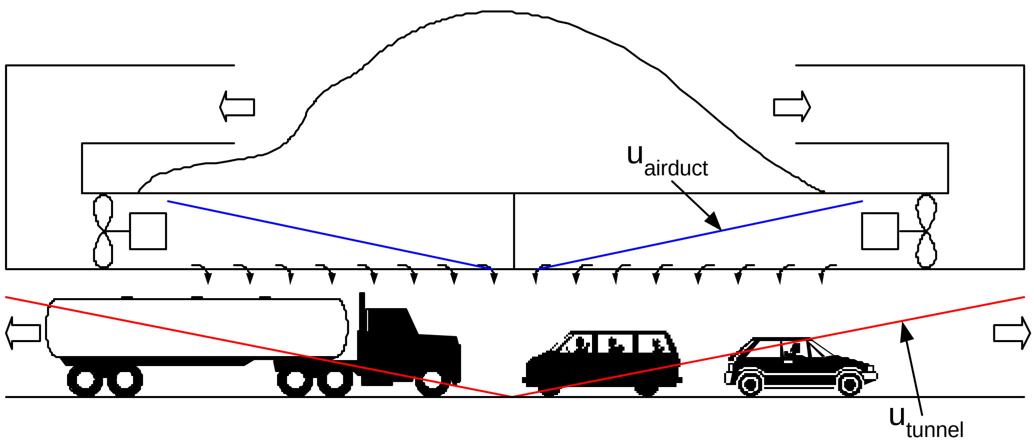

Fig. 8: Semi transverse system fresh air type

The next figure depicts the principle of an exhaust system under normal operation, again including the characteristics of the air flow speed u. Fresh air have to be sucked into the tunnel via the portals and will be taken out of the traffic area at the end of the air duct.

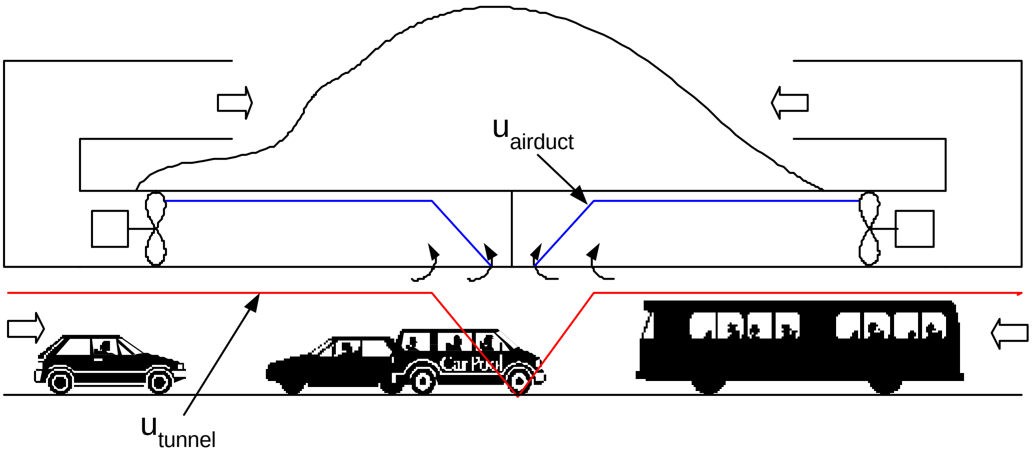

Fig. 9: Semi transverse system exhaust type

Using the same assumptions for both systems leads to a higher necessary power consumption for the exhaust system. The reason is that the pressure loss in the air duct is significant higher, based on the air flow characteristic.

But the main advantage is the essential improved extraction volume of smoke. The system is combined with electrical adjustable dampers, which will be closed in the zones not affected and opened close to the fire zone.

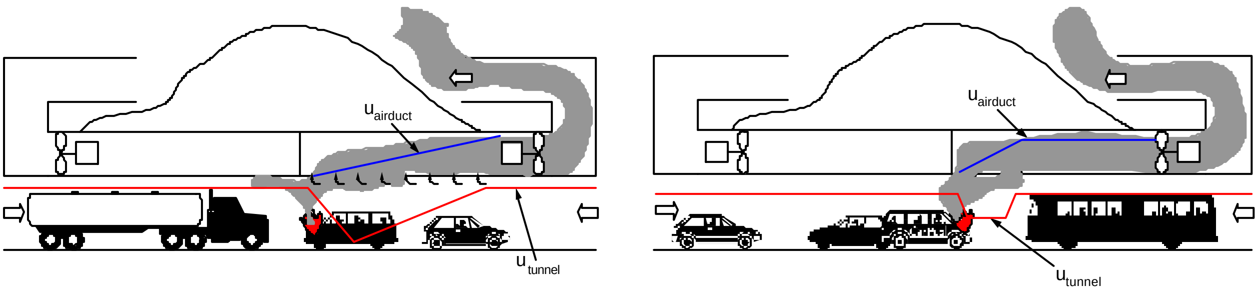

Fig. 10: System operation in case of a fire

The operation in case of fire for both systems is shown in Figure 10. Due to the high amount of fresh air leakage through the inlet openings, the efficiency of the smoke extraction at supply systems is reduced. Therefore the spread of smoke at supply systems is more than at exhaust systems. This could be seen during fire tests at adapted systems.

The operation experience with an exhaust system demonstrated that the control of the system under normal operation needs a higher amount of air quality measurements. One of the reason for that conclusion is, that the influence of the traffic on the tunnel air speed is much more higher. This yields to a higher necessary number of metering instruments.

To improve the exhaust system it should be foreseen to install a damper which allows to connect both air ducts together. This leads to a higher amount of air exhaust in case of a fire and in addition to that, you do have the possibility to operate your system in a reduced way at a fan breakdown.

3. CONCLUSION

Simulation is a good tool to get an idea of the main effects of the ventilation operation. Several scenarios can be calculated and experience will be gained without having any real accidents or high operation costs. It will help to save time and money to find answers and solutions. But as start up tests and tests runs demonstrates, the aspect of practical experience is still necessary and important.

METHODOLOGY TO ASSESS TUNNEL SAFETY

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ABSTRACT

Implementation of new standards in tunnel safety will require the investment of millions of Euro. In consideration of tight government budgets, tunnel management must then find answers to the questions: which tunnel must be upgraded first and which safety measures are to be implemented for the greatest benefit. Application of the presented methodology gives an overview of the existing safety level. The main deficits are identified and prioritised in an order of significance.

A tunnels safety is evaluated by comparing its existing safety features with the safety measures required by law, and also, by a judgment of acceptable risk. The result is a list of additional safety measures that, when implemented, will either remove the existing safety deficiencies or reduce risk to an acceptable level.

Based on the level of risk and the level of noncompliance, the prioritisation of tunnels within an inventory of tunnels is determined. As well, the cost/benefit prioritisation of safety measures required for each tunnel is resolved. The selection process is based on an appraisal of the risk and the risk reduction value of each new safety measure. The results of the assessment and the prioritisation can be used for establishing the planning process of tunnel renovations.

Key words: tunnel, safety, assessment, risk analysis

1. CENTRAL QUESTIONS

Tragic accidents that occurred in recent years have made tunnel safety a central theme in the news. National and international committees have taken up the subject and compiled measures to improve the safety of tunnel systems. These perceptions were incorporated in new standards and directives such as the Swiss Tunnel Code (SIA, 2002).

Tunnel management have a legal obligation to upgrade their tunnels to the new required safety standards. However, implementation of the new standards in tunnel safety will require the investments of millions of Euro. In consideration of tight government budgets, tunnel management must find answers to the questions:

- Which tunnel within an inventory has the largest deficit?
- Does the tunnel under consideration fulfil all the requirements of the new standard?
- Which safety measures substantially increase the tunnels safety?
- Which safety measures have favourable cost/benefit quotients, and therefore, should be implemented with high priority?

Tunnel management need therefore a methodology to assess tunnel safety, to prioritise an inventory of tunnels, as well as to prioritise the additional measures to improve tunnel safety.

2. GENERAL PROCEDURE OF THE ASSESSMENT PROCESS

The assessment of a tunnels safety is divided into two main steps (see Figure 1). In the first step, the actual state of a tunnels safety is assessed. The assessment comprises a comparison of the existing safety measures (actual state) with the safety measures provided by the directives (target state) and a judgement of the acceptability of the risk. The assessment of the actual state is carried out in three parts:

- Comparison of the existing with the state-of-the-art
- Risk analysis for the transportation of dangerous goods
- Risk analysis of high frequency incidents

The second step involves both the prioritisation of tunnels according to the severity of the deficiencies and the prioritisation of new safety measures according to the efficiency level in eliminating a given deficit. The second step is part of the decision phase of the planning process.

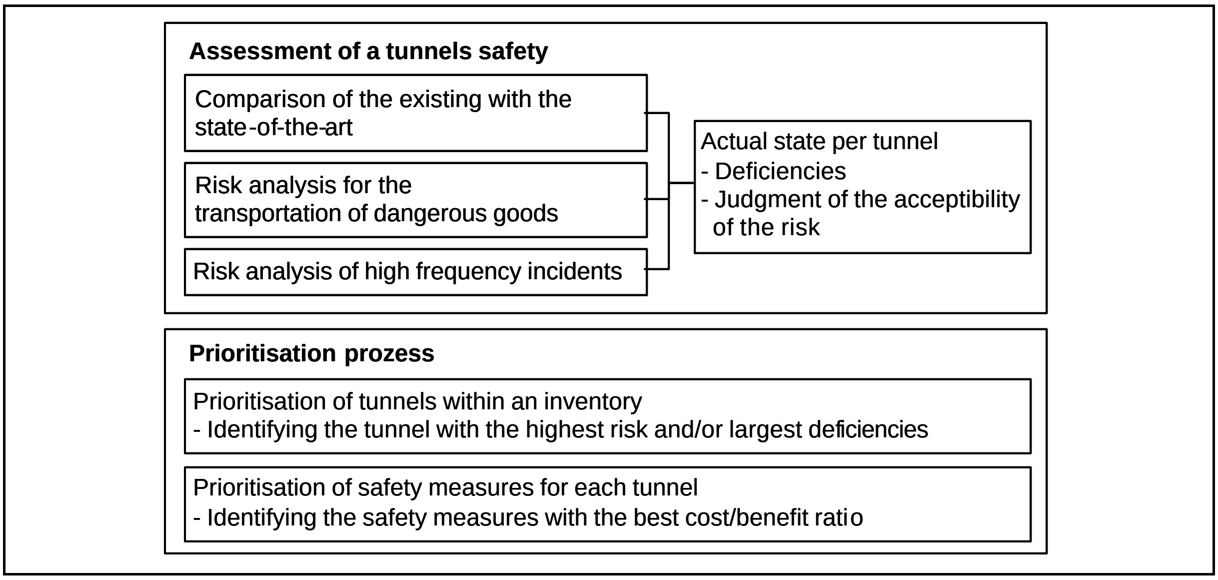

Figure 1: General procedure of the assessment process

3. ASSESSMENT OF A TUNNELS SAFETY

3.1. Classification Of Safety Measures

For the prioritisation of the safety measures, one must first classify them according to their area of impact. This classification ensures that only safety measures within the same area of impact are compared with one another. The following areas were distinguished:

- Prevention: safety measures to control or influence tunnel operation such as a traffic management system (equipment to stop vehicles, close the tunnel or control the height of vehicles), lighting, etc.
- Maintenance: safety measures supporting the maintenance of a tunnel system such as providing a service tunnel or support for the fast re-opening of a tunnel after an incident
- Incident management
  - Detection: safety measures that detect incidents such as video with automatic incident detection, fire detectors, exhaust detectors, etc.
  - Escape: safety measures supporting the escape of the tunnel occupants such as emergency exits, ventilation, signs, lighting, etc.
  - Rescue: safety measures supporting the rescue of the road user by emergency services such as emergency passages, communication system with loudspeakers, etc.
  - Intervention: safety measures supporting intervention by emergency personnel such as fire hydrants, radio communications, etc.

3.2. Comparison Of The Existing With The State-Of-The-Art

First, all necessary data to carry out the analysis of a tunnels safety level are collected. The entered data contains all necessary information to carry out the comparison with the current state-of-the-art requirements (see directives in section 7). This comparison involves the following checks:

- Check whether all safety systems required by the current safety standard are installed
- Check whether the installed safety measures fulfil the requirements of the current safety standard
- Check the existence of safety measures that would increase the tunnels safety even though they are not mandatory requirements.

The result of these checks is a list of new safety measures that increase the tunnels safety. Further the areas of impact with the largest deficiencies are identified.

3.3. Risk Analysis For The Transportation Of Dangerous Goods

Risk analysis for the transportation of dangerous goods involves the assessment of the risk to road users. With the risk analysis, the frequencies (F) and the extent of the damage (number of fatalities: N) for different scenarios "fire", "explosion" and "release of toxic gases" are determined and displayed in a F/N-diagram (Farmer diagram, see Figure 2). The method used to determine the risk is a classic risk analysis method and is in accordance with the Swiss Directive "Störfallverordnung" (StFV, 1991; BUWAL, 1992).

To judge the acceptability of the risk, the appraisal criteria of the Swiss Directive "Störfallverordnung" (BUWAL, 2001) are used (see Figure 2). To describe and compare easily the F/N-curve of different tunnels, the F/N-diagram is additionally divided into five risk regions R1 to R5. A tunnel is assigned to the highest risk category or region which its F/N-curve crosses. For instance, the example shown in Figure 2 is assigned to the risk category R2 because it crosses region R1 and R2. This categorisation helps to differentiate between tunnels with high damage potential and tunnels with low damage potential and it is used for the prioritisation process.

If the F/N-curves cross into the R4 or R5 region, new safety measures must be considered. All safety measures that reduce the risk to an acceptable level, that is, lowering the F/N-curve into the acceptable region, are added to the list of new safety measures compiled earlier in the comparison of the existing with the current state-of-the-art.

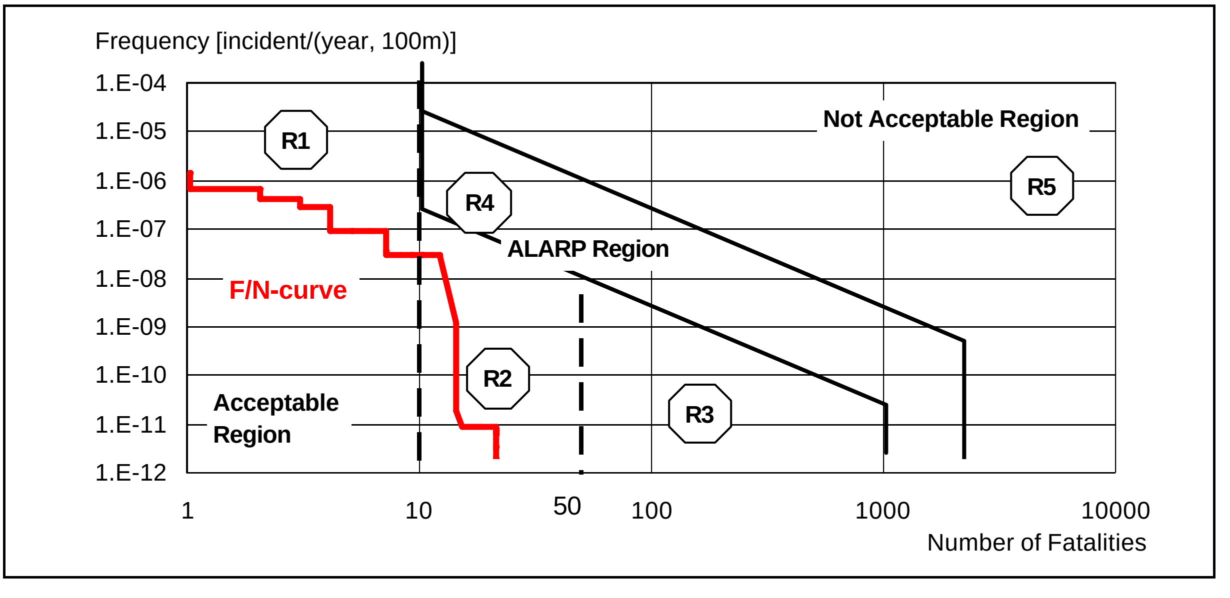

Figure 2: F/N-diagram and appraisal criteria based on the Swiss Directive "Störfallverordnung"

3.4. Risk Analysis Of High Frequency Incidents

The risk analysis of high frequency incidents consists of a simplified quantitative risk analysis for the scenarios "breakdown", "collision" and "fire" that are not connected with the transportation of dangerous goods. In comparison with incidents involving dangerous goods, these scenarios occur with significantly higher frequency (see Figure 3). Damages are expressed in the number of fatalities, the number of injured persons and the time period of total or partial shutdown of a tunnel. To quantify both the damage and frequency of an incident, a categorisation is used. The corresponding categorisation classes are shown in Table 1 and Table 2. Finally, the risks of the scenarios are displayed in a simplified F/N-diagram (see Figure 4). The ALARP region (as low as reasonably possible) and the not acceptable region are chosen in accordance with the Swiss Directive "Störfallverordnung".

If the results are lying in the ALARP region or not acceptable region, additional safety measures have to be considered. All safety measures that reduce the risk to an acceptable level are added to the list of new safety measures compiled earlier in the comparison of the existing with the actual state-of-the-art.

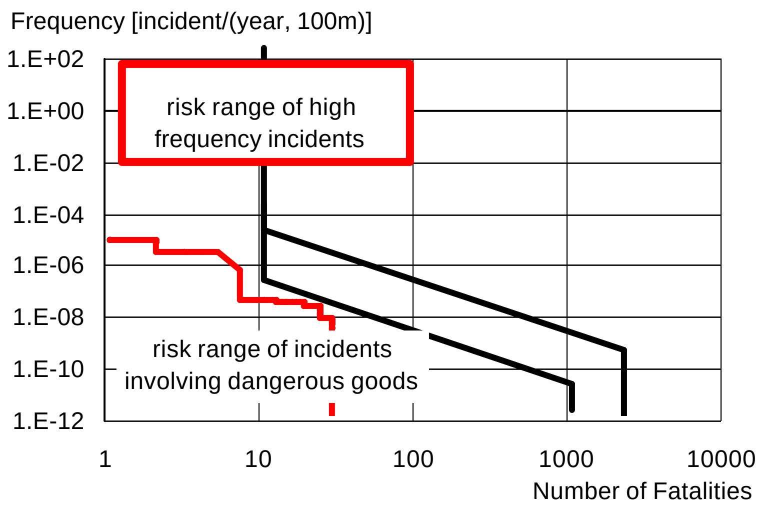

Figure 3: Comparison of the risk range of the different scenarios

Damage class	Number of fatalities	Number of injured persons	Time period of shutdown
I	0	0	< 0.5 h
II	1 – 2	1 – 5	0.5 – 2 h
III	3 – 5	6 – 10	2 – 10 h
IV	6 – 10	11 – 20	10 – 24 h
V	> 10	> 20	> 24 h

Table 1: Categorisation classes of damage

Frequency class	Number of incidents per year
A	< 0.01
B	0.01 – 0.1
C	0.1 – 1
D	1 – 10
E	> 10

Table 2: Categorisation classes of frequency

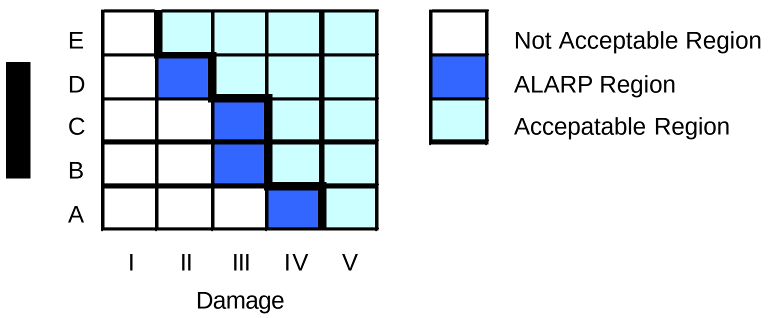

Figure 4: Simplified F/N-diagram

4. PRIORITISATION PROCESS

4.1. Prioritisation Of Tunnels Within An Inventory

Based on a risk approach, prioritisation of tunnels within an inventory follows the principle: "The higher the risk to the road user, the higher the priority of the tunnel in the upgrading process". The prioritisation is carried out in the following steps (see Figure 5):

1. Ranking according to the risk categories from R5 to R1 in descending order
2. Ranking in accordance with total risk values (area under the F/N-curve) within a risk category entered in descending order
3. Ranking in accordance with high frequency incidents, in the order "fire", "collision", "breakdown", and then, within a risk category in descending order
4. Finally, ranking in accordance with deficiency of the identified impact area: in the order prevention, escape, detection, rescue, intervention and maintenance

With this ranking we identify the worst tunnel, that is, the tunnel within an inventory with the highest risk and/or largest deficiencies.

	Incidents involving dangerous goods		High frequency incidents			Deficiencies	
Tunnel	**Risk Cat.**	**Total Risk**	**Fire**	**Collision**	**Breakdown**	**Impact Area**	**Prio.**
C	R5						**1**
F	R4						**2**
A D B	R3 R3 R3	descending	descending	descending	descending	1. prevention 2. escape 3. detection 4. rescue 5. intervention 6. mainenance	**3** **4** **5**
G E	R2 R2	descending	descending	descending	descending		**6** **7**
H	R1						**8**

Figure 5: Principle of the prioritisation of tunnels within an inventory

4.2. Prioritisation Of Safety Measures

After identifying the worst tunnel, the next step in the prioritisation process is to identify the safety measures with the best cost/benefit ratio for each tunnel. The benefit of a safety measure is the amount of risk reduction achieved by the measure. First, the new safety measures are classified according to their area of impact (see section 3.1 above). In this way it is ensured that only safety measures within the same category are compared.

Then, within an area of impact category, the safety measures are ranked according to their safety costs. The safety cost of a measure is defined by the quotient of the installation cost of the measure divided by the corresponding risk reduction. The risk reduction is determined by carrying out the risk analysis one time with the safety measure installed and one time without. The difference, then, is the risk reduction.

Finally, the resulting "best cost/benefit measures" are ranked in the order: prevention, escape, detection, rescue, intervention and maintenance. For each individual tunnel, this is the ideal order for renovation and can be used for defining an upgrade program.

5. CONCLUSIONS

The methodology to assess tunnel safety gives a superior view into the current state of a tunnel or inventory of tunnels. It can both rank the tunnels in an inventory, and for these, provide a cost/benefit prioritisation of required safety improvements. The assessment is based on consistent criteria and is reproducible. The methodology is a helpful decision tool in the planning process of repairing or upgrading tunnels to current safety standards. Tunnel management can fulfil their legal obligation under consideration of an optimal application of resources and funds.

Besides the assessment of the actual state of a tunnels safety or of an inventory of tunnels, part of the methodology can be used for other purposes. For this, the following aspects can be mentioned:

- Compilation of an equipment list for tunnel projects of different tunnel classes
- Comparison of different tunnel designs for the planning process with respect to safety and risk

6. ACKNOWLEDGEMENTS

The methodology to assess tunnel safety was developed together with the Authorities of the Highway Department of the Canton Basel-Landschaft, Switzerland. It has been applied to all ten tunnels of the Canton. The results of the assessment were used as the basis for the upgrading program to the new standards.

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A COMPARATIVE RISK ANALYSIS FOR SELECTED AUSTRIAN TUNNELS

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ABSTRACT

Public opinion about tunnel safety is often based on irrational assumptions. This is especially the case in the aftermath of severe tunnel accidents. The public calls for the implementation of costly measures like the installation of sprinkler systems in all tunnels. To rationalise decisions concerning tunnel safety a Quantitative Risk Assessment (QRA) software was developed in a joint OECD, PIARC and EU project. This software makes it possible to calculate the societal risk in the form of F/N curves. F/N curves show the relationship between accident frequency and accident severity.

In the year 2001 the Federal Ministry of Transport, Innovation and Technology initiated an Austrian tunnel safety board. The issue of tolerable risk was discussed in this committee. The members of the safety board agreed on threshold values for tolerable and non tolerable risk. Between this two there is an area of conditional tolerable risk which is called ALARP-region (As Low as Rational Possible). The QRA software in combination with this definition makes it possible to assess the risk for existing and planned tunnels. If the F/N curve of a tunnel is in the range of tolerable risk, no action is required. If the F/N curve touches the area of non tolerable risk, immediate action is required independent from costs. If the F/N curve is situated in the ALARP region, mitigation measures are necessary, but issues of cost effectiveness can be taken into account.

In a project funded by the Federal Ministry of Transport, Innovation and Technology the Institute for Transport Planning and Traffic Engineering carried out a QRA study for 13 selected Austrian tunnels. The tunnel length ranged from about one to ten kilometres. The selection covered uni- and bi-directional tunnels as well as a broad range of different ventilation systems. None of the analysed tunnels reaches the area of non tolerable risk. All F/N curves are situated more or less within the ALARP region. None is lying exclusively in the area of tolerable risk. Suggestions for risk mitigating measures were made.

Key words: tunnels, quantitative risk assessment, heavy goods vehicles, dangerous goods

1. INTRODUCTION

Public opinion about tunnel safety is often based on irrational assumptions. This is especially the case in the aftermath of severe tunnel accidents like the Tauerntunnel accident in 1999 or the Gleinalmtunnel accident in 2001. The public calls for the implementation of costly measures like the installation of sprinkler systems etc. in all tunnels. A tunnel safety board was installed by the Austrian Federal Ministry of Transport, Innovation and Technology after the fatal accident in the Gleinalmtunnel. To rationalise decisions concerning tunnel safety the use of Quantitative Risk Assessment (QRA) was suggested in this committee. A QRA software suitable for this purpose was developed in a joint OECD, PIARC and EU project (Knoflacher, 2001; Knoflacher and Pfaffenbichler, 2001; OECD, 2001). This software makes it possible to calculate the societal risk in the form of F/N curves. F/N curves show the relationship between accident frequency and accident severity. A more detailed description about risk and F/N curves is given in (Knoflacher and Pfaffenbichler, 2001). The application of the QRA software to the case study Tauerntunnel was shown in (Knoflacher et al., 2002).

The question of tolerable risk was extensively discussed in the Austrian tunnel safety board. The members of this committee agreed on threshold values for tolerable and non tolerable risk (Figure 1). The basis for the threshold of non tolerable risk is that the risk in tunnels must not exceed that on open road. The threshold for tolerable risk is about the same magnitude as getting killed by a lightning or a similar natural disaster. Between these two thresholds there is an area of conditional tolerable risk. This is given the name ALARP-region (As Low as Rational Possible). Another principle is that each fatality is valued equally, i.e. the tolerated frequency for an incident causing ten fatalities is one tenth of that of an incident causing one fatality. This assumption defines the slope of the tolerance curves. The software in combination with this definition makes it possible to assess the risk in existing tunnels. If the F/N curve of a tunnel is completely in the range of tolerable risk, no action is required. If the F/N curve touches the area of non tolerable risk, immediate action is required no matter what it costs. If the F/N curve is situated in the ALARP region, mitigation measures are necessary, but issues of cost effectiveness can be taken into account.

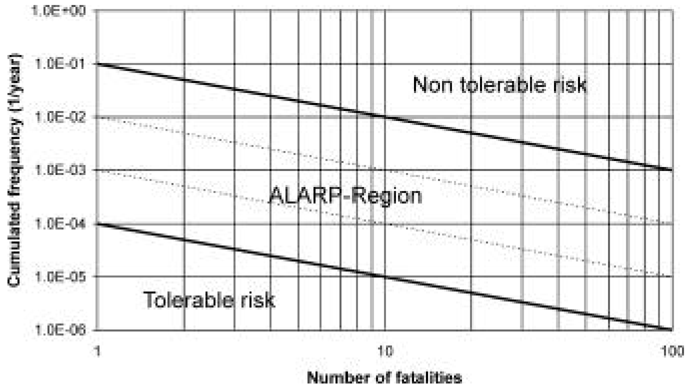


Figure 1: Tolerable risk as suggested by the Austrian Commission for Tunnel Safety for a 1 km road tunnel

2. TEST TUNNELS

In a project funded by the Federal Ministry of Transport, Innovation and Technology the Institute for Transport Planning and Traffic Engineering, Vienna University of Technology carried out a QRA study in 13 selected Austrian tunnels (see Figure 1 and Table 1). The tunnel length ranged from about one to ten kilometres. The selection covered uni- and bi-directional tunnels as well as a broad range of different ventilation systems (see Table 1).

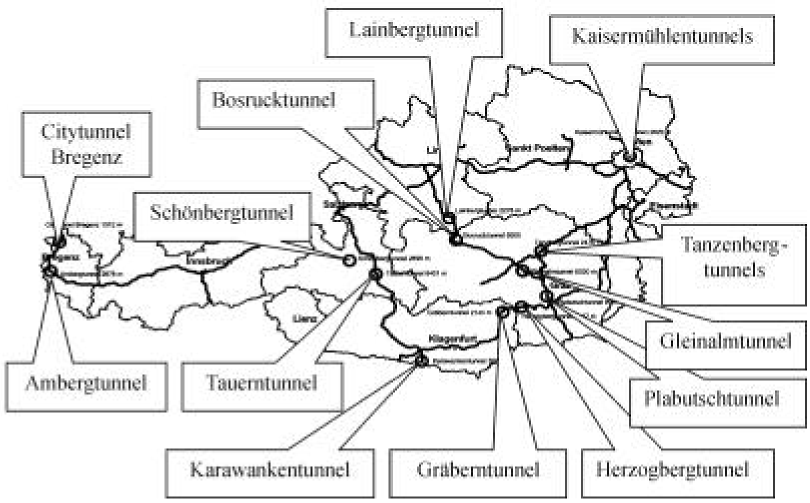


Figure 2: Location of the QRA case study tunnels

Table 1: Basic characteristics of the QRA case study tunnels

Name	Length (km)	Bores	Ventilation	Emergency exits[1)]	AADT (Veh./d)	HGV share
Ambergtunnel	2.978	one	ST	-	22,721	8.6 %
Bosrucktunnel	5.500	one	T	366 m	7,365	38.5 %
Citytunnel Bregenz	1.311	one	L plus extraction	656 m	12,911	3.7 %
Gleinalmtunnel	8.320	one	T	-	14,068	10.7 %
Gräberntunnel	2.144	one	ST	-	16,505	18.9 %
Herzogbergtunnel	2.007	one	ST	-	16,118	19.8 %
Kaisermühlentunnel	2.020	two	L	100 m	84,644	10.6 %
Karawankentunnel	7.864	one	L and T	393 m	5,106	10.4 %
Lainbergtunnel	2.278	one	L	760 m	9,435	20.2 %
Plabutschtunnel	9.919	two/one	T	3,036 m	20,681	15.4 %
Schönbergtunnel	2.988	one	L	998 m	8,448	12.9 %
Tanzenbergtunnel	2.384 / 2.476	two	ST/L	408 m	21,479	11.2 %
Tauerntunnel	6.397	one	T	-	13,200	21.0 %

Abbreviations: L...Longitudinal ventilation, ST...Semi-transverse ventilation, T...Transverse ventilation
1) "-" no emergency exits; distance as used in the QRA software

3. QRA RESULTS

This section presents the societal risk[1] as calculated in the 13 case studies in the form of F/N-curves (Knoflacher et al., 2003). Section 3.1 shows a compilation of all results. The sections 3.2 to 3.5 give a more detailed presentation of the results for five selected tunnels. These results include the societal risk of a base case and the effects of several tunnel specific mitigation measures and scenarios.

3.1. Summary

Figure 3 shows a compilation of the F/N-curves of all 13 tunnels tested. The highest societal risk was calculated for the Viennese Kaisermühlentunnel. As the Kaisermühlentunnel has by far the highest traffic volumes (nearly four times that of the next highest, the Ambergtunnel) this result was expected. The highest number of potential fatalities was calculated for the Plabutschtunnel. Again the result is plausible. The Plabutschtunnel is the longest tunnel in the case study. The two tunnels with the lowest risk levels are the Citytunnel Bregenz and the Schönbergtunnel. The Citytunnel is relatively short and has a very low share of heavy goods vehicle (HGV) traffic. The Schönbergtunnel is rather new and has a low traffic volume.

Five tunnels were selected for a more detailed presentation of their QRA results. The Kaisermühlentunnel was chosen for the high level of societal risk. On the other end of the spectrum the Schönbergtunnel was chosen because of the low risk level. The highest share of HGV traffic of the tested tunnels was the reason for the selection of the Bosrucktunnel. The Gleinalmtunnel is seen as representative for the average longer one bore tunnels. The Tanzenbergtunnel was chosen because besides the Kaisermühlentunnel this is the only two bore tunnel in the case study.

[1] Note: The QRA software calculates the societal risk caused by incidents with HGV involvement. The risk of incidents involving only passenger cars is not included.

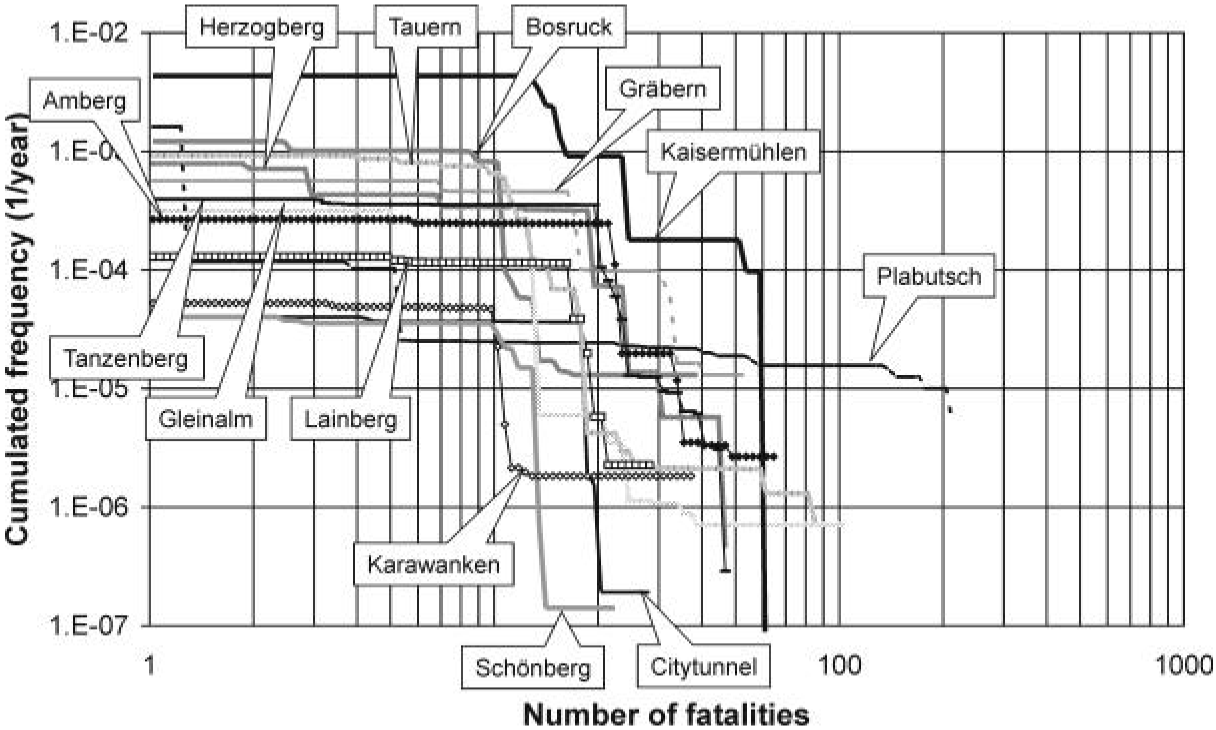


Figure 3: Comparison of the F/N curves of the 13 case study tunnels

3.2. Kaisermühlentunnel

The Kaisermühlentunnel is an urban tunnel and is part of the highway A22 "Donauuferautobahn". The traffic volumes are very high. There are entrance and exit ramps within the tunnel. Due to a nearby tank farm the share of HGVs carrying flammable liquids (motor spirit, diesel oil,...) is high. The societal risk calculated for the Kaisermühlentunnel was the highest of all tested tunnels (Figure 4). Nevertheless it still stays clear from the threshold for intolerable risk. The F/N-curve of the base case is situated within the ALARP region. I.e. mitigation measures taking cost effectiveness into account should be implemented. In Figure 4 the effects of two potential mitigation measures are shown. The first is banning heavy goods vehicles transporting dangerous goods (DG-HGV) from the Kaisermühlentunnel. The grey triangles in Figure 4 show the F/N-curve of this scenario. The potential to mitigate the risk is rather low. The major effect is for incidents with more than eleven fatalities. Additionally it would be necessary to reroute the DG-HGVs over two bridges and a road with heavy traffic and intersections. The total risk of the DG-HGV ban would be higher than in the base case. Especially the risk for third parties would be higher. The second measure tested is a regulation that HGVs have to keep a minimum distance of 150 meters to the vehicle driving ahead. The risk reduction potential is rather high and significant for incidents with more than seven fatalities.

Since August 2003 a section control is in operation in the Kaisermühlentunnel (ASFINAG, 2004). This instrument reduces the accident rate dramatically. No accidents were observed since the installation of the section control. Detailed data are not yet available. For the QRA it was assumed that the section control reduces the accident rates by a factor of ten. In Figure 4 the QRA results for this scenario are marked with crosses. A combination of the 150-meter regulation and the section control has the potential to bring the risk near to the threshold for tolerable risk.

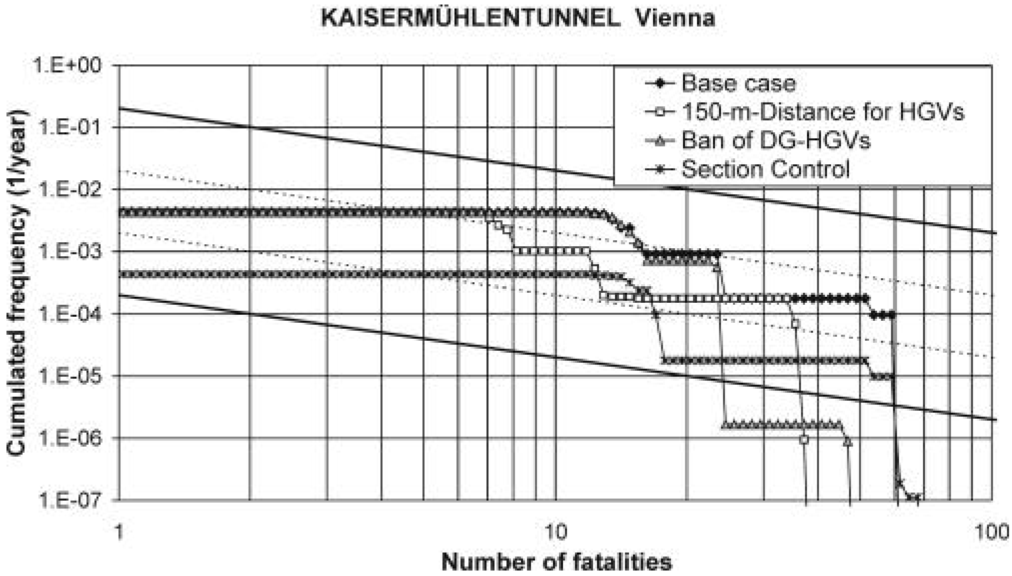


Figure 4: F/N curves Kaisermühlentunnel Vienna

3.3. Schönbergtunnel

The Schönbergtunnel is a one bore tunnel on a rural trunk road. The tunnel is rather new (opened in November 1999) and the traffic volumes are low (about 8,500 vehicles per day). Nearly the complete F/N-curve is below the threshold for tolerable risk. Therefore no additional scenarios were calculated for the Schönbergtunnel.

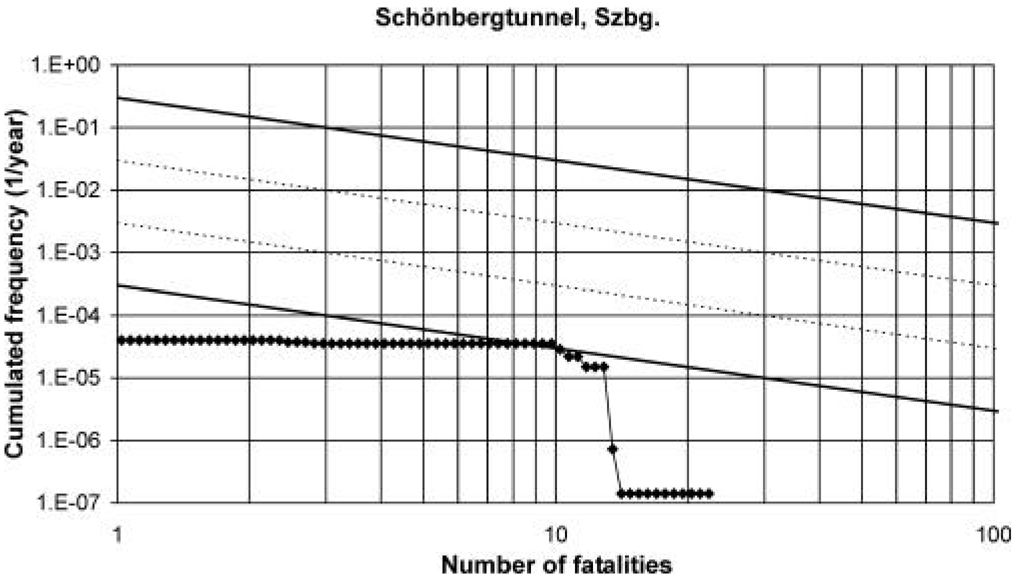
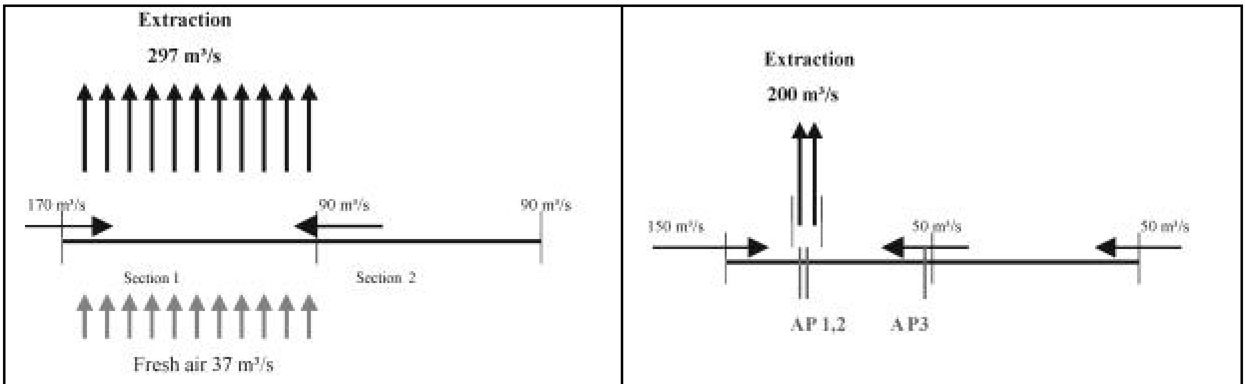


Figure 5: F/N curves Schönbergtunnel, Salzburg

3.4. Bosrucktunnel

The Bosrucktunnel is a one bore tunnel on a rural stretch of the highway A9. The Bosrucktunnel has a share of HGVs of nearly 40%. The renewed Bosrucktunnel has a separated escape tunnel. About all 400 meters there are waiting rooms. In the case of emergency persons are escorted by the fire brigade from the waiting rooms through the escape tunnel. The ventilation system of the Bosrucktunnel was modified during renovation. In the old ventilation system air was extracted through slots of one ventilation segment which was half of the tunnel length (Figure 6, left). In the modified ventilation system there are 51 discrete openings (jalousies 3x3 m) along the whole tunnel. In case of emergency all will be shut, except the one nearby the fire where the air will be extracted (Figure 6, right).



Old emergency ventilation	New emergency ventilation

Figure 6: Ventilation systems Bosrucktunnel

The effect of the new ventilation regime was tested in the QRA (Figure 7). The base case with the old ventilation regime is depicted by black diamonds. The new ventilation regime is shown using triangles. A considerable risk reduction appears only for incidents with more than ten fatalities. As in section 3.2 the effect of a regulation, forcing HGV-drivers to keep a minimum 150-meter distance to vehicles ahead, was tested. In Figure 7 the result for the combination of the old ventilation regime and this regulation is shown with black circles. The risk mitigating effect is substantial. The last scenario tested the combination of the new ventilation system with the distance regulation for HGVs. Under these assumptions the risk mitigating effect of the new ventilation is much higher. The combination of both measures moves the F/N-curve quite near to the threshold for tolerable risk.

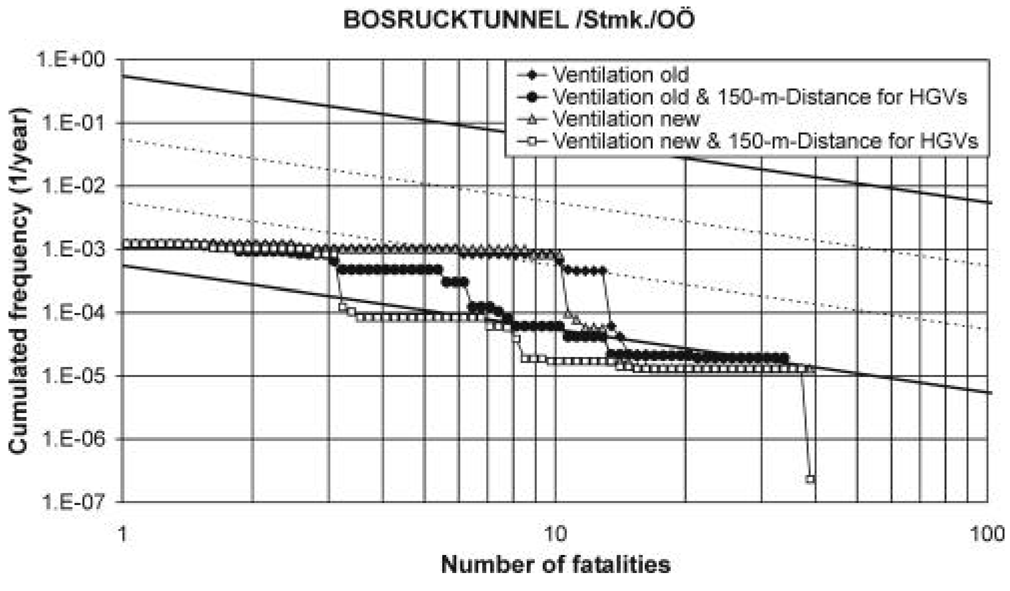


Figure 7: F/N curves Bosrucktunnel

3.5. Gleinalmtunnel

The Gleinalmtunnel is a one bore tunnel on a rural stretch of the highway A9. The ventilation system of the Gleinalmtunnel was modified similar to the Bosrucktunnel (see Figure 6). In the old system air could be extracted from six sections. In the modified ventilation system there are 84 discrete openings (jalousies 3x3 m) along the whole tunnel. In Figure 8 the old and the new system are depicted by black and white triangles respectively. The F/N-curves are quite near or even under the threshold for tolerable risk. Again there is a mitigating effect for incidents with more than ten fatalities. An additional scenario tested what would happen if the total traffic volumes increase by 40% while the share of HGVS doubles. The results for the two ventilation systems in this scenario are shown with black and white diamonds.

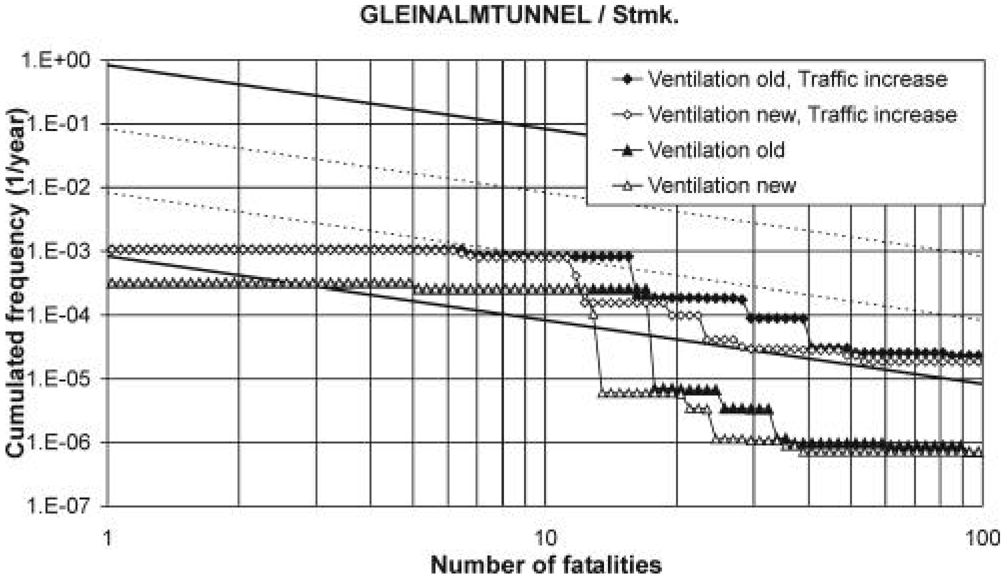


Figure 8: F/N curves Gleinalmtunnel

3.6. Tanzenbergtunnel

The Tanzenbergtunnel is a two-bore tunnel on a rural stretch of the dual carriageway S6. A noticeable characteristic of the Tanzenbergtunnel is that during the observed period the accident rate in both bores differed by a factor of ten. The accident rate in the Northern bore was about 0.232 accidents with personal injury per million vehicle kilometres while it was about 0.023 in the Southern bore (Knoflacher et al., 2003). Therefore an additional scenario reducing the accident rate in the northern bore by 50% was tested.

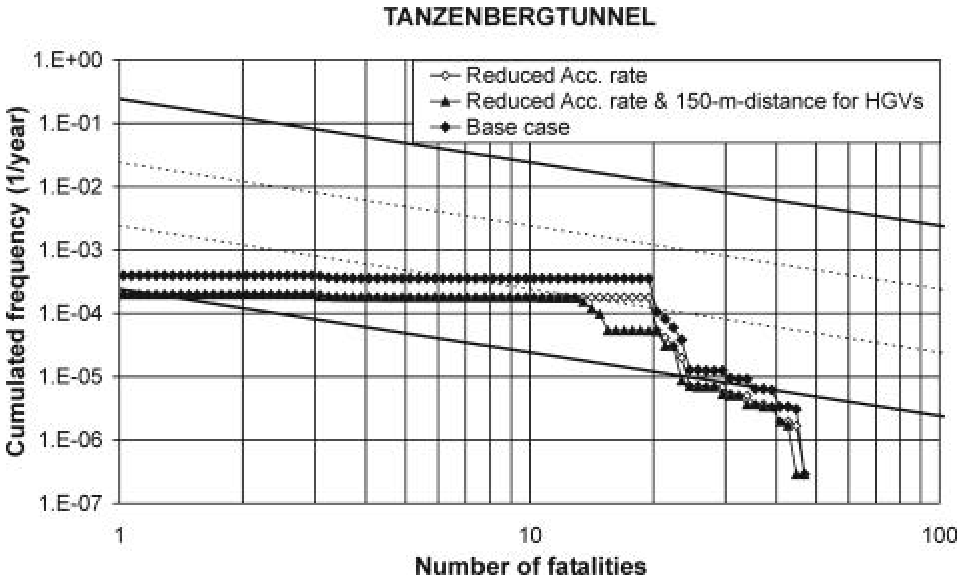


Figure 9: F/N curves Tanzenbergtunnel

4. CONCLUSIONS

The QRA software developed in a joint OECD, PIARC and EU project is a useful tool to rationalise decisions concerning road tunnel safety. The main result of the presented study is that in none of tested tunnels the risk caused by HGV traffic reaches the threshold of non tolerable risk. The F/N curves of all analysed tunnels are situated in different positions within the ALARP region. At the time of the study the need for mitigation measures was highest in the Kaisermühlentunnel. The responsible authorities already responded to this finding with the implementation of a section control. As the period of observation is still short, it was not possible to assess the effect of the section control in detail. The most effective other measure was the regulation, forcing HGV-drivers to keep a minimum 150-meter distance to vehicles ahead. The policing of this instrument could be included in future section control systems. The risk reducing effect of other, more costly infrastructure measures like changes in the ventilation system or the distance between emergency exits was smaller. A combination with the 150-meter regulation improved the effectiveness. The use of a section control measuring speed and distance and enforcing the compliance with their limits could be recommended for all major road tunnels.

5. GLOSSARY

AADT .... Annual Average Daily Traffic (Veh/d)
ALARP ..... As Low As Rationale Possible
DG .... Dangerous Goods
HGV .... Heavy Goods Vehicles
QRA .... Quantitative Risk Assessment

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ROAD SAFETY IN TUNNELS WITH UNI- AND BI-DIRECTIONAL TRAFFIC IN AUSTRIA

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ABSTRACT

The probability of an accident occurring and/or a motorist being killed in an accident is lower in a tunnel than on other road sections. However, if an accident occur in a tunnel, the severity of the injuries sustained is significantly higher than on other types of roads. This means, that the cost per accident and the risk of being killed in an accident are higher in tunnels than on motorways or expressways. In tunnel with unidirectional traffic, road safety is significantly higher than in tunnels carrying bi-directional traffic. In tunnels with bi-directional traffic, the accident rate is 28% and accident costs are 66% higher than in tunnels with unidirectional traffic. The probability of being killed or involved in an accident is 65 to 71% higher in tunnels with bi-directional traffic than in tunnels carrying unidirectional traffic.
Key words: tunnels, road safety, unidirectional, bi-directional

1. BACKGROUND

In recent years, a number of spectacular traffic accidents occurred in tunnels, which triggered debates about the safety of road tunnels. Every year, an average of 71 accidents in motorway and expressway tunnels occurs in Austria which causes an average of 15 fatalities, 38 severe injuries and 91 minor injuries. The macroeconomic costs amount to a total of EUR 13 million. The study "Tunnels with Uni- and Bi-directional traffic" of the Austrian Road Safety Board by order of the Federal Ministry of Transport, Innovation and Technology (Robatsch K., Nussbaumer C., 2004) explores the traffic safety of road tunnels on motorways and expressways compared with safety on other types of roads and also compares traffic safety in tunnels carrying bi-directional traffic with safety in tunnels with unidirectional traffic.

The relative accident rates of all motorway and expressway tunnels studied are compared with the corresponding rates for motorways and expressways as well as federal roads on open sections. A detailed comparison of all motorway and expressway tunnels with unidirectional and bi-directional traffic takes place. Moreover motorway and expressway tunnels of a minimum length of one kilometre with unidirectional and bi-directional traffic are compared.

2. SAFETY IN TUNNELS VERSUS SAFETY ON OTHER TYPES OF ROADS

A variety of relative accident rates and the distance travelled in all of the tunnels studied are compared with the corresponding figures for motorways, expressways and federal roads on open sections.

In tunnels the accident rate and the casualty rate are significantly lower than on motorways, expressways and federal roads on open sections. A comparison of the accident cost rates show that cost rates of tunnels are higher than these of motorways, expressways and the open sections of federal roads. Also, the fatality rate in tunnels is higher than on motorways and expressways.

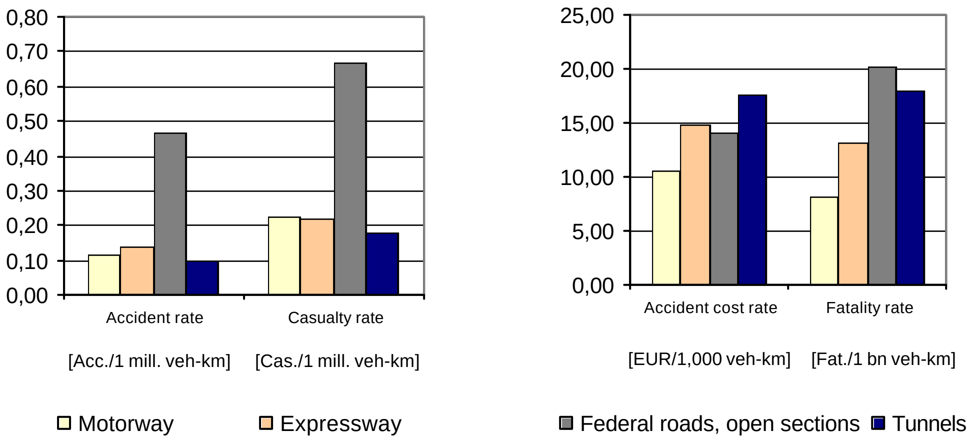

Figure 1: Relative accident rates for tunnels and other types of roads (2000-2001)

The probability of an accident occurring or road users being injured in a tunnel is lower than on motorways, expressways and federal roads on open sections. But if an accident occurs the injury severity in tunnels is especially high. Therefore the accident cost rate and the fatality rate is higher in tunnels than on motorways and expressways.

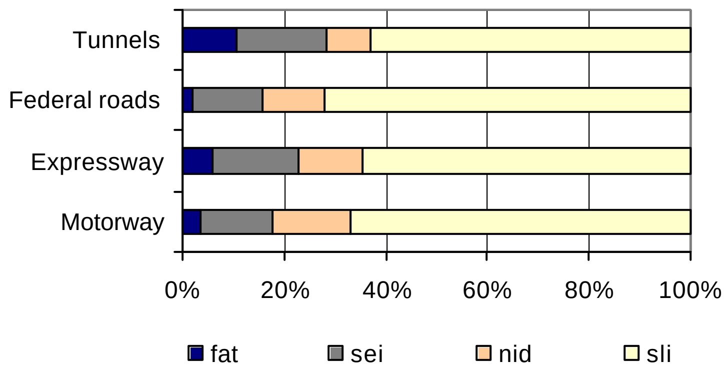

Figure 2: Severity of casualties in tunnels versus other types of roads (1999-2001)

The severity of casualties in tunnels is higher than on motorways, expressways and federal roads on open sections. While 3.6% of casualties on motorways result in death, this rate in tunnels is substantially higher at 10.6%. The proportion of those severely injured is slightly higher in tunnels than on other types of roads.

3. SAFETY IN TUNNELS WITH UNI- AND BI-DIRECTIONAL TRAFFIC

This chapter compares accidents occurring in all studied tunnels with unidirectional and bi-directional traffic on motorways and expressways.

3.1. Comparison of types of personal injury accidents

In tunnels with unidirectional traffic, same-direction accidents (including rear-end collisions and accidents while changing lanes) account for about 57% of all accidents. In tunnels with bi-directional traffic, the corresponding percentage is 45%. The main cause of rear-end collision is the failure to maintain a safe distance to the vehicle in front. In tunnels with bi-directional traffic, opposing direction accidents are the second most frequent type of accidents at 41%. In tunnels with unidirectional traffic the second most frequent type of accidents are single-vehicle accidents.

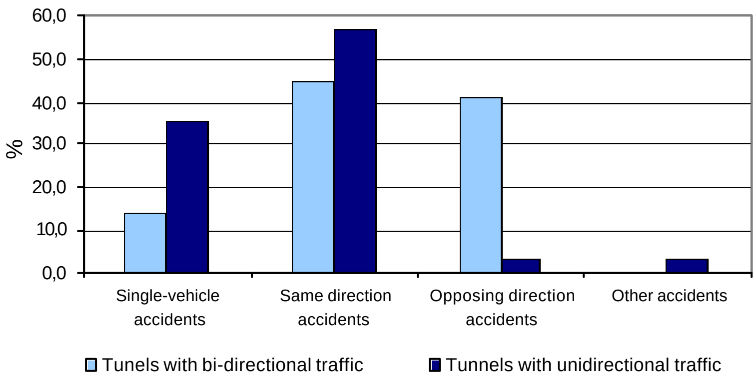

Figure 3: Types of personal injury accidents of tunnels with bi-directional versus unidirectional traffic in % (2001)

3.2. Selected assessment criteria

Table 8: Number, length and traffic intensity of tunnels with bi-directional and unidirectional traffic (status 2000)

	Tunnels with bi-directional traffic	Tunnels with unidirectional traffic
Number of tunnels studied	21	115
Total length [km]	87,709	101,357
Average length [km]	4,177	0,881
Traffic intensity [ADT]	12.704	8.958

In the calculations below, 21 tunnels with bi-directional traffic are compared with 115 tunnels carrying unidirectional traffic. On average, a tunnel with bi-directional traffic is four to five times as long as a tunnel with unidirectional traffic. At 12,704 vehicles per day, bi-directional tunnels have more traffic intensity than unidirectional tunnels, which carry 8,958 vehicles per day.

3.2.1 Comparison of relative accident rates

In the analysis below, a variety of relative accident rates have been calculated and compared for tunnels with bi-directional traffic and unidirectional traffic. In addition to the absolute accident figures and the relative accident rates it is helpful to also include the severity of casualties. The calculations below comprise accident rates, accident cost rates, casualty rates, fatality rates and involvement rates for accidents in tunnels with bi-directional and unidirectional traffic.

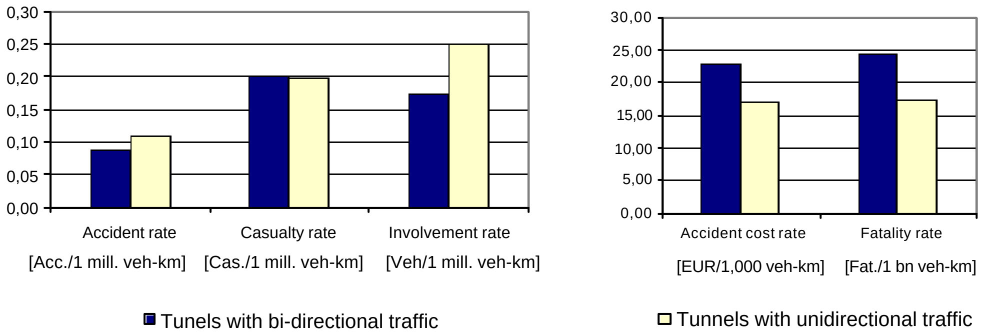

Figure 4: Relative accident rate for tunnels with bi-directional traffic and tunnels with unidirectional traffic (1999-2001)

In tunnel with unidirectional traffic, the accident rate and the involvement rate are higher than in tunnel with bi-directional traffic. The casualty rate is approximately equal in tunnels with unidirectional and bi-directional traffic. The fatality rate and the accident cost rate are higher in tunnels with bi-directional traffic than in tunnels with unidirectional traffic.

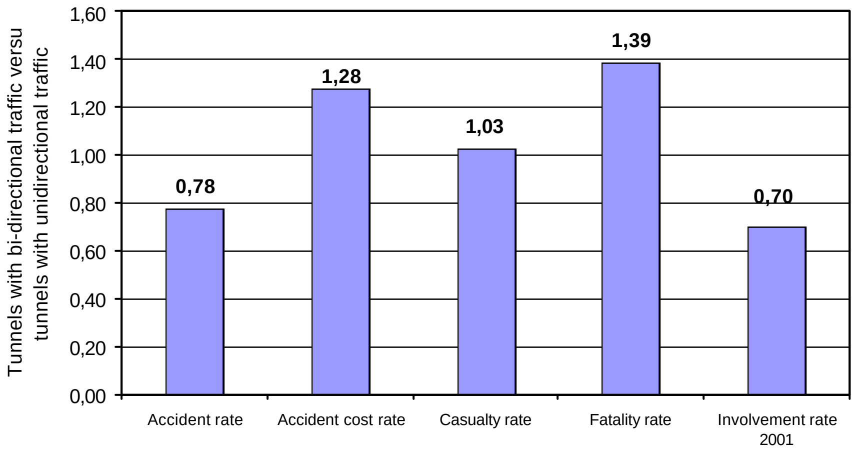

Figure 5: Relative accident rates for tunnels with bi-directional traffic versus tunnels with unidirectional traffic (tunnel with bi-directional traffic versus tunnels with unidirectional traffic) (1999-2001)

It is not possible to draw a conclusion about the safety of tunnels with bi-directional traffic and those with unidirectional traffic, as the relative accident rates have different characteristics and other factors (such as traffic intensity, length of the tunnels) also have to be taken into account. The impact of traffic intensity and tunnel length on relative accident rates will be explored below.

3.2.2 Relationship between relative accident rates and traffic intensity

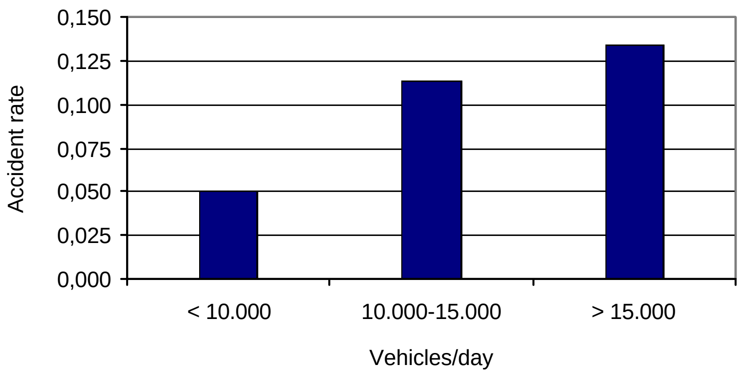

Figure 6: Average annual daily traffic (vehicles per day) and accident rate (personal injury accidents per 1 million vehicle-km) of tunnels with bi-directional and unidirectional traffic (1999-2001)

Both in tunnels with bi-directional traffic and in tunnels with unidirectional traffic the accident rate rises with increasing traffic intensity, as in tunnels with bi-directional traffic. In tunnels with bi-directional traffic the risk of a head on collision and in tunnels with unidirectional traffic the risk of a rear-end collision becomes higher.

3.2.3 Relationship between relative accident rates and tunnel length

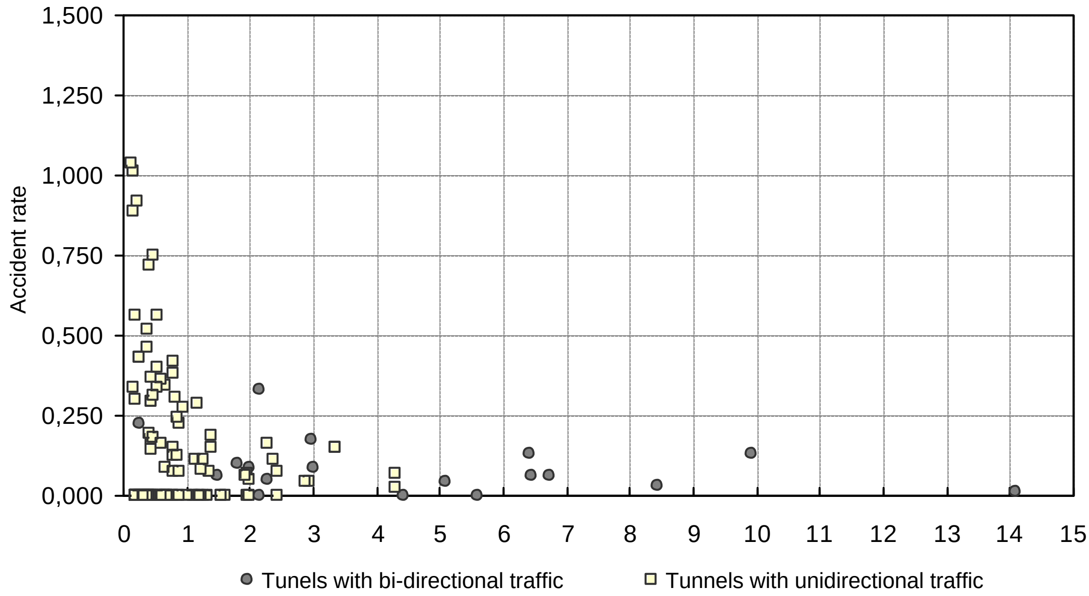

Figure 7: Accident rate (personal injury accidents per 1 million vehicle-km) of tunnels with bi-directional traffic and unidirectional traffic versus tunnel length (km) (1999-2001)

As shown in Figure 7 the length of the tunnel has a strong influence on the accident risk. Up to a tunnel length of 1 kilometre the values are significantly higher than in longer tunnels.

Due to the major differences in length of tunnels with bi-directional traffic and unidirectional traffic, the relevant data are not comparable. While 84 tunnels with unidirectional traffic are less than one kilometre long, only two tunnels with bi-directional traffic fall into this category. Therefore, further restrictions have to be introduced to enable a comparison of tunnels with bi-directional traffic and unidirectional traffic.

Accident rate, casualty rate, involvement rate, fatality rate and accident cost rate depend heavily on the length of the tunnel. This is particularly evident when comparing tunnels of less than one kilometre length with longer tunnels. The highest risk for a tunnel accident to occur is at the entrance area of a tunnel. At short tunnels this risk introduces more heavy in the relative accident rates.

3.3. Selected assessment criteria for tunnels of more than one kilometre length

The length of a tunnel has a very substantial influence on relative accident rates. Particularly tunnels of less than one kilometre length have very high accident rates. As the share of short tunnels varies greatly, a comparison of safety is not possible. 73% of all tunnels with unidirectional traffic (84) and 10% of all tunnels with bi-directional traffic (2) are shorter than one kilometre. The question of whether tunnels with bi-directional traffic or tunnels with unidirectional traffic are safer arisen, only with regard to longer tunnels, as short tunnels are usually built as twin tube tunnels. For statistical reasons it seems meaningful to compare only tunnels of a length of one kilometre and more.

The tables below compare 19 tunnels with bi-directional traffic and 31 tunnels with unidirectional traffic after various relative accident rates. On average, tunnels with bi-directional traffic that are longer than one kilometre are 2,3 times as long as tunnels with unidirectional traffic.

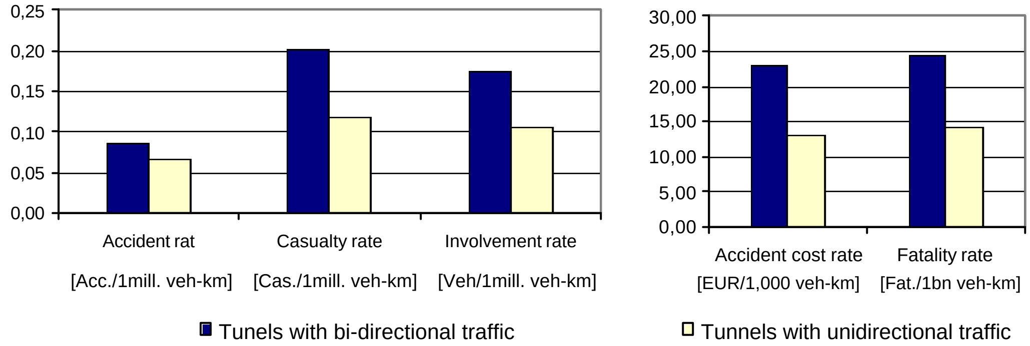

Figure 8. Comparison of relative accident rates of tunnels of over 1 kilometre length with bi-directional traffic and unidirectional traffic (1999-2001)

A comparison of tunnels of more than one kilometre length with bi-directional traffic and unidirectional traffic shows that all of the relative accident rates selected are higher in tunnels with bi-directional traffic than in tunnels with unidirectional traffic. The figures for tunnels with bi-directional traffic include the Tauern tunnel accident (29th May 1999), which cause 12 fatalities, 4 severe injuries and 35 minor injuries. This accident is a rare catastrophic event, but even when this accident is disregarded or given less weight, the relative accident rates for tunnels with bi-directional traffic are still higher than those for tunnels with unidirectional traffic.

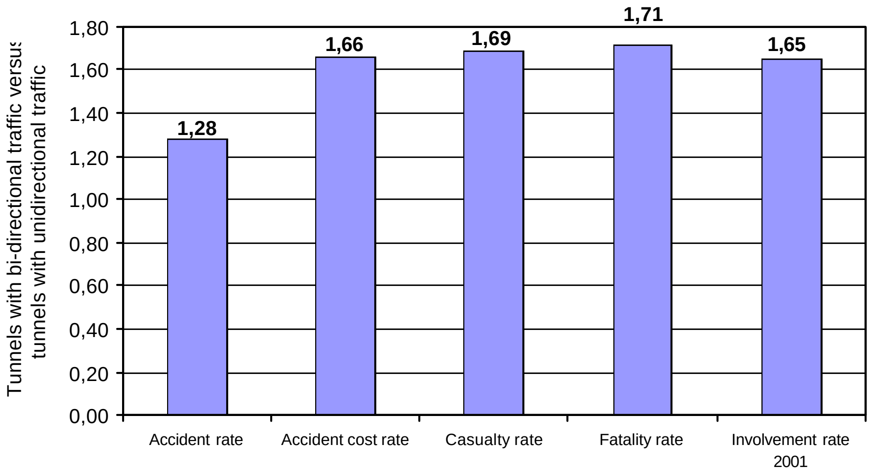

Figure 9: Relative accident rates in tunnels of over 1 kilometre length with bi-directional traffic versus relative accident rates in tunnels with unidirectional traffic (tunnels with bi-directional traffic versus tunnels with unidirectional traffic) (1999-2001)

4. SUMMARY

The probability of an accident occurring and a road user being injured is lower in a tunnel than on motorways, expressways and federal roads on open sections. However, if an accident occurs in a tunnel, the severity of the injuries sustained is significantly higher. This means, that the accident cost rate and the fatality rate are higher in tunnels than on motorways or expressways.

In comparison of tunnels of over 1 kilometre length, the accident cost rate and the involvement rate are higher in tunnel with bi-directional traffic than in tunnels with unidirectional traffic.

In a tunnel of more than one kilometre length with bi-directional traffic the probability of being

- injured is 69% higher
- killed is 71% higher and
- involved in an accident is 65% higher

than in tunnels with unidirectional traffic.

Accidents in tunnels are not the main problem within the Austrian road network. The lacking traffic morals regarding to maintain the speed limits and the failure to maintain a safe distance between vehicles are fundamental problems. Every second tunnel accident can be attributed to the short driving distance between vehicles. Instruments measuring driving distances between vehicles as well as speed radar or section control equipment contribute to increased awareness and a reduced accident risk. These measures have to be introduced in the entrance area of a tunnel where the highest risk for accidents exists.

Since tunnel accidents are quite seldom and the reasons for their occurrence are not exclusively due to the specific situation in a tunnel, problems with statistical significance of accident data for tunnels are possible.

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SYSTEMS, INFRASTRUCTURE OR USERS? WHICH IS THE BEST INVESTMENT TO IMPROVE TUNNEL SAFETY?

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ABSTRACT

Even before the fatal fires in the Mont Blanc, Tauern and Gotthard Tunnels by far the greatest proportion of the investments in road tunnels was concerned with fire safety. Since those incidents the proportion has increased even further even though the total number of fatalities in road tunnel fires worldwide ever is just 114.

The largest proportion of effort and money being spent on improving safety in tunnels is being invested in systems – incident, smoke and fire detection systems, public address systems, ventilation systems to extract smoke from close to a fire, etc. This paper examines whether these large investments in ever more complex systems would be better spent in changes to the design and layout of the tunnel. Is it better to invest more in passive safety measures such as the internal décor of the tunnel, guidance signs and notices, escape facilities and the like or are active systems more effective? Or should the investment be in more training exercises for the operators and the emergency services? Or should more be invested in reducing the primary hazard – the lack of knowledge and understanding of the tunnel users? The paper also addresses whether or not the same solutions to the investment dilemma are valid in all countries, which aspects should be common and which should not.

Key words: tunnels, systems, infrastructure, ventilation, safety, users

1. INTRODUCTION

The design and layout of road tunnels, the facilities and systems included in them and the way in which they are operated has developed through the years based on a mixture of experience, common sense and knowledge about the physical processes. This has resulted in many countries producing their own guidelines to enable their designers to benefit from the experience and knowledge gained. Each set of guidelines has, inevitably, been based on the type of tunnels prevalent in the particular country. Some, like the UK and the Netherlands, have only a few relatively short twin tube tunnels on major roads (often with little overburden) whereas other countries (such as the Alpine countries and Norway) have longer single tube tunnels often passing through mountains and carrying very little traffic. Whilst there are some common features between different guidelines, there are also many differences. In longer tunnels a ventilation system, lighting, fire hydrants and fire extinguishers are required in all guidelines but the need to provide emergency exits ranges from none to one every 100m. In many cases the requirements for a particular type of tunnel is mandatory; there are no options, irrespective of the cost effectiveness of a particular requirement. Only in Austria (RVS, 1996) is there the possibility to optimise the costs of a tunnel project by carrying out a crude sort of safety analysis to play one safety feature off against another. Almost without exception the emphasis is on providing facilities with the assumption that those involved in an incident; particularly a fire incident, will "self-rescue". Very little if any thought is given to informing the tunnel users of what is in the tunnels and what they are expected to do.

The Mont Blanc, Tauern and Gotthard incidents have resulted in many countries revising (strengthening) their guidelines with respect to the facilities needing to be provided in their road tunnels in the event of a fire (e.g. ASTRA, 2003 and RABT, 2003). Even the EU has drafted a Directive on the minimum safety standards required for tunnels on the Trans European Road Network (EU, 2004). This is expected to be ratified soon and it is anticipated that it will be the basis to define the minimum requirements in all road tunnels in Europe, not just those on the TERN. The Directive gives just the absolute minimum requirements for a "normal" tunnel and, if there are special characteristics or situations (such as longitudinal gradients greater than 3%, narrow lanes or particularly high flows of trucks), a comprehensive risk analysis is required in accordance with Article 13 of the Directive.

Alongside the guidelines and the EU Directive are the international projects concerning tunnel fires and the like which have started in recent years such as FIT, UPTUN, DARTS, SAFETUNNEL, etc. These projects are in addition to those which have been taking place within PIARC working groups and the like for many years. All of these activities will undoubtedly lead to an increase in understanding and knowledge but will they lead to a real increase in the safety levels in tunnels?

The projects are resulting in a vast amount of resources being invested into research and development on the subject of fires in tunnels. It has been suggested (Worm, 2003) that all these activities are an over-reaction and that a "grip on reality will be lost", that duplication of effort could be taking place and that more time, energy and money is being put into ever diminishing returns. In addition to these sums there are the large additional investments and resources that are being required to be made in old and new tunnels as a result of changes in guidelines. These latter investments far outweigh those being made in other possible improvements to safety in tunnels (i.e. non-fire related) even though a simple cost benefit assessment clearly demonstrates that the converse should be the case (Day, 2003b).

So where should research and investments be best directed to improve safety in tunnels? The next three sections attempt to address this question – should it be in educating tunnel users; in improving the tunnel infrastructure to reduce the frequency of incidents or improve escape facilities; or should it be in improving systems for incident detection and mitigation? Section 5 asks if the same solution(s) are applicable in all countries whilst the final section suggests some answers to the questions posed.

2. TUNNEL USERS

Everybody concerned with the design, construction and operation of road tunnels knows and agrees that tunnel users must "self rescue" because it is not possible for rescuers to reach an incident in a tunnel, particularly a fire incident, in time to effect a traditional rescue operation. Unfortunately many tunnel users are not aware of this and prefer to stay in what they perceive to be the safety of their vehicle. They are unaware of either the impending danger they are in or of the facilities provided for them to fight a fire or for them to escape from the tunnel.

The incident reports from all the major road tunnel incidents have each identified that the number of casualties was increased by the inappropriate behaviour of the tunnel users involved. Why did they not know what to do? It is almost certainly because nobody had tried to convey the appropriate information to them on what to do – even after what has been said about the major incidents. Many authorities seem to have taken the pessimistic attitude that "nobody will listen to what they have to say so there is no point in us saying it!"

It's very easy to say that people will not listen to advice and so its pointless wasting money trying to give it to them. But even if only a few of them listen and know what to do others will follow as has been clearly demonstrated in the tests carried out by TNO for the Dutch Centre for Tunnel Safety (Boer, 2002). Doing nothing is not a solution: the Swiss Tunnel Task Force recognized this in their report in the autumn of 1999 as did the Ad hoc

Multidisciplinary Group of Experts on Safety in Tunnels in their report (UNECE, 2001) and it has been clearly identified in the draft Directive from the EU (EU, 2004) – paragraph 4 of Annex I states *"Information campaigns regarding safety in tunnels shall be regularly organized and implemented in conjunction with interested parties on the basis of the harmonized work of international organizations. These information campaigns shall cover the correct behaviour of road users when approaching and driving through tunnels, especially in connection with vehicle breakdown, congestion, accidents and fire."*

That said such campaigns are not new. To give credit where it is due, some responsible authorities have been trying to do something. A couple of years ago the Swiss traffic safety society had a campaign on tunnel safety involving leaflets to every house, notices on billboards, television programs and the like and the society still has a direct link from their home page (www.verkehrssicherheitsrat.ch) to a page on tunnel safety. This year a leaflet produced by the Zurich Police on driving in tunnels (Figure 1) was sent out with each and every car license renewal form and they have a link directly from their homepage (www.kapo.zh.ch) to information on what to do in a tunnel fire (www.tunnelbrand.ch.vu)

Tunnelbrand – Rette Dich!

bei Stau

Gasse bilden

Fahrzeug seitlich am Tunnelrand anhalten (Gasse für Rettungsfahrzeuge). Meldung über Ereignis via Notrufsäule an die Polizei (wer–was–wo–wie viele?). Ruhe bewahren.

Radio einschalten

Die Polizei hat die Möglichkeit, den Fahrzeuglenkende(n) über die Tunnel-Radiofrequenz DRS in verschiedenen Sprachen Anweisungen zu erteilen

bei Rauch

Motor abstellen, Zündschlüssel stecken lassen

und

sofort Fluchtweg suchen

Den Tunnel zu Fuss verlassen – bezeichnete Fluchtwege benutzen (Notausgänge, Rettungsstollen, Rettungsnischen) oder sich der Tunnelwand entlang zum Ausgang begeben
– niemals dem Rauch entgegen laufen!

Zusätzlich gilt für Liefer- und Lastwagenlenkende:
Nie am Brandobjekt vorbeifahren, wenn sich im Fahrzeug gefährliche Güter (SDR) befinden (frühzeitig ausstellen).

Niemals wenden oder rückwärts fahren

Einfahrende Rettungsfahrzeuge werden ansonsten blockiert oder zu Fuss flüchtende Personen können angefahren oder überfahren werden.

Beginnt das Fahrzeug während der Fahrt zu brennen, wenn möglich bis zum Tunnelausgang weiter fahren.

Tunnel fire – rescue yourself!

If there's congestion

Leave a passage between vehicles

Turn on your radio

If there's smoke

Turn off motor, leave keys in vehicle

and

Immediately find an escape exit

Never turn or drive backwards

Figure 1 Leaflet by the Zurich police distributed in 2004 with car licence renewal forms

3. INFRASTRUCTURE

Should we be changing the tunnel infrastructure to improve safety? This means not just so that people can more easily escape from the tunnel once an incident occurs; it also means improving the tunnel infrastructure so that there is less likelihood of an incident occurring in the first place. If you don't have the incident you don't have the consequences of the incident!

As has been demonstrated (Day, 2003b) the societal costs of fires in tunnels are much lower than those for other incidents so efforts should really be made in that direction. Apart from a few projects (notably those being carried out by Gerhard Eberl of OESAG in Austria) nobody currently seems to be trying to understand what is good and bad about the way tunnels and the approaches to them are designed in an effort to reduce the likelihood of incidents occurring.

The problem with changing the design or layout of a tunnel, its portals and the like is that it probably results in an increase in the capital cost of the project. However the ongoing costs of such measures are normally minimal and the whole life costs can be very low.

Nevertheless, the principal advantage of infrastructure measures (whether they be to reduce the likelihood of an incident occurring or the consequences if it does occur) is that they are passive; they will always "work"; they do not rely on something happening or somebody doing something for them to be effective.

4. SYSTEMS

The emphasis in recent years has been the development and improvement of systems for either detecting incidents or reducing the consequences of them. This section looks in detail at changes to ventilation systems for tunnels and to other systems.

4.1. Tunnel ventilation system

The system with the most radical changes through the years is that for ventilating the tunnel. Prior to the 1990s tunnels, even short tunnels, needed relatively massive amounts of mechanical ventilation during normal operation to be able to maintain the then required in-tunnel air quality for CO emissions and for visibility. Ventilation systems were typically based on the transverse ventilation concept and the exhaust ventilation required in an emergency was usually easily within the system's capabilities. The reductions in emissions brought about by the on-going vehicle exhaust emission legislation mean that, in many countries, twin-tube tunnels up to 5 km long or more can be naturally longitudinally ventilated portal to portal during normal operation; no intermediate air exchange shafts are required. Even relatively long single tube tunnels can be longitudinally ventilated during normal operation even with the currently more stringent in-tunnel air quality requirements, particularly for the concentration of CO. The ventilation needs for emergency operation are no longer easily achieved by the system required for normal operation and the design case for the ventilation system has become its operation in an emergency.

Initially this just meant installing some more jet fans to ensure that all of the smoke was blown to one side of the fire. However this assumed that all the vehicles on the downstream side of the fire could leave the tunnel to safety and, in single tube tunnels and twin tube tunnels with congested traffic, this is clearly not the situation. For longer tunnels in several countries dedicated smoke extraction systems have been introduced which are capable of extracting smoke from the tunnel close to a fire through remotely controlled mechanical dampers. The concept behind this approach is to open one or more dampers close to the fire and, using large fans connected to the exhaust duct, extract the smoke from the tunnel close to its source. The extraction will draw in fresh air from the tunnel portals and the length of the tunnel which is affected by smoke will be limited. Unfortunately this concept is not as simple and straightforward as it first appears.

During normal tunnel operation there will be a significant longitudinal airflow through the tunnel from one portal to the other and, when the fire occurs, the smoke will initially propagate at that speed and continue to do so until the exhaust flow is established. Once established the exhaust flow should, ideally, induce roughly equal quantities of fresh air from each portal. Using the exhaust flow alone this is obviously not possible if the fire is close to one of them; most of the fresh air would be drawn from the closest portal. In many tunnels there is an additional complication, especially if the tunnel is through a mountain; that there could be a large difference in the ambient pressures at the tunnel portals. This pressure difference would induce a significant natural longitudinal flow through the tunnel, possibly greater than the exhaust flow, which would mean that not all of the smoke would be exhausted (Day, 2001 and Norghauer, 2001). A similar situation exists in tunnels with significant longitudinal gradients where the thermal buoyancy forces could induce similar high natural longitudinal flows (Day, 2003a).

There are two possibilities to overcome the adverse effect of these high natural longitudinal flows; massively increase the exhaust flows or counteract the forces causing the flow. The former would result in a significant, and probably unacceptable, increase in the size (and cost) of the tunnel and its exhaust system. Counteracting the natural forces can be achieved either by using jets of fresh air (Almbauer, 2003) or with jet fans (Day, 2001 and Norghauer, 2001) and similar flows from each portal can be achieved even when the fire occurs near one portal. Unfortunately the fresh air jets or the jet fans need to be controlled and this means that air velocity sensors are needed in both tunnel portals – not just one but at least three at each portal to ensure data reliability. Furthermore the fresh air jets or the jet fans have to be actively controlled throughout the period of the emergency ventilation to ensure that the required fresh air flows into each portal are achieved irrespective of the changing forces on the mass of air within the tunnel.

The resulting system is complex with numerous interfaces and interactions and, as such, requires careful design and, more importantly, regular maintenance and testing to ensure that all of the components of the system are working and interacting correctly.

4.2. Other systems

The concepts for many of the systems for normal and emergency operation that have been (and are still) required in road tunnels have not changed radically over the years. The particular types of equipment used in, for example, the lighting system may have changed as technology changed but the basic concepts remain the same – adaptation lighting near the portals and lower light levels through the remainder of the tunnel. Even the emergency-only systems have changed little – the provision of fire hydrants at regular intervals throughout the tunnel for example.

With the advances in electronics and the like the capabilities and reliabilities of systems such as incident detection and fire detection have improved significantly. Many of these new approaches are being based on continually analysing CCTV images with the aim of detecting and identifying incidents as quickly and reliably as possible so that remedial measures can be instigated at the earliest opportunity and, hopefully, an escalation of the incident can be avoided.

Some "new" systems, as yet not required in tunnels, do address mitigating the consequences of incidents, in particular fires, such as water deluge or water mist fire suppression systems. There are a few systems which have been introduced with the direct aim of reducing the likelihood of an incident occurring – one such is kerbside lighting to clearly identify the kerb and, hopefully, to stop users from hitting it.

All of these are complex systems that rely on the integrity of a chain of components, wiring and equipment to function correctly. One failure or error in a chain means that the whole system fails and it is out of commission. Whilst this may not be a serious issue for systems being used during the normal operation of the tunnel (lighting, CCTV, AID and the like) because its failure will be quickly seen and remedied, it is an important issue with emergency only equipment and systems. If a fire hydrant cannot be relied upon why put them in the tunnel? Luckily with hydrants there is a lot of experience about their reliability and how often they need to be serviced but the same cannot be said for other emergency-only systems. Regular maintenance and testing of such equipment and systems is absolutely essential if the necessary reliability levels are to be achieved. And if such commitments from the owners/operators cannot be guaranteed then the installation of those systems in tunnels – and that includes smoke extraction systems with dampers – must be questioned.

5. SHOULD THINGS BE THE SAME IN EVERY TUNNEL IN EVERY COUNTRY?

There are basically two issues here:

a) should all tunnels be the same from the point of view of the tunnel users?
b) should all tunnels be provided with the same equipment and systems?

5.1. From the users point of view

The answer to the first question is almost certainly yes. With the large amount of cross-border travel which takes place all tunnels should be the same for tunnel users as should the instructions given to them on how to behave when different incidents occur while they are driving through a tunnel. Having the users from different countries doing different things during the same incident is just asking for problems (and casualties).

In the event of a fire the signs should clearly indicate to escaping users the direction(s) to the emergency exit(s). Equipment such as fire extinguishers and (maybe) hose reels should be provided for tunnel users to attack the fire if they wish to. Facilities should be provided to enable users to attract the attention of the operators even if proper communication is not really possible because of language difficulties. To a greater or lesser extent these fire related facilities are provided in most tunnels although the spacing between emergency exits in different countries varies considerably as does the provision of communications and fire fighting equipment. The whole of Annex III of the EU draft Directive (EU, 2004) is concerned with having a common set of signs for use in tunnels throughout Europe.

Whilst the provisions in tunnels for a fire emergency may be fairly similar in most countries, the same cannot be said of other facilities that are supposedly provided to increase safety in tunnels and reduce the risk of incidents occurring in the first place. A classic example of this is the recently introduced kerbside LED lighting being installed in ever more tunnels. The colours of those LEDs vary from country to country depending on their local, often historic, regulations which are usually not included in the Vienna Convention. For example, irrespective of whether the traffic is uni- or bi-directional, in Austria the LEDs are red on the right hand side and white on the left; in Switzerland they are white on both sides and in Italy they are yellow on both sides! In addition to this potential confusion for drivers it is also understood that in some tunnels a) the LEDs are put into “flashing mode” to indicate a hazard in the tunnel and b) that it has been suggested that they be used in “running mode” to indicate the signalled speed in the tunnel. It would be illuminating to find out how many drivers knew what the LEDs and their different operational modes were meant to indicate. Remember, these are supposed to be one of the latest ways of improving in-tunnel safety!

5.2. Equipment and systems

The need to provide common safety features for tunnel users in all countries seems to be obvious but is the same true for other facilities, those which have no impact on the tunnel users? Ideally one would say yes, all tunnels should be provided with the “best” systems to provide the “highest” level of safety in all tunnels. But can this be achieved in reality? The answer to that is almost certainly no. Many of the so-called “best” systems are emergency-only systems and rely on complex equipment which needs regular testing and maintenance if there is to be any chance of it working correctly on the very rare occasions it is needed. In how many countries could such regular testing and maintenance be relied upon not just during the first few months after the tunnel is opened but throughout its life? Very few I suggest. In many countries such activities are just not done on any equipment let alone any that might be installed in a remote tunnel. And, if the effectiveness of this “best” system cannot be relied upon, it should not be even be suggested by the designers or supported by them if their client wants to install such systems. In such situations there are two approaches that can be adopted: the first is only to use systems which are an integral part of the normal operation of the tunnel so that any failure is immediately apparent and must be repaired to keep the tunnel operating. The second approach is to use systems that do not require the levels of maintenance and testing required by the “best” system.

A good example of one of these “best” safety systems is an exhaust system capable of extracting smoke from the tunnel close to a fire through remotely controlled mechanical dampers. Such systems are emergency-only and rely on regular testing and maintenance to remain effective. But are they appropriate for all countries, irrespective of their maintenance and testing ethic? Or should a simple traditional transverse ventilation system with linear extraction be adopted? Transverse systems only rely on the maintenance of the exhaust fans (which are located outside the tunnel) for the system to remain effective.

6. SYSTEMS, INFRASTRUCTURE OR USERS?

With a few exceptions the investments being required by the new guidelines are in measures related to fires in tunnels and are almost exclusively in active systems in an attempt to reduce the consequences of a fire – smoke extraction systems, PA systems, emergency lighting systems and the like. All such systems are not normally in operation and require one or more things to happen successfully before such a system becomes effective in an emergency and, hopefully, reduce the consequences of the fire. It is obviously necessary to have systems in tunnels, particularly those to reduce the risk of incidents occurring or to minimise the consequences should they occur. However systems are prone to failure – even if only due to Murphy’s Law – and reliance on them alone would almost certainly lead to an increase in casualties, particularly in countries where maintenance and servicing are less than ideal.

Other fire safety provisions are passive and, although they may not be “in operation” during normal tunnel operation, they are immediately available to reduces the consequences – emergency exits and signage to them are the obvious examples – and they do not rely on anyone or anything to happen for them to be effective. Measures incorporated into the infrastructure of the tunnel will always be effective irrespective of the tunnel’s location..

So why is there this emphasis on systems being the solution to the problem? Could it be commercial interests? Systems mean manufactured hardware and will involve ongoing repair and maintenance by their suppliers whereas passive measures are usually a one-off cost when they are provided. Or could it be that it is far more straightforward (and definitely easier and more “glamorous”) to develop systems than to attempt to understand and educate the general public?

Many people working in the service industries will say that their job would be fantastic if it were not for the customers! The same is true of tunnels; they would be a nice safe environment if it were not for the behaviour of the users. Bad driving habits are universal but the responsible authorities are trying to clamp down on the offenders. Driving in tunnels poses different hazards than the open road which the general public are not aware of and nor are they aware of what to do if they are involved in an incident in a tunnel. The responsible authorities have recognised this and some of them have done something about it. Swiss drivers should be better informed than those from many other countries so we can only hope that at least one of them is involved in every tunnel incident because they should know what to do and, hopefully, the herd instinct will prevail and the other users involved will follow their lead!

Systems, infrastructure or users? No – firstly the users, then the infrastructure and finally systems should be the order.

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SMALL EMERGENCY TUNNELS INSIDE ROAD TUNNELS

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ABSTRACT

When fire provokes in a road tunnel, it is most important to let the drivers escape from the tunnel as rapidly as possible. In order to do this, an emergency tunnel is supposed to be one of the best ways. The week point of emergency tunnels that have been built separately from the main road tunnel is its high cost. To solve this problem, the idea of small emergency tunnel inside a road tunnel has occurred.

On the other hand, the idea to cover up the pedestrian pass inside a road tunnel for the sake of walkers' comfort has come into reality in Japan. So it is considered good to take advantage of this inside pedestrian tunnel to make inside emergency tunnels.

As emergency tunnels have different requirements from those of pedestrian tunnels, research has been started to examine the requirements of both small tunnels. The main requirements of emergency tunnels include heatproof capability and design to prevent smoke .The main requirements of sidewalk tunnels includes level of atmospheric cleanness and lighting.

Key words: emergency tunnels, pedestrian tunnels, sidewalk tunnels requirements, safety

1. BACKGROUND

Japan has 8889 road tunnels, as shown in Table 1, and the safety is a large subject for a road administrator. When an accident, such as a fire, occurs in a tunnel, in order to minimize the damage, there are facilities for emergencies, for example, a fire extinguisher, a fire detector, and an emergency tunnel. The emergency facilities for a road tunnel are installed according to traffic volume and tunnel length in Japan. For example road tunnels the traffic of which is 20,000 vehicle /day and the length of which is 3000 m are classified as AA class tunnel. AA tunnels have to install an emergency tunnel or smoke-eliminating equipment. The emergency tunnels have so far been built by different line from the main tunnel like Figure 1. For this

Table1 Road tunnels in JPN

Tunnel length	Number of tunnels
Above3000m	67
above2000m below3000m	118
above1000m below2000m	540
below1000m	8164
total	8889

Note) data of April 1st 2002

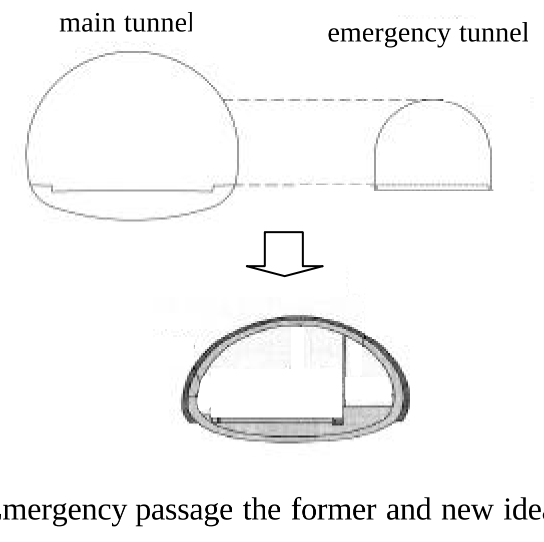


Fig. 1 Emergency passage the former and new idea

reason, although the emergency tunnel is effective especially for refuge, it has a difficulty that the cost is high. To solve this problem, the idea of small emergency tunnel inside a road tunnel shown in Figure1 has occurred. On the other hand, the idea to cover up the pedestrian pass inside a road tunnel for the sake of walkers' comfort has come into reality in Japan. So it is considered good to take advantage of this inside pedestrian tunnel to make inside emergency tunnels.

As emergency tunnels have different requirements from those of pedestrian tunnels, research has been started to examine the requirements of both tunnels. The main requirements of emergency tunnels include heatproof capability and design to prevent smoke .The main requirements of sidewalk tunnels includes level of atmospheric cleanness and lighting.

2. EXAMPLE OF A SMALL SIDEWALK TUNNEL INSIDE A ROAD TUNNEL

2.1. Outlines

The first small sidewalk tunnel was built in Utatsu road tunnel on national highway No. 159 (Fig. 2, Fig. 3)(Murata 2003). That was bypass construction aiming at relief of the chronic traffic congestion of the Kanazawa city zone. In order that this tunnel might connect the area where a residential section, a high school, and a university are located, many bicycles and pedestrian traffic were assumed. The sidewalk is 3m wide and passage by walk takes 20 to 30 minutes because the tunnel is 1,220m of length. The images of the walk in a tunnel were something like -- "exhaust gas is a smell", "noise being noisy", "dark", and " since it is danger". Considering the creation of comfortable space for bicycle and pedestrian, the idea of the wall between sidewalk and driveway occurred to the road administration, and it lead to a small sidewalk tunnel in a road tunnel

Concerning the design of the small sidewalk tunnel, the partition wall desirably should be transparent and it also should be strong, durable in tunnel, reasonable in price and semi- non-flammable. It results in using the polycarbonate board (t= 5mm) as the panel of sidewalk-tunnel wall and H shaped steel beam as the support of the panels. Moreover, the door is installed in the wall at the place where disaster prevention equipment like an extinguisher is set in the wall of main tunnel and passing to a sidewalk from a driveway is enabled in an emergency. For the purpose of security, cameras for sidewalk and monitors are to be installed in respect of crime prevention, and four images of the sidewalk can be simultaneously shown by the six monitors in a sidewalk tunnel so that passing situation can be checked by the public

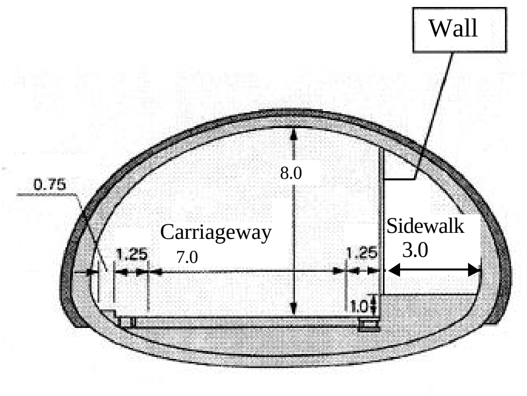


Fig. 2 Section of Utatsu Tunnel

Fig. 3 View from the carriage way

2.2. The environmental improvement by the sidewalk tunnel

As a result of installing a partition wall, the noise by large-size car is 80dB or more on the driveway and has changed to be 67-72dB in the sidewalk tunnel, which means that 13.2-13.7dB reductions is achieved. As for the atmosphere, suspended particulate matter on the driveway is 0.570mg/m3 and that in the sidewalk tunnel is 0.180 mg/m3, which is about one third of driveway value. Nitrogen dioxide concentration also became 0.025 ppm of sidewalk parts to 0.085 ppm of driveway parts, and this also became the value of the around 1/3 of a driveway part. This is a value equivalent to the measured value of 0.012-0.036 ppm of a neighbouring open sidewalk.

3. PERFORMANCE OF EMERGENCY TUNNEL AND SIDEWALK TUNNEL

3.1. Preface

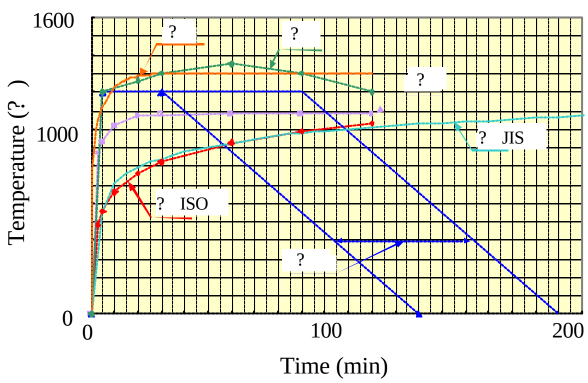
The research of performance has just started in 2003 and the standard concept and numerical value which are shown in this paper is based on the results in this time of the research and can be changed by future research

3.2. Performance of Small Tunnel Only for Emergency

3.2.1 <u>Performance of Geometry and Structure</u>

a) Width and clearance
The width and clearance in the case of installing the small tunnel only for emergency escape in a road tunnel is to secure the width in which safe escape is possible. In Japan, there are the following regulations for a refuge passage width and clearance.
According to the law on barrier-free, "passage should be effectively more than the width: 1.4m". According to the installation standard for road tunnel emergency facilities (administrative document), escape passage should be 1.5m wide or more and 2.1m high or more. Therefore, width of 1.4 or 1.5m and height of 2.1m has been considered as width and clearance value for emergency tunnel.

b) Heat resistance
As for the heat resistance, the resistance which can secure the escape time to take people in the tunnel to the place where the people are not involved in smoke or gas anymore is necessary. However, the above-mentioned time differs by fire scale. An assumption fire scale is the item, which must be examined in the future. Any way in Japan, there are the following regulations for building heat resistance.



	Name (Max temperature)
?	Standard of ISO - temperature curve- (1,029?)
?	JIS A 1304- 1975,Japanese Standard - temperature curve of a building fire- (1,010?)
?	HC: hydro carbon fire curve Supposing oily fire or a HC fire (1,080?)
?	RABT: a guideline on facilities and management of road tunnels in Germany, ZTV Tunnel Curve (1,200?)
?	HCM: modified curve of HC fire (1,300?)
?	RWS: a curve of the ministry a public works and transport, flood control head office in Holland (1,350 ?)

Fig. 4 Various temperature curves including Japanese Standard Curve?

According to the Building Standard Law of Japan, the performance of the fire prevention equipment of a building is prescribed by the temperature curve. Fire prevention facilities are classified into the following two groups on the basis of the JIS curve that is almost the same as ISO curve (Fig. 4).

?One is the specific fire prevention facilities used for the door or a window installed in an indoor wall of fire prevention division (JIS curve 60 minute 945 degree C)

?The other is the fire prevention facilities used for the door or window of an outer wall of a fireproof building (JIS curve 20 minute 781 degree C)

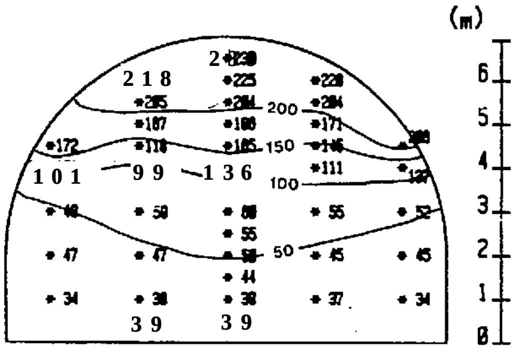
As the point which should be taken into consideration

a) Considering that it might be rational to keep the risks of each field in accordance in one country, the door or the window of emergency tunnel should have fireproof ability of 20 minutes on JIS curve because those facilities are supposed on the outer wall of the emergency tunnel.

b) Considering the tunnel fire , heat-resistant time for a certain heat-resistant temperature are needed to secure the escape time. 600m of escape distance will be secured if the heat resistance is 20 minutes and the start of escape is assumed to be 10 minutes after the outbreak of a fire, and walk speed is assumed to be 1 m/s .

c) The temperature in the past tunnel fires amounts to 600-1,150 degrees C . However, according to the results of the real-scale-bus-fire experiments (Mizutani 1982), the temperature distribution in a tunnel section near the fire of the tunnel shows that the temperature of upper part of the tunnel is very high and the temperature of the side wall is low (Fig. 5). Taking this into consideration, the design with more economical performance might be achieved in the future.

Future research is supposed to focus on above-mentioned a) and also taking b)and c) into account .



Temperature distribution ?

bus fire

elaped time 16min
at the section 5m away from the fire

Fig. 5 Temperature distribution and bus fire experiment in tunnel

d) Protection from smoke
The requirements about protection from smoke should come from the performance that escape walking does not become difficult by smoke for people to escape to the place where they are not involved in smoke anymore. Experiments have revealed that smoke is usually distributed near a ceiling in layers till about 10 minutes after the outbreak of a fire in a tunnel but after that smoke becomes cooled and descending. As for the numerical value of the smoke concentration to which walking does not become difficult, extinction coefficient Cs of 0.4 (m^{-1}) at 1.5m in height from the road surface is usually used (Takekuni 2002).
Although the door closing automatically is to be installed on the wall of an emergency tunnel, if people in the main tunnel escape continuously through the door, there is a risk of smoke advancing into an emergency tunnel. In order to intercept the smoke that comes into the passage in the small tunnel, one solution is to install an interception wall and a door in an emergency tunnel. However, attention must be paid to the point that the width of that portion of the small tunnel might become narrower.

3.2.2 Performance on environment

a) Atmosphere
Since people do not pass along a refuge passage at the time of usual, it considers that air environment of the small tunnel should be the same grade as a driveway.
According to the road tunnel technical standard (ventilation section) (documents on administration), it has been prescribed as follows from the demand on driving operation on the environment of a driveway. In consideration of the comfort and the safety on a run, 50% or more of light transmissivity over 100m should be secured by design speed 80 km/h, and 40% or more by 60 km/h. Carbon monoxide concentration should be 100 ppm or less in consideration of 30 minutes maintenance work in a tunnel
b) Illumination
The performance of illumination in the case of installing a small emergency tunnel in a road tunnel should come from the requirements that safe refuge can be performed. According to the standard for tunnel emergency facilities (documents on administration), illumination required as an escape passage is specified as from 10 to 20 lx of average illumination from a viewpoint of the safety of refuge. So the numerical value can be 10-20 lx for average level illumination.
c) Crime prevention
Since the pedestrians do not usually use emergency passage, there is no necessity of crime prevention performance for small tunnels only for emergency. However, it is necessary to examine necessity of the surveillance and correspondence system in case of a fire.

3.3. Performance of Small Tunnel Only for Sidewalks (Pedestrians)

3.3.1 Performance of Geometry and Structure

a) Width and clearance
According to the Road Structure Ordinance, sidewalks must be 2.0m wide or more and 2.5m high or more.
b) Heat resistance
Heat resistance is not a performance required as a sidewalk. However, if the safety in case of a fire is taken into consideration, it is desirable to use non-flammable material or semi- non-flammable material for sidewalk-tunnel material. The problem is that non-flammable material is not necessarily heat-resistant material. It should be judged from

cost and a social request how far the small tunnel only for sidewalks is asked for heat resistance.

One direction of future examination is to pursue heat resistance so far as the cost does not increase greatly. The other direction is to give up the heat resistance for a sidewalk tunnel and make it easy to combine an emergency tunnel and a sidewalk tunnel.

c) Protection from smoke

Protection from smoke is not a performance required as a sidewalk.

3.3.2 Performance on environment

a) Atmosphere

In Japan, there are following regulations for atmospheric environment.

According to the road tunnel technical standard (document of administration), in the tunnel in which a sidewalk is installed the design concentration for carbon monoxide shall be set up by taking exposure time into consideration, and the design concentration of the smoke or SPM (suspended particulate matter) shall be set up by taking comfort of pedestrians into account. Furthermore, wind velocity should be less than 7 m s^{-1} from a viewpoint of pedestrian's safety and comfort. It also shows that as the relation between smoke transmissivity and unpleasantness, the condition of 60% transmissivity of light over 100m can be described as fairly good state.

On the other hand, according to the environmental quality standard, as for CO, the one day average value of 1-hour values shall be 10 ppm or less and the 8-hour average value of 1-hour values shall be 20 ppm or less. Moreover, as for SPM the one day average value of 1-hour values shall be 0.1 mg m^{-3} or less and the 8-hour average value of 1-hour values shall be 0.2 mg m^{-3} or less, and as reference it shows that the petition of residents' displeasure will increase by three or more beyond 0.6 mg m^{-3}.

On the other hand, according to the labour sanitary standard, the limit of carbon monoxide concentration for the exposure of 8-hour labour per day and 40-hour labour per week shall be 50 ppm and the limit of carbon monoxide concentration for the exposure of several hours shall be 100 ppm.

A numerical value for the performance on environment can be considered as the following.

? Smoke

On the basis of the road tunnel technical standard, 60% of transmissivity over 100m which is the same as $K_{VI}=0.51x10^{-2}$ (m^{-1}) by natural logarithm concentration expression is supposed to be the value for smoke.

On the basis of the environmental quality standard, SPM is supposed to be less 2.0-6.0 mg m^{-3} from the comfort to the body.

However, since it is unknown whether the above values show the same smoke level, examination is still required.

? Carbon monoxide : 100ppm

? Wind velocity 7m s^{-1} or less

b) Illumination

The performance of illumination in the case of installing a small sidewalk tunnel in a road tunnel should come from the requirements that pedestrians do not become unsafe or unpleasant within a pedestrian's walk time through the tunnel.

According to the pedestrian-underground-crossing technical standard (administration document), 50 or more lx of illumination should be set up at the stairs and the passage of an underground pedestrian crossing. Therefore, a numerical value is supposed to be 50 or more lx of average level illumination.

c) Crime prevention
When sidewalk in a road tunnel is covered up from the driveway, drivers can not see what happens on the sidewalk. This condition is considered to be likely to generate crimes resulting in the mental pressure to pedestrians. In a survey of pedestrian's feeling by questionnaire, the proposal of no transparent boards on the wall of small sidewalk tunnel has been refused, and all large majorities has supported the proposal using transparent boards.
Then, as the required performance from a viewpoint of preventing a crime, attention to prevent the crime resulting from the closed space must be paid in the design of small sidewalk tunnel.
For this, while using a transparent boards for the side wall of a sidewalk tunnel , it is possible to install emergency warning equipment or the television for surveillance, if necessary. However we have demerits in implementing such measures. The transparent board becomes the hindrance of the heat-resistant characteristic so that it becomes difficult to make a double purpose small tunnel for both sidewalk and emergency service. Moreover, the television for surveillance needs some staffs to keep the management, which raises the cost of maintenance. In the previous Utatsu tunnel, the monitors of camera and television have been set up at the portals and in the sidewalk tunnel itself, which gives the presence-of-situation inside sidewalk tunnel to the majority of pedestrians walking at that time. Such method could make better performance by using the Internet and giving the presence-of-situation inside sidewalk tunnel not only to the majority of pedestrians but also to the people in public.

4. CONCLUSION

The required performance of small sidewalk or emergency tunnels in road tunnels has been examined and the main results are as follows.
As for the heat resistance of the small tunnel only for emergency , heat resistance for JIS curvilinear 20 minutes seems most in accordance with current building fire regulations. As a future research subjects, there are possibilities of the necessity for 60-minute heat resistance. In order to make cost down, it is necessary to take the difference of temperature in a fire section into account and also to examine the appropriate fire scale to assume.
As for the environment requirements of the small tunnel only for sidewalks, SPM of less 2.0-6.0 mg m^{-3} has been proposed from the comfort to the body and the natural logarithm smoke concentration below K_{VI}=0.51x10^{-2} (m^{-1}) also has been proposed from how to be visible.

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SAFETY STANDARDS FOR ROAD AND RAIL TUNNELS – A COMPARATIVE ANALYSIS

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Introduction

The development of common European Union directives for underground road and rail transportation provides important evidence of what constitutes a minimum safety standard for underground transportation safety in the European Union.

These directives are an important articulation of European practice but are, as a matter of law, evidence (not proof) of what may constitute sound practice in Europe and potentially elsewhere in the world.

This does not render each member states countries domestic regulations, practices and codes obsolete – nor does it deem them inappropriate or unsafe. However it does provide more evidence of what constitutes current European safety practices.

The effect of the Directives is to provide evidence of what constitutes a minimum European level of safety. The central obligation of engineers to exercise due professional care remains intact even where there are directives in place,

This paper briefly explores the regulatory frameworks of Germany, Switzerland in comparison with the EU Road Tunnel directive to illustrate the differences in approach – and then explores Japans approach to the same issues to illustrate an alternative, but none the less appropriate response. Such differences are to be expected when comparing Road and Rail tunnel guidelines from around the world.

Ultimately the peculiarities of each project demand each tunnel be designed and be considered on its own merits – and even where compliance is deemed to meet all requirements there will remain circumstances were engineering judgement may still need to be exercised when determining aspects of the final design and operation.

Multiple Guidelines

It is to be expected that there will be many differences between what is required under European Union Road Tunnel and Rial Tunnel requirements and that which is required within each of the EU member states. The reasons for these variations are numerous – such variations are to be expected and managed.

This means that for a long road or rail journey the nature of the risks may change along a single journey. The “changes” to the risk profile do not prove that the level of risk has changed unacceptably – nor does not follow logically that such changes are conclusive proof that parts of the journey is unsafe, or that appropriate standards have not been met.

However it does mean that it is a comparatively simple task to document the differences between countries – and subsequently make assertions about the appropriateness of achieved levels of safety after a serious safety incident..

Congested Unidirectional Tunnels – Comparative Ventilation EU - D - CH

A simple comparative analysis of the German, Swiss and EU directive for roads tunnels illustrates the variation in requirements in road tunnels between the Trans European network, Germany and Switzerland.

For illustrative purposes the table summarises the guidelines for, unidirectional congested Tunnels of differing lengths.

The simplified analysis is tabulated in figure 1. (Guidelines for unidirectional tunnels of differing lengths)

INFORMATIVE SUMMARY OF MINIMUM REQUIREMENTS

Tunnel Category: **Congested Unidirectional**

KEY
○ Not Mandatory for all Tunnels
■ Final decision after predetermined risk analysis conducted
● Mandatory for all Tunnels

Origin of guideline	Category	Tunnel Length (M) <400m	400-500m	500-600m	600-800m	800-1000m	1 000 - 1200 m	1200 - 1500 m	1500-3000m	>3000m	Comment
DIRECTIVE (EU)	Mechanical ventilation	○	○	○	○	○	●	●	●	●	May be varied if risk assessment demonstrates acceptable in special circumstances
	Special provisions (fresh air ducts and/or smoke extraction)	○	○	○	○	○	●	●	●	●	May be varied if risk assessment demonstrates acceptable in special circumstances
Germany (D)	Mechanical ventilation	○	●	●	●	●	●	●	●	●	Detailed decisions about smoke extraction etc driven by requirements of fire case.
	Special provisions (fresh air ducts and/or smoke extraction)	○	●	●	●	●	●	●	●	●	Detailed decisions about smoke extraction etc driven by requirements of fire case.
Switzerland (CH)	Mechanical ventilation	○	○	○	○	●	●	●	●	●	Lower Risk -Ventilation decisions driven by risk analysis .
		○	○	○	●	●	●	●	●	●	Higher Risk - Ventilation decisions driven by risk analysis
	Special provisions (fresh air ducts and/or smoke May extraction)	○	○	○	○	■	■	■	●	●	. Lower Risk -Ventilation decisions driven by risk analysis
		○	○	○	■	●	●	●	●	●	Higher Risk - Ventilation decisions driven by risk analysis

Figure 1: (Simplified summary of EU, D and CH Guidelines for unidirectional congested tunnels of differing lengths)

It is apparent from the table that there are a range of requirements between Switzerland, Germany and the EU directive for ventilation.

The most notable areas of variation of approach between the EU and both member states is that in Germany and Switzerland mechanical ventilation is required in shorter tunnels than prescribed by the EU. Furthermore detailed risk analysis is critical in the ventilation choices – particularly in tunnels less than 1000m long.

As between Germany and Switzerland there are also differences. For example In Germany the requirement for ventilation commences in shorter tunnels than in Switzerland, and

Switzerland appears to retain more design flexibility for ventilation in non congested longer Tunnels than Germany.
Under the draft EU road directive congested tunnels in excess of one thousand metres require mechanical ventilation, and if the ventilation type chosen is longitudinal – other safety measures are required too.

> *2.9.2. A mechanical ventilation system shall be installed in all tunnels longer than 1 000 m with a traffic volume higher than 2 000 vehicles per lane.*
>
> *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.*
>
> *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 according to 2.9.3. These systems shall be able to exhaust smoke in case of fire.*

(Draft EU Directive on minimum safety requirements for tunnels in the Trans-European Road Network)

As illustrated above under Articles 2.9.3 and 2.9.4 tunnels with congested unidirectional traffic are directed not to have longitudinal ventilation unless a prescribe risk assessment demonstrates such a ventilation system is acceptable given the particular circumstances of a tunnel including traffic management, emergency exit distances and smoke exhaust intervals. The preference is for transverse or semi transverse ventilation systems which are able to exhaust smoke in the case of a fire.

The following table extracted from the draft Road Directive which appears at direction 2.1(ix) of the EU Road Tunnel Directive does not prescribe at what length smoke extraction is required nor the circumstances in which it would be necessary.

● mandatory for all tunnels ❍ not mandatory
* mandatory with exceptions ◐ recommended

INFORMATIVE SUMMARY OF MINIMUM REQUIREMENTS			Traffic ≤ 2 000 veh. per lane		Traffic > 2 000 vehicles per lane			Additional conditions for implementation to be mandatory, or comments
			500-1 000 m	>1 000 m	500-1 000 m	1 000-3 000 m	>3 000 m	
Lighting	Normal lighting	§2.8.1	●	●	●	●	●	
	Safety lighting	§2.8.2	●	●	●	●	●	
	Evacuation lighting	§2.8.3	●	●	●	●	●	
Ventilation	Mechanical ventilation	§2.9	❍	❍	❍	●	●	
	Special provisions for (semi-) transverse ventilation	§2.9.5	❍	❍	❍	❍	●	Mandatory in bi-directional tunnels where there is a control centre.
Emergency stations	At least every 150 m	§2.10	*	*	*	*	*	Equipped with telephone and 2 extinguishers. A maximum interval of 250 m is allowed in existing tunnels.
Water supply	At least every 250 m	§2.11	●	●	●	●	●	If not available, mandatory to provide sufficient water otherwise.
Road signs		§2.12	●	●	●	●	●	For all safety facilities provided for tunnel users (see Annex III).
Control centre		§2.13	❍	❍	❍	❍	●	Surveillance of several tunnels may be centralised into a single control centre.
Monitoring systems	Video	§2.14	❍	❍	❍	❍	●	Mandatory where there is a control centre.
	Automatic incident detection and/or fire detection	§2.14	●	●	●	●	●	At least one of the two systems is mandatory in tunnels with a control centre.
Equipment to close the tunnel	Traffic signals before the entrances	§2.15.1	❍	●	❍	●	●	
	Traffic signals inside the tunnel at least every 1 000 m	§2.15.2	❍	❍	❍	❍	◐	Recommended if there is a control centre and the length exceeds 3 000 m.

Figure 2: *(Extract from draft EU Road Directive)*

In Germany the requirement for smoke requirement could arise in unidirectional tunnels exceeding 600 metres in length but would depend upon detailed risk assessment. Once such tunnels exceed 1200 metres in length smoke extraction using adjustable dampers and a false ceiling would be required. (See Figure 1)

In Switzerland smoke extraction would be required for high risk tunnels over 800 metres in length (or over 1500 metres in tunnels determined to have a lower safety risk).

In Austria the approach taken would be similar to that adopted in Germany however the ultimate decision will be dependent upon detailed design aspects of the proposal including traffic volume, length and gradient.

From the brief summary from Germany, Austria and Switzerland noted above it is apparent that a range of design options could legitimately arise by applying the local member countries guidelines. Each of these local design outcomes may legitimately be different to the minimum requirements contained in the EU Directive.

For an excellent review of the key regulatory requirements in Europe there is currently no better source of data than at www.etnfit.net. That source provides summary documentation and is continually being updated.

For the engineer responsible for the design, operation or refurbishment of road tunnels this variation in guidelines creates a potential regulatory dilemma.

Should the prudent engineer follow the EU Directive because it is comparatively recent and compiled as a result of the deliberations of many experts from all of the EU countries, or should they be persuaded by the domestic regulatory environment?

The answer – as a matter of law – is clear.

In order to discharge the engineer's professional obligations it is necessary to turn their expert skills to the question of what is appropriate in the circumstances of the particular tunnel. Even where there are laws prescribing what must be done there is an overarching legal policy requirement that the engineer be satisfied that what is proposed is appropriate.

Is there a *correct engineering* answer?

While the performance of each of the design outcomes under the minimum EU Directive requirements or those required under each countries laws may be different, it does not follow that any of the designs are acceptable or unacceptable.

In extreme circumstances minimal compliance with the EU Directive might not discharge the legal responsibility of the engineers.

By way of further example there could be unusual HGV traffic using the trans European network in that area which rendered the minimum treatment measures contained within the EU Directive ineffective from a safety perspective.

Likewise circumstances may exist where strict adherence to a countries tunnel regulation might discharge the engineer's obligations.

However design construction operation of these facilities in accordance with the accepted or prescribed national regulatory regime provides strong evidence that the design in question is appropriate.

There are many cases in all jurisdictions which illustrate this point.

For example the highest Australian Court stated it early last century as;

> –*"The mere fact that a defendant follows common practice does not necessarily show that he is not negligent, though the general practice of prudent men is an important evidentiary fact. A common practice may be shown by evidence to be itself negligent"* *Mercer v Commissioner for Road Transport and Tramways* (1936) 56 CLR 580 per Latham CJ at 589 §*Lettice v. Council of the Shire of Muswellbrook[2000] NSWSC 81*

Or more recently,

–*"a finding of want of due care can properly be made even though the defendant has obeyed all statutory requirements and followed a common or universal practice."*

Podmore v. Aquatours Pty Ltd (1984) NSWLR 111 at p 116

Accordingly as engineers there is an obligation to understand and properly apply due professional skill to tunnel safety.

Divide and conquer ?

There are differences between the regulatory environment the different member states and countries (often neighbouring each other), the EU directive and other standards (such as in the United States of America and Australasia). It is not uncommon outside the EU for neighbouring jurisdictions to have differing standards. (eg Hong Kong and Mainland China, Korea and Japan, Victoria and New South Wales – Australia, New York State and Pittsburgh USA.)

The following table summarises the requirements for safety equipment in the Japanese Road Authorities Jurisdiction.

The first stage of the Japanese process is characterisation of the tunnel type. (see fig3). From this table tunnel risks are characterised from a length/ traffic number perspective.

Table 2-2 Types of safety facilities (MOLIT)

Class	Safety facility	AA	A	B	C	D
Communication/ alarm facilities	Emergency telephone	O	O	O	O	
	Push button	O	O	O	O	
	Fire detector	O	Δ			
	Emergency alarm	O	O	O	O	
Fire-extinguish facilities	Fire extinguisher	O	O	O		
	Fire hydrant	O	O			
Evacuation guidance facilities	Emergency guidance panel	O	O	O		
	Smoke extractor, evacuation route	O	Δ			
Other facilities	Water supply hydrant	O	Δ			
	Leaky feeder system	O	Δ			
	Radio (re-) broadcast, loudspeaker system	O	Δ			
	Water sprinkler *	O	Δ			
	Monitoring equipment	O	Δ			

O: Must be installed, Δ: Installed if deemed necessary

* Water sprinklers are not regarded as equipment for fire extinguish

Figure 3: (extracted from Bouwdienst Rijkswaterstaat Directoraat-Generaal Rijkswaterstaat Ministry of Transport, The Netherlands Sprinklers in Japanese Road Tunnels Final Report December 2001 Chiyoda Engineering Consultants Co.,Ltd.

The second stage describes what is required. (See fig 4)

Table 2-3 Safety facilities per tunnel category (JH)

Safety facility		Classification	AA	A	B	C	D	Remarks
Information and alarm	Emergency telephone		O	O	O	O	O	Not in D-Class tunnels with L<= 200m
	Push button		O	O	O	O		
	Fire detector		O	O				Not in tunnels without ventilation system
	Emergency alarm equipment	At tunnel entrance	O	O	O	O	O	Not necessary in tunnels with L<= 200m
		In tunnel	O	Δ				Necessary in A-Class tunnels with L>= 3,000m
Fire extinguishing	Fire extinguisher		O	O	O	O	O	
	Fire hydrant		O	O	Δ			To be installed in B-Class tunnels with L>= 1,000m
Escape and guidance	Emergency guidance panel	Emergency exit light	To be installed in tunnels with evacuation routes					
		Guide board (A)	To be installed in tunnels with evacuation routes					
		Emergency exit sign	To be installed in tunnels with evacuation routes					
		Guide board (B)	O	O	O			To be installed in tunnels without evacuation routes
	Smoke extractor, evacuation route		– Evacuation routes installed in tunnels with L>= 750m – Smoke extraction installed in tunnels with L>= 1,500m – Install evacuation routes in AA-Class tunnels and in A-Class tunnels with L >= 3,000m, with bi-directional traffic and longitudinal ventilation					
Other equipment	Water supply hydrant		O	O	Δ			To be installed in B-Class tunnels with L >= 1,000m (water ports near portal).
	Leaky feeder system	Coaxial cable	O	Δ				Necessary in A-Class tunnels with L >= 3,000m
		Entrance/exit telephone	O	O				
	Radio (re-) broadcast		O	Δ				Necessary in A-Class tunnels with L >= 3,000m
	Loudspeaker system		Installed in tunnels with radio (re-broadcasting equipment)					
	Water sprinkler		O	Δ				Necessary in bi-directional A-Class tunnels with L >= 3,000m and more than 4,000 vehicles/day
	Monitoring equipment	Type A (200m interval)	Installed in tunnels with sprinklers					
		Type B (at lay-by)		Δ				Necessary in A-Class tunnels with L >= 3,000m
	Emergency lighting equipment		Installed in tunnels with L >= 200m					
	Emergency power supply	Generator	Installed in tunnels with L >= 500m					
		Uninterruptible power supply	Installed in tunnels with L >= 200m					

O: must be installed, Δ: installed if deemed necessary

Figure 4: (extracted from Bouwdienst Rijkswaterstaat Directoraat-Generaal Rijkswaterstaat Ministry of Transport, The Netherlands Sprinklers in Japanese Road Tunnels Final Report December 2001 Chiyoda Engineering Consultants Co.,Ltd.)

The Japanese approach can readily be compared to the EU approach which is summarised in Figure 2. It is systematic, and considered – but different to EU and member state systems

There is no "correct" approach. Each system will perform differently. The differences in performance may be critical for management of a particular event – say a vehicle fire. In a long busy Japanese tunnel ("aa" type) water deluge sprinklers are prescribed.

Under a range of scenarios the use of water deluge sprinklers could impact injury rates and infrastructure damage. The nature of the impact will depend upon the scenario. The range of potential impacts extends from positive to negative. If the impact is negative (ie more injuries) it could be argued that prescribing the water deluge system was wrong. If no one is injured – it is unlikely to be more than an obscure statistical reference in an operators log book.

Understanding regulatory differences

These types of regulatory variations provide an opportunity to argue subsequent to a safety event that not only was a particular design defective but that had the design practices of another jurisdiction been followed injuries would have been avoided.

The impetus for such argument should not be underestimated and the sentiments and dissatisfaction of the public towards a legal system which does not find liability subsequent to a tragedy are well illustrated by a number of engineering related tragedies in recent years.

The role of standards was recently highlighted when an Austrian court in Salzburg acquitted 16 people of the responsibility for the Kaprun ski train blaze that killed 155 tourists in November 2000. In the determination of the court the Judge noted that:

> *"the train confirmed to the latest technical standards and all requirements were fulfilled".*

Importantly the Judge accepted the defendants' arguments that no-one could have foreseen the chain of events that lead to the deaths and that none of the defendants had any reason to suspect that the heater was not up to standard.

The importance of considered engineering decision making underlies all guidelines. These guidelines are tools to assist engineers perform – not recopies which guarantee success.

Conclusions

A comparative analysis between road and rail directives and member nation guidelines readily demonstrates the vast range of design and operational options articulated globally with respect to underground transportation safety.

There is such variation in key safety parameters such as ventilation, lighting, emergency evacuation, control systems and pedestrian ways that expert engineering decisions are still required. The common EU position – as expressed in the draft EU Tunnel Directive is an extremely useful articulation of minimum requirements –but is not, and could never be, the safety standard for the European Union.

The domestic regulations in Member States remain extremely important documents in determining appropriate conduct. The variation in approaches highlighting the importance of providing considered advice no matter what conclusion is arrived at following a systematic analysis of a safety critical issue.

It is the differences between regulatory approaches which highlight the increasing importance of informed expert decision making for professional management of underground transportation safety.

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