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“TUNNEL SAFETY AND VENTILATION”
Graz, Mai 12 - 13, 2014

POSTERPRESENTATIONS

PREFACE

Ladies and Gentlemen, Dear Participants,

In 2002, the Institute of Internal Combustion Engines and Thermodynamics organized an International Conference on Tunnel Safety and Ventilation. The aim of that conference was to provide a forum for information exchange among operators, users, technicians, scientists and companies involved in the design, construction and equipping of road and rail tunnels. The success of the 2002 conference led to the organization of biennial follow up meetings.

Each conference has been accompanied by an exhibition, and each year, like the conference itself, the exhibition has grown. The success of the exhibitions has forced us to leave the confines of our University campus and to move to the roomier facilities of the trade fair centre.

Our interests and focus have also changed and this is reflected in our topics. The first conferences were strongly influenced by the tunnel incidents of the late 1990's and related safety issues. Nowadays road tunnel operation, the conflict between the needs for upgrading existing road tunnels and requirements given in a legal framework dominate.

Traffic is increasing, at both a national as well as an international level. Thus, while in densely populated areas there is much greater demand for sub-surface transportation, in rural areas there is an increasing need to upgrade the road infrastructure. The implementation of the EU Directive on the minimum safety requirements for tunnels in the trans-European road network (2004/54/EC) forced many of the tunnel operators to upgrade the existing tunnels.
Many of the existing tunnels (i.e. those 20 to 30 years old), are currently being refurbished and upgraded by the addition of a second tunnel tube. The upgrading process as well as the construction of second tubes constitutes a big challenge in practice, as – in contrast to new tunnel construction – several prevailing structures and systems act as constraints and have to be taken into consideration in planning. There is also the additional need to ensure that traffic flow can be maintained throughout the construction period.

The question of tunnel safety is a highly controversial field. It is often claimed that several new techniques are now on the market and that these can help improve safety due to quicker and more reliable detection, more efficient installations and/or additional equipment. However, such 'improvements' often result in significant increases in complexity, as well as in the cost of operation and maintenance of the new safety equipment.

Cost benefit analyses combined with risk assessment studies provide a valuable tool when attempting to deal with questions of safety at an acceptable cost level. The time is now right for us to discuss what safety standards are required in our tunnels and at what price. We hope that the present conference will be of some value in such a discussion.

This conference wouldn't be the "Graz" conference without the related exhibition. Many companies have put a lot of effort into presenting their latest developments and technologies. Conference participants now have the chance to get into contact with leading companies in the electro-mechanical tunnel business, to establish new contacts, and also to strengthen existing ones.

Another exciting and distinguishing aspect of the “Graz” conference is its live fire test. This final highlight of the conference will be performed in the Plabutsch Tunnel close to the city of Graz. In fact the conference returns to the location where its first fire test took place in 2004. Many thanks to the tunnel operator ASFiNAG as well as to the rescue forces (fire brigade of the City of Graz, Red Cross and other relevant organizations). Special thanks to Mrs. Dagmar Jäger, Mr. Alois Knoll, Mr. Josef Heschl from ASFiNAG and to Mr. Gerald Wonner from the fire brigade of the City of Graz as well as to Michael Bacher and Thomas Nöst from our Institute for organizing this test.

We wish to extend a special thank you to our scientific committee for its valuable work in defining the objectives of this conference, and in selecting the presentations.

We also extend our professional thanks to the authors for their hard work in preparing abstracts, papers, posters, and of course their presentations.

And finally, we wish to offer our sincere thanks to all the people in the background who have been working to ensure that this will be a smooth, enjoyable and effective conference for us all.

It is my pleasure to welcome you all on behalf of the conference scientific committee and to wish you all a successful meeting and a sound basis for fertile networking in the future.

Peter J. Sturm

Graz, May 2014

IMPLEMENTATION OF THE EU DIRECTIVE ON MINIMUM SAFETY REQUIREMENTS FOR TUNNELS IN THE TRANS-EURPEAN ROAD NETWORK – STATUS REPORT

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ABSTRACT

This report gives a status of the application of the EU Directive 2004/54/EC in Austria under the Road Tunnel Safety Law for the year 2014.

Because of the high number of the foreseen approval procedures of tunnel preliminary drafts and the putting into operation of tunnels and economic and legal reasons the Road Tunnel Safety Law and the recommendation for the content of safety documentation were adapted twice since 2006.

The Austrian Administrative authority BMVIT fulfilled nearly 200 inspections in the years 2007 till 2012. The collection and analysis of incidents and fires lead to an upgrade of the Austrian tunnel risk model.

Keywords: Tunnel safety management

1. INTRODUCTION

The Austrian Road Tunnel Safety Law STSG BGBl. I Nr. 54/2006 has been in force since May 2006 and represents the basis for the planning, construction and maintenance of the Austrian motorway and expressway tunnels. The implementation of this law was mainly based on the EU Directive 2004/54/EG issued by the European Parliament and the Council on 29 April 2004. But there was an over-compliance in some safety measures, like video monitoring, emergency stations, access for the emergency services, water supply.

With the amendment BGBl. I Nr. 111/2010 the over-compliance was reduced and simplified procedures for modifications of tunnel preliminary drafts and for non-substantial modifications in the structure, equipment and operation were established. Because of economic reasons the deadline for the refurbishment of tunnels outside the Trans-European road network (TERN) was extended to the year 2029. Because of the new Austrian administrative tribunals the Austrian Road Tunnel Safety Law was revised in 2013 again.

2. STATUS OF COMPLIANCE OF EXISTING TUNNELS

In April 2006 59 motorway and expressway tunnels longer than 500m on the TERN and 12 tunnels outside the TERN were in operation. For these tunnels the Austrian administrative authority carried out the first report with the review of safety documentations and inspections of each tunnel. In April 2007 only three tunnels fulfilled the minimum standards of the STSG.

In March 2014 75 tunnels longer than 500m are in operation on motorways and expressways. 15 of them fulfil the minimum standards of the STSG. To reach the minimum standards for 49 tunnels on the TERN the Tunnel-Manager ASFINAG will invest approximately 1.6 billon € till April 2019.

In Austria the implementation of safety requirements focuses especially on the construction of the second tunnel tubes. Figure 1 shows a list of the tunnels on motorways and expressways in Austria, which are already built, are under construction or are in the planning stage.

Tunnel	Road	Length of the tunnel [m]	Second Tube opening date/status
Selzthal	A09	958	Apr.00
Gräbern	A02	2145	Okt.03
Amberg	A14	2967	Dez.03
Plabutsch	A09	10085	Jän.04
Herzogberg	A02	1956	Jun.06
Lainberg	A09	2208	Feb.08
Katschberg	A10	5418	Apr.08
Ganzstein	S06	2100	Aug.08
Roppen	A12	5100	Sep.09
Tauern	A10	6546	Apr.10
Pfänder	A14	6700	Jun.12
Bosruck	A09	5425	Jul.13
Gleinalm	A09	8320	under construction
Klaus	A09	2192	under construction
Spering	A09	2862	under construction
Falkenstein	A09	784	under construction
Perjen	S16	2990	planning stage
Karawanken	A11	7865	planning stage
Total		76621	

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

Only five STSG-Tunnels in the western Austrian region will remain as bi-directional tunnels. One example is the longest tunnel Arlberg, with a length of 13972m , which will be upgraded to the technical state-of-the-art. Fixed Fire Fighting systems and new emergency exits are planned for this tunnel, too.

Furthermore main measures of the implementation work are the construction of emergency exits at a maximum distance of 500m and emergency stations at a maximum distance of 250m and the implementation of measures for the fire resistance. As after more than 20 years in operation most electric equipment in the existing tunnels has normally reached its maximum functional lifespan, the corrective maintenance and upgrading to the technical state-of-the-art leads to significant extra costs.

3. SAFETY DOCUMENTATION

For each tunnel longer than 500m on motorways and expressways in Austria one safety documentation was prepared, which contains all safety-related information about the respective tunnel.

The new guideline 2014 for the preparation of the tunnel safety documentation is now available under the BMVIT web side: http://www.bmvit.gv.at/verkehr/strasse/tunnel/sicherheit/index.html. Examples for the tunnel safety documentation are given by the Tunnel-Manger ASFINAG on the web side: http://www.asfinag.net/Home/Tunnelmanagement.

The new guideline for the preparation of the tunnel safety documentation aims at supporting the consultants and the administrative procedures. Since May 2006 the design of 29 tunnels and the putting into operation of 38 tunnels were approved by the Austrian Administrative authority. Another 26 approvals for the design and 57 approvals for the putting into operation are planed till 2019.

The new guideline for the preparation of the tunnel safety documentation was adapted twice since 2006, because the administrative procedures normally have to be accomplished at a tight time schedule (approx. 14 weeks for the procedure to put into operation a new or refurbished tunnel). So the tunnel safety documentation and the additional documents have to be complete and of good quality.

4. COLLECTTION AND ANALYSIS OF INCIDENTS

The EU Directive 2004/54/EC requires reports on fires in tunnels on accidents, which clearly affect the safety of road users in tunnels, and on the frequency and causes of such incidents.

The Austrian web based data based is in operation since 1.1.2006. Till 15.3.2014 in total 3264 events were collected, covering 68 tunnel fires in the years 2006 till 2012. This new database leads to the evaluation and the new publication of the Austrian Tunnel Risk Modell TuRisMo RVS 09.03.11 [1].

Figure 2 shows the trend of the accident casualties 1999 till 2011 in Austria prepared by the Austrian Road safety board KFV [2] (The red line shows the deaths, the blue line the casualties, the grey line the accidents with casualties).

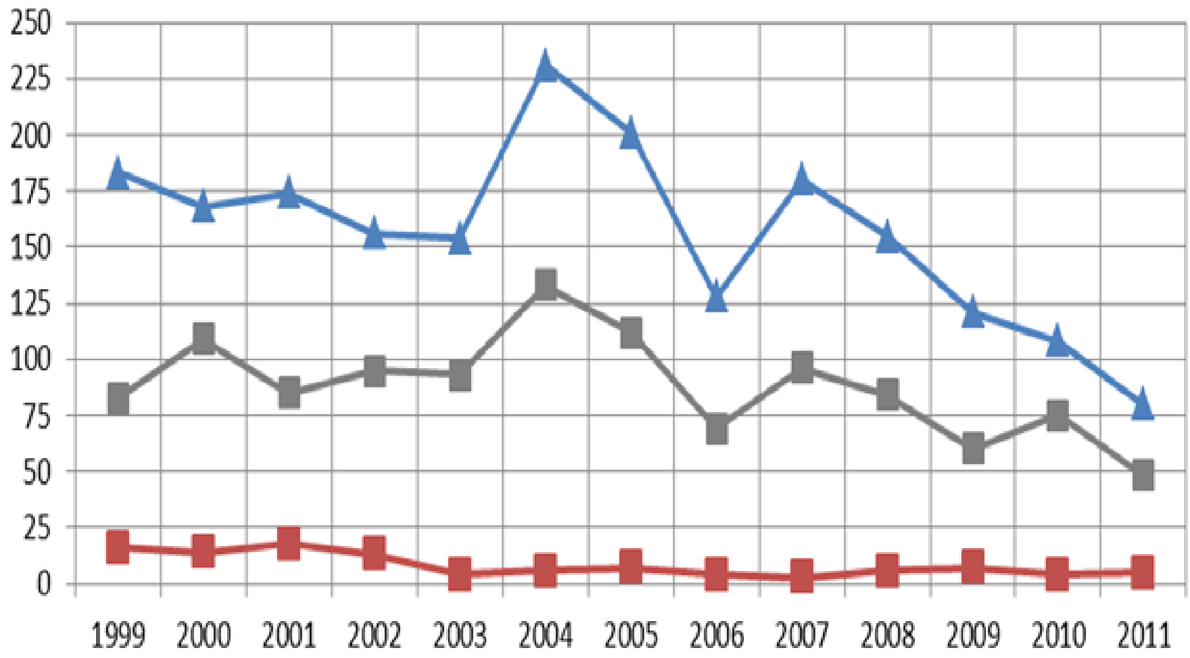

Figure 2: Trend of the accident victims 1999 till 2011 in Austria

In average per year 272 accidents occur without victims. In approximately 40 % of the accidents HGV are involved. In the year 2001 there were 18 deaths, 2013 3 deaths.

5. INSPECTIONS

Because of the EU Directive 2004/54/EC the member states shall ensure that inspections, evaluations and tests are carried out by inspection entities. In Austria the Austrian Administrative authority BMVIT fulfilled nearly 200 inspections in the years 2007 till 2012.

These inspections included detailed inspection of the tunnel and it´s whole safety equipment with fire tests, integral tests, tests of the lightning etc.

Since 2008 the portal areas and the lay-bys were on the inspection list, too, because of 17 deaths in these areas in the years 2006 till 2012. In sum about 650 areas were inspected and corrected according RVS 09.01.24 [3] and RVS 09.01.25 [4].

6. CONCLUSIONS

After more than 8 years of experience with the application of the EU Directive 2004/54/EC in Austria the number of casualties decreases. The Tunnel safety management is now well developed, but causes al lot of approval and inspection procedures in a time with restricted human resources in the authorities. It will be a hard work to reach the minimum safety requirements till April 2019 on the TERN because of economic and terminable reasons in Austria. Due to this the deadline for the refurbishment of tunnels outside the TERN was extended to the year 2029.

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HOW FREQUENT ARE FIRES IN TUNNELS – ANALYSIS FROM AUSTRIAN TUNNEL INCIDENT STATISTICS

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ABSTRACT

The paper combines vehicle fire data, accident data and traffic data from all tunnels within the Austrian primary road network. As a result, a number of key numbers typically required for tunnel risk analyses is derived. This includes the rate of tunnel fires per vehicle kilometre and the distribution of fires intensities as well as the conditional fire probability given vehicle breakdowns or accidents and a number of other relevant results.

Keywords: Vehicle fire, tunnel fire, fire intensity, fire statistics

1. INTRODUCTION

From an international perspective, there has long been a lack of reliable statistics on vehicle fires in road tunnels. The reasons for this are manifold: Small datasets as well as incomplete or inconsistent datasets – often caused by regionally varying data collection practices – account for some of the challenges. Another issue is the lack of a suitable basis of comparison, i.e. the total travelled distance inside all tunnels (both in tunnels with and in tunnels without observed vehicle fires).

Since 2006, the state-owned highway operator ASFiNAG has been collecting vehicle fire data for all Austrian highway and expressway tunnels in a standardised and detailed way, including information on fire causes, fire development, detection, extinguishment and many more. This dataset is compared to a complete accident dataset and a complete traffic dataset from the same period, allowing for a number of new and more precise statements on tunnel fires.

The present paper addresses a number of issues, including

- the rate of vehicle fires in tunnels per travelled kilometre and vehicle type
- the rate of spontaneous vehicle fires per vehicle breakdown
- the rate of crash-induced fires per accident and vehicle type
- the probability of stopping a burning vehicle in front of the tunnel or driving the burning vehicle out of the tunnel
- the distribution of different fire intensities and their correlation with fire brigade deployment times
- the contribution of different types of fire detection and fire extinguishment

2. DATA

2.1. Fire incident data

The analysis is based on the tunnel fire database of the Austrian motorway and expressway operator ASFiNAG. It covers the period between May 2006 and January 2013, i.e. roughly 2006-2012. During this period, ASFiNAG registered 67 independent occurrences of vehicle fires in tunnels, excluding trivial events.

2.2. Traffic data

Traffic data are needed in order to estimate the fire rate in tunnels per travelled vehicle kilometre. Annual average daily traffic (AADT) values are taken from the ASFiNAG road section register for the year 2010 and scaled to the duration of the observation period for fire incidents. The road section register indicates separate AADT values for vehicles up to 3.5 tonnes (cars) and vehicles above 3.5 tonnes (HGVs and busses), respectively.

2.3. Breakdown data

The applied rate of breakdowns per vehicle kilometre is based on observations at the Tauern and Katschberg tunnels in Austria and has been validated against other European road tunnels. The underlying data were collected and analysed as part of the previous version of Guideline RVS 09.03.11 TuRisMo (FSV, 2008).

2.4. Accident data

Data on vehicle accidents in motorway and expressway tunnels are needed in order to estimate the conditional fire probability in case of a vehicle accident. For the present analysis, a dataset from ASFiNAG covering the years 2006-2009 is used (scaled to the duration of the observation period for fire incidents).

3. FREQUENCY OF VEHICLE FIRES IN TUNNELS

The vehicle fires observed in 2006-2012 are roughly split in two halves between car fires on one hand and HGV and bus fires on the other hand (Table 1). Approximately 90 % of the events can be categorised as spontaneous ignitions, whereas 7 % were caused by accidents, i.e. collisions.

In the case of car fires, 13 % of the events were caused by accidents, whereas only 3 % (1 event) of the HGV and bus fires occurred in the aftermath of a collision. In fact, the only case of an accident-induced HGV fire occurred after a collision with a car, where the car caught fire in the first place and the fire subsequently flashed over to the HGV.

Table 1: Total number of vehicle fires in Austrian motorway and expressway tunnels (2006-2012)

Fire cause	Cars (vehicles ≤ 3.5 tonnes)	HGVs and busses (vehicles > 3.5 tonnes)	Total[1]
Spontaneous ignition	32	28	60
Accident	5	1	6
- single vehicle accident	*2*	*0*	*2*
- collision front-front	*2*	*1*	*3*
- collision front-rear end	*1*	*0*	*1*
Unknown	1	1	2
Total	38	30	68

[1] In one of the events, both a car and an HGV caught fire. Thus, the total value is not always equal to the sum of car and HGV/bus fires.

The numbers include vehicle fires at and next to the portals (11 out of the 67 events). These events need to be treated as regular tunnel fires; if the driver had not intentionally stopped the burning vehicle in front of the tunnel, or if he/she had not intentionally driven the burning vehicle out of the tunnel, most cases would have ended as fires inside the tunnel. The probability of stopping inside the tunnel depends on the vehicle type, as discussed below (Section 3.4).

3.1. Fires per travelled vehicle kilometre

In order to determine the fire rate in tunnels, the number of travelled vehicle kilometres in all motorway and expressway tunnels needs to be known, including tunnels where no fires have been observed. In Table 2, this number is compared to the number of fires for different vehicle types. Apparently, HGVs and busses are 6 times more susceptible to catching fire than cars.

Table 2: Rate of vehicle fires in Austrian motorway and expressway tunnels

Vehicle type	Number of fires	Travelled vehicle km in tunnels (2006-2012)	Fires per billion km
Cars (vehicles ≤ 3.5 tonnes)	38	9.1 billion	4.2
HGVs and busses (vehicles > 3.5 tonnes)	30	1.2 billion	25.0
All vehicles	67	10.3 billion	6.5

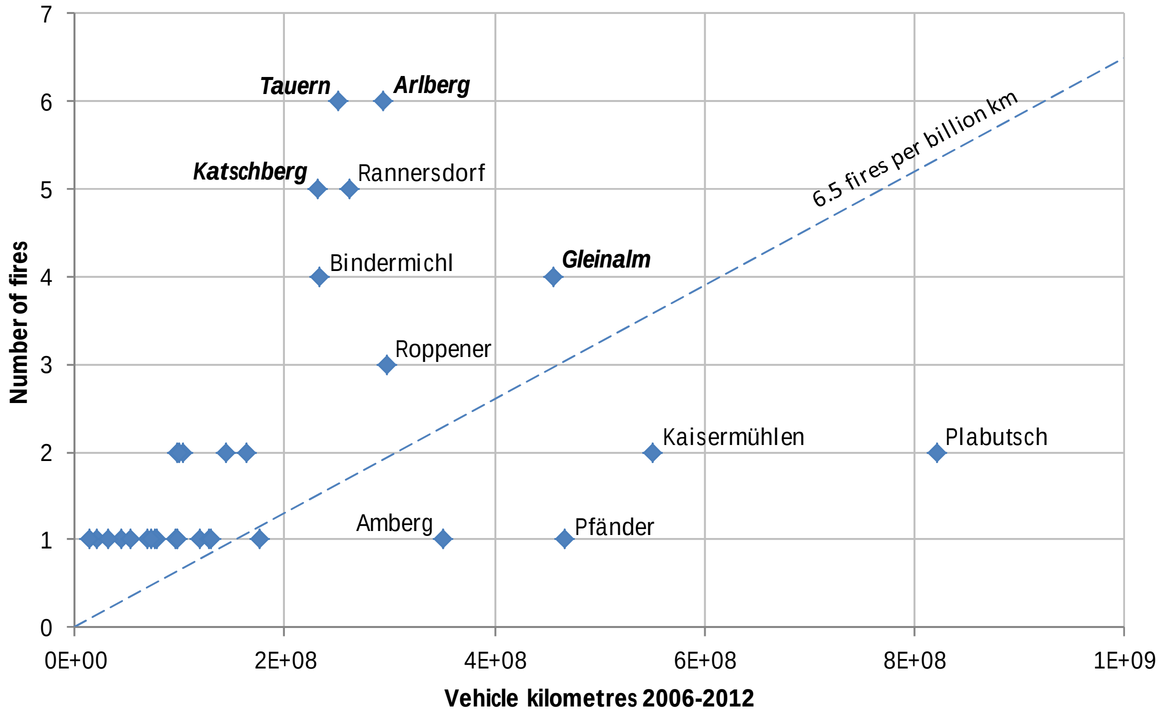

Figure 1: Number of fires vs. travelled vehicle kilometres in different Austrian tunnels (tunnels with long and steep approaches *in italics*)

Figure 1 illustrates the relationship between travelled vehicle kilometres and number of fires for all tunnels with at least one fire. It appears that tunnels with long and steep approaches have an above-average incidence of tunnel fires. Here, HGVs run at the limit of their engine capacity and are thus subject to the risk of overheating.

3.2. Probability of fire after vehicle breakdown

Table 3 relates the number of spontaneous fires in tunnels to the number of breakdowns. Unfortunately, no separate breakdown statistics for cars and HGVs/busses have been available.

Table 3: Fires per vehicle breakdown in tunnels

Vehicle type	Spontaneous fires per million km travelled in tunnels	Breakdowns per million km travelled in tunnels	Fires per 1,000 vehicle breakdowns
Cars (vehicles ≤ 3.5 tonnes)	0.0035		1.5
HGVs and busses (vehicles > 3.5 tonnes)	0.0234	2.372	9.9
All vehicles	0.0058		2.5

3.3. Probability of fire after accidents with casualties

Table 4 relates the number of accident-induced vehicle fires to the number of accidents with casualties. The reasons for referring to accidents with casualties rather than to all accidents are twofold:

- Using only accidents with casualties excludes trivial accidents that are unlikely to result in a fire.
- Accidents with casualties require a police record and are generally registered in a more consistent and reliable way.

In the case of cars, roughly one percent of the accidents with casualties lead to a fire. In the case of HGVs and busses, the number is approximately 0.4 %. Since the latter result is based on a single event, the 95 % confidence interval is relatively large (0.1 to 2.2 %).

Splitting the five observed cases of accident-induced car fire up into different accident categories for further analysis may appear delicate; nevertheless, the resulting conditional fire probabilities are in line with the intuitive ranking of accident hazardousness: Front-front collisions (2.0 % fire probability) are followed by single-car accidents (1.2 %) and front-rear end collisions (0.6 %).

Table 4: Fires per accident with casualties in tunnels

Vehicle type	Fires due to accidents	Accidents with casualties (scaled up to 2006-2012)	Fires per 1,000 accidents with casualties
Cars (vehicles ≤ 3.5 tonnes)	5	523	9.6
HGVs and busses (vehicles > 3.5 tonnes)	1	245	4.1

3.4. Probability of stopping inside the tunnel given spontaneous vehicle fire

As discussed at the beginning of this section, vehicle fires at and next to the portals need to be included in the fire statistics, since they are only prevented from occurring inside the tunnel by intentional and responsible action of the respective driver. For risk analyses, it is relevant to know the likelihood of such behaviour. Table 5 describes the conditional probability of a vehicle stopping inside the tunnel given spontaneous vehicle fire.

It is striking that HGV and bus drivers (75 % of the burning vehicles stopped inside the tunnel) generally react more appropriately than car drivers (almost 100 % stopped inside the tunnel). Considering the high hazard potential of HGV and bus fires, this is an important finding.

Table 5: Probability of stopping inside the tunnel given spontaneous vehicle fire

Stopped inside tunnel?	Number		Fraction	
	Car	HGV/bus	Car	HGV/bus
Yes	30	21	94 %	75 %
No	2	7	6 %	25 %
Total	32	28	100 %	100 %

4. FIRE INTENSITY

4.1. Fire intensity distribution

The analysis of the distribution of fire intensities is limited to spontaneous vehicle fires. The number of vehicle fires due to accidents is too small for a sensible investigation. Due to the high mechanical energy released during accidents with casualties it can be assumed that the ensuing fire is generally in the highest intensity class (fully-developed fire).

Tables 6 and 7 describe the intensity distribution of spontaneous fires in tunnels for cars and HGVs/busses, respectively. In the case of cars, two intensity classes have been introduced (fully- and non-fully-developed fire). In the case of busses and HGVs, fully-developed fires have been subdivided further into fire of the cabin including the engine compartment (typically 10-15 MW) and fire of the entire vehicle (typically beyond 30 MW and sometimes up to 100 MW and more).

More than a third of all spontaneous car fires and half of the HGV/bus fires are categorised as fully developed. In the case of HGVs and busses, 11 % of the fires (21 % of the fully-developed fires) belong to the highest category where the entire vehicle is on fire.

Table 6: Intensity of spontaneous car fires in tunnels

Maximum intensity	Number of events	Fraction
Fully-developed fire	12	37 %
Non-fully-developed fire	20	63 %
Total	32	100 %

Table 7: Intensity of spontaneous HGV and bus fires in tunnels

Maximum intensity	Number of events	Fraction
Fully-developed fire (entire vehicle)	3	11 %
Fully-developed fire (cabin only)	11	39 %
Non-fully-developed fire	14	50 %
Total	28	100 %

4.2. The effect of the approach duration of the fire brigade

Another relevant aspect is the effect of the fire brigade and its approach duration. The approach duration is defined as the period of time between fire detection (roughly equal to the alarm time) and the arrival of the first fire engine at the fire site.

The relevant numbers are available for 11 out of 14 fully-developed HGV and bus fires in tunnels. Two of them covered the entire vehicle, whereas the remaining nine were limited to the cabin (Table 8). Although the statistical sample is rather small, the numbers appear to support the notion that shorter approach duration leads to fewer fires extending to the entire vehicle.

Table 8: Intensity of spontaneous HGV/bus fires vs. approach duration of the fire brigade

Maximum intensity	Number of events with known approach duration	Average approach duration [minutes]	Standard deviation [minutes]
Fully developed fire (entire vehicle)	2	17.0	4.0
Fully developed fire (cabin only)	9	13.9	6.6
Fully developed fire (total)	11	14.5	6.3

5. FIRE DETECTION AND EXTINGUISHMENT

Table 9 indicates the means of fire detection registered. In some of the events, more than one means of detection was used, which is why the number of fire detection reports is larger than the number of fires.

In 87 % of the car fires, professional services (operator personnel, automatic detection, emergency forces) detected the fire. In 48 % of the cases, the driver of the burning car or other traffic participants detected the fire. In the case of HGVs and busses, the respective numbers were 77 % for professional services and 30 % for drivers and other traffic participants.

Table 9: Detection of vehicle fires in tunnels

Means of fire detection	Number		Fraction	
	Car	HGV/bus	Car	HGV/bus
Operator personnel	11	6	29 %	20 %
Automatic detection	16	12	42 %	40 %
Police, fire brigade etc.	6	5	16 %	17 %
Manually actuated alarm	4	1	11 %	3 %
Emergency telephone	13	5	34 %	17 %
Mobile telephone	1	3	3 %	10 %
Others	4	6	11 %	20 %
Total number of reports	55	38	145 %	127 %
Total number of fires	38	30	100 %	100 %

In terms of extinguishment, there is only little difference between cars and HGVs/busses (Table 10). In both cases, one third of the fires were put out by the driver, while the rest were extinguished by professional services (fire brigade, operator personnel etc.).

Table 10: Extinguishment of vehicle fires in tunnels

Extinguished by…	Number		Fraction	
	Car	HGV/bus	Car	HGV/bus
Driver	11	10	29 %	33 %
Professional services (fire brigade etc.)	27	20	71 %	67 %
Total	38	30	100 %	100 %

6. IMPLEMENTATION OF THE RESULTS IN GUIDELINE RVS 09.03.11 (TURISMO)

Many of the findings described in this paper have been directly incorporated into the latest version of Guideline RVS 09.03.11 Tunnel Safety/Methodology of Risk Analysis (TuRisMo) issued by the Austrian Association for Research on Road-Rail-Transport (FSV, 2014). This includes

- the rate of vehicle fires in tunnels per travelled kilometre
- the probability of fire given vehicle breakdown
- the probability of fire given an accident
- the probability of stopping inside the tunnel given vehicle fire
- the intensity distribution of spontaneous vehicle fires

Other findings, such as the effect of the fire brigade approach duration, have informed the methodological set-up or the choice of parameters in the guideline.

7. CONCLUSIONS

The paper combines vehicle fire data, accident data and traffic data from all tunnels within the Austrian primary road network. The comprehensiveness and consistency of each of these datasets provides a unique opportunity to derive reliable key numbers on vehicle fires in tunnels. This includes the rate of tunnel fires per vehicle kilometre as well as the conditional fire probability given vehicle breakdowns or accidents and a number of other relevant results that were presented in the paper.

However, dividing a sample of 67 tunnel fires into sub-sets turned out to be delicate in a few cases where it lead to a very small number of events (e.g. number of HGV fires after accidents, number of fully-developed fires of an entire HGV with known fire brigade approach duration). Nevertheless, the ensuing results are consistent with general reasoning even in those cases. Apart from this, they, too, are based on what is one of the most complete datasets available, also from an international perspective. Thus, they can truly be called best estimates – not only in the statistical, but also in the literal sense.

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TECHNICAL TRADE-OFFS USING FIXED FIRE FIGHTING SYSTEMS

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ABSTRACT

The increasing use of fixed fire-fighting system (FFFS) in tunnels has put focus on a topic that has a history of being controversial. An upcoming controversy is related to the question if it is possible to reduce the design fire for the ventilation system or reduce the protection of the tunnel construction when a FFFS is installed? Additional subject sometimes discussed is the potential increase in the distances between escape exits. All these subjects need careful discussion and thinking before they can be fully accepted. The advantages and disadvantages needs to be thoroughly debated and discussed. The paper gives an overview of the arguments and discussion about the physics related to introduction of trade-offs when installing FFFS in tunnels.

Keywords: fixed fire-fighting systems (FFFS), heat release rate (HRR), critical velocity, fire ventilation, constructions, escape exits, heat fluxes, and temperatures.

1. INTRODUCTION

In recent years FFFS have continuously find their way into new key tunnel projects in Europe and North America. However, ten years ago this was not the case. In Australia and Japan the installation of FFFS has been more traditional, especially for road tunnels with high traffic load and over a given tunnel length (>3 km). In Australia they are more or less mandatory in new road tunnel projects. A reduction of the design fire for other fire safety systems, i.e. making a "technical trade-off", is often discussed but usually it is decided not to benefit from the installation of FFFS. There may be many reasons for that. For example, the uncertainty about the mitigation effects in case of a fire and how it may affect the situation for the tunnel users are still disputed. A more common reason is related to the question what will happen if the FFFS would not operate as planned. The reliability and maintenance of the system becomes a key issue in the decision process. Designers or owners are still not ready to take the step to fully use the advantages of an FFFS installation on the fire safety. Other reason, equally important, is that there are no guidelines or standards available that can quantify or evaluate the effects of the technical trade-off against other systems. Before we are able to go into a careful discussion of technical trade-offs using different systems, we need to come up with the way to relate it to. In other words, there is a need to estimate or quantify these effects and they may be different depending on the system in focus.

The basic concept proposed here is to reduce the design fire and from that estimate the effects on different technical systems based on physical relations that can be derived from the effects of the FFFS on the tunnel environment. Three different design criteria are considered:

- critical velocity for ventilation systems, both exhaust and longitudinal
- heat fluxes to tunnel construction
- and distance between escape exits.

Every part is treated individually and separated from each other. Although the design fire affects the three different technical systems in different ways, there are possible methods that can be explored in order to quantify the effects of FFFS on these systems. Based on the analysis, a methodology to determine the physical benefits of the installation is presented in the following.

2. TECHNICAL SYSTEMS

2.1. Critical and confinement velocity

In design of the critical velocity, the convective part of the total HRR is the most relevant parameter for the dimensioning of ventilation systems in tunnels. The critical velocity could be derived from the Froude number (Fr_c) which is the ratio of the buoyancy forces created by the convective heated flow to the momentum force created by the incoming longitudinal flow. These two constitute the governing parameters that determine the critical velocity. Thomas [1] was first to present the concept of critical velocity. The critical velocity was defined as the minimum longitudinal velocity needed to prevent backlayering of hot gases. In NFPA 502 [2], a method to determine the critical velocity in road tunnels can be found. It is based on equation (1) given by Danziger and Kennedy [3], which in turn is based on Thomas' original work:

$$V_c = K_g \left(\frac{gQ_c H}{\rho_o C_p T_f A \mathrm{Fr}_c}\right)^{1/3} \qquad (1)$$

where

$$T_f = \frac{Q_c}{\rho_o C_p A V_c} + T_o$$

and where V_c is the critical ventilation velocity, g is the acceleration due to gravity, Q_c is the convective HRR, H is the tunnel height, A is the cross-sectional area of the tunnel, ρ_o is the ambient density, c_p is the specific heat capacity of air, K_g is grade factor, Fr_c is Froude number set as 4.5 by Kennedy [4], T_f is average smoke temperature and T_0 is ambient temperature both given in Kelvin.

The main problem with the critical velocity correlation (equation (1)), which has a 1/3 exponent, is that it could be only valid for flame heights lower than the ceiling height [5]. In order to solve this problem, Ota and Atkinson [5] conducted model scale tests and found that for low HRRs the test data approximately followed cube root relation but then flattened out. Later work in this area includes, among other studies, those presented in references [6-8]. An interesting aspect also valid for this study is the definition of "confinement velocity", which relates to determination of the critical velocity for exhaust systems on both sides of the fire. Important works on this can be found in references [7, 9]. The common aspect within these studies is the relation between the HRR and the critical velocity. Given that the smoke control is mainly related to the convective heat, the convective HRR is focused on in the following, despite many literature used the total HRR which, however, can be simply transformed into convective HRR.

We could divide the convective HRR for the ventilation system with FFFS into two issues: the total HRR with FFFS and the convective fraction. The total HRR with FFFS apparently differs from one system to another, depending on fire scenario, FFFS, ventilation, detection and activation algorithms. At present this value is mainly obtained from full scale fire suppression tests for typical fire scenarios. Despite this, the full scale tests carried out recently by Land Transport Authority of Singapore (LTA) in 2011 [10] and full scale tests carried out by SP and Swedish Transport Administration (STA) in 2013 [11] could give some hints on how large the fire with FFFS can be. The test results showed that the normal deluge water spray systems operated at a water flow rate of approximately 10 mm/min reduced the fire size to a range of 25 % to 50 % of that without FFFS, and a value of 50 % could be used for safety reasons. Note that the fire suppression system used nowadays has a wide diversity, and its performance could differ significantly from the ones tested in the literature.

Another issue that will be addressed in the following is the convective fraction. The total HRR (or the chemical HRR) consists of both the convective part carried away by convective fire plume, and the radiative part radiated from the hot flame and gas/smoke volume towards the surrounding tunnel surfaces and to the fuel source. In laboratory tests with fires directly under a hood system, the convective part of the total HRR is usually found to be in the order of 70 %, whereas the radiated part is usually found to be 30 % of the total HRR. The total HRR is usually measured using oxygen calorimetry, where the oxygen consumed in the fire is determined. Water vapors (gas) are generally not excluded in the measurement of the mass flow rate, but can be easily excluded by measuring the moisture inside the flow. Further, this parameter has insignificant effect if the temperature is far from the flame temperature.

In a tunnel fire with FFFS, the convective fraction is expected to be lower due to the cooling effect. Tarada et al [12] proposed that the convective fraction could be assumed to be 50% of the suppressed fire heat release rate, based on laboratory tests carried out within a project undertaken by LTA [10]. The tests were carried out in a compartment-shape enclosure (5m × 5m × 10m) with one small vertical opening at the floor level on one side and one horizontal opening up to the hood on the other side. The fuel mock-up consisted of a single pile of wooden and plastic pallets, about 80 % wood and 20 % plastic pallets. The pallet height was about 3 m and 2 m from the top of the pallet stack, and four water spray nozzles with 3 x 3 m spacing were mounted at the ceiling. In total 11 tests were carried out, using different spray nozzles. It was estimated that after activation the convective HRR varied between 25 – 51% and in average of 43%. They also pointed out that depending on the risk assessment process undertaken, and the degree of confidence attached to the performance of the FFFS, a significantly lower value for the fire heat release rate may be assumed. An example of a case is presented that the total fire size with FFFS is 30 MW, instead of potentially 100 MW without FFFS, and the convective HRR with FFFS is 15 MW for ventilation system as the convective part is assumed to be 50% of the total. Tarada et al [12] also pointed out that the fire will also create pressure drop which influence the design of the ventilation system. This include both the fire source itself, which has been analyzed by Dutrieue and Jacques [13] and the thermal resistance due to negative slope in relation to the fire positions as shown by Li et al [14]. On the other side, the presence of the water droplets will increase the pressure drop within the tunnel due to friction the droplets and the bypassing airflow [12]. In the design of exhaust ventilation systems, the same physical laws apply as for longitudinal ventilation system.

The proportion of convective HRR would be lower for mist systems compared to low pressure deluge systems as pointed out by Tarada et al [12]. This conclusion is apparently correct without any doubt, however, the difference in the convection part for these two typical systems needs to be clearly addressed. In order to answer this question, data from one of the best documented test series related to this subject, namely the one carried out by Arvidson [15], will be analyzed. Arvidson [15] carried out a series of large-scale fire suppression tests to simulate a fire on the ro-ro deck of a ship containing heavy goods freight trucks and trailers. The total HRR and convective HRR were measured in a hood system above a fuel mock-up in a fire laboratory. The fuel mock-up was constructed to geometrically replicate a typical trailer of a freight truck with the exception that the overall length was shorter than in reality. The measures of the fuel mock-up were 5.5 m long, 2.6 m wide, 2.8 m high and 1.1 m above floor level. The mockup was placed under a calorimetry hood with a capacity of 15 MWs. Tests were conducted both with and without a roof over the cargo space (steel plates) of the trailer model. The commodity used consisted of corrugated cartons 600 mm×400 mm×500 mm (L×W×H) filled with polystyrene cups placed on a standard EUR wood pallets. Above the commodity a water spray system was placed 1 m above the top of the commodity. The system consisted of four 2” branch lines with nozzle connections for eight nozzles at a 3.2 m ×3.0 m nozzle spacing, i.e. a coverage area of 9.6 m^2 per nozzle. Both low pressure and high pressure nozzles were tested. The low pressure nozzles consisted of medium velocity nozzles with nominal pressure of 1.2 bar to 4.9 bar. High pressure water mist nozzles were operated at 84 to100 bar. The water densities of the medium velocity nozzles were designed for 15 mm/min, 10 mm/min and 5 mm/min at low pressures (1.2 – 1.9 bar). Test with 10 mm/min at higher pressure (4.9 bar) was also carried out. The high-pressure water mist system generated water densities of 3.75 mm/min, 4.6 mm/min and 5.8 mm/min, respectively at pressures varying from 84 – 100 bar. The system was activated at a given total HRR of 5 MW, and in one test at 10 MW.

The results show that when there was no roof present a discharge density of 15 mm/min provided immediate fire suppression, 10 mm/min provided fire suppression, and 5 mm/min provided fire control. Improvements in performance were also documented with a higher system operating pressure and associated smaller water droplets. The high-pressure water mist system provided fire control at a discharge density of 5.8 mm/min. However, tests at 3.75 mm/min and 4.6 mm/min, respectively, provided no fire control when no roof was present. For the fires, where the fire was shielded from direct water application, the tested systems had a limited effect on the total HRR and the associated total energy, as almost all combustible material was consumed in the tests. The most efficient reduction of the convective HRR and the associated convective energy was demonstrated with 10 mm/min at a higher system operating pressure (4.9 bar). The high-pressure water mist system provided an improved reduction of the convective HRR and the associated convective energy as compared to the water spray system. However, no improved reduction of the total HRR and the associated total energy, was documented, i.e., the ability to reduce the actual HRR was not improved. In Figure 1, the ratio of convective HRR and the total HRR is given for two different methods to calculate, one based on absolute maximum/peak values after activation, and one based on maximum one minute average around the maximum/peak values after activation. The results show that this ratio is mainly in the range of 40 – 60 % (0.4 – 0.6), instead of 70 % which is usually measured without FFFS, although high-pressure systems tends to be in the range 40 – 50 %, whereas water spray tends to be in the range of 50 – 60 %. The better cooling effects of the high-pressure systems can be clearly observed. The difference in using peak values instead of 1 minute average is not that much, although one minute tends to be a bit lower.

In summary, the performance of FFFS differs from one to another, and the total HRR with FFFS is mainly obtained from full scale fire suppression tests. Despite this, the full scale tests carried out recently show that a normal deluge water spray system could reduce the fire size to 50 % of that without FFFS for a water flow rate of 10 mm/min. Further, assuming 60 % as the convective fraction of the total HRR of suppressed fire instead of 50% proposed by Tarada et al [12] for design of the ventilation system appears to be a conservative value to apply. This means if a 100 MW free burn fire is proven to be reduced to 50 MW by the FFFS, 30 MW convective HRR can be used for design of the critical velocity and other parameters related to the design, such as pressure loss due to fire and negative slope. As high-pressure water mist systems tend to reduce the total HRR not as effectively as water spray systems it is recommended not to use the advantage of better cooling effects. Therefore, it is reasonable to assume 60% as the convective fraction for suppression systems as a general rule.

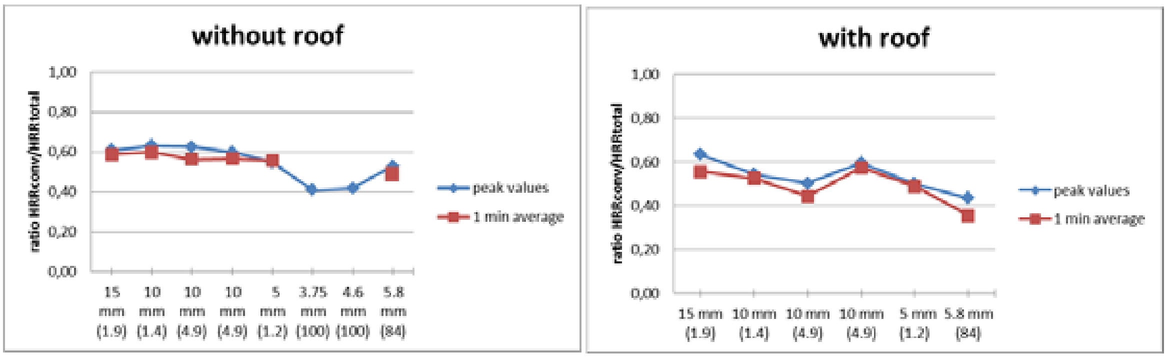


Figure 1: The measured ratio of convective HRR (HRR_{conv}) and total HRR (HRR_{total}) for different water densities (mm) and pressures (bar), both without and with roof above the fuel mock-up.

2.2. Heat fluxes to tunnel construction

When discussing heat fluxes to tunnel construction or tunnel structure protection, reference is made to different standardized time-temperature curves that represent "heat impact" on the construction, as shown in figure 2. Example of such standardized time-temperature curves are not found for tunnels with FFFS. In order to obtain some kind of quantified terminology which can be used to connect to the free burn situation using ISO, HC, RWS, HCM and RABT curves, one needs to change to terminology such as total net heat flux to the construction. In reality, a tunnel construction which is exposed to fire is heated up through both radiation and convection. Part of the incident radiation heat flux is absorbed by the surface and part is reflected back. The energy that is absorbed heats up the surface of the construction and travel further into the construction. The energy absorbed is the total net heat flux which can be approximately expressed in the form as proposed by Lemaire et al [16]:

$$\dot{q}''_{tot} = \varepsilon_w(\sigma T_{PT}^4 - \sigma T_w^4) + h_w(T_{PT} - T_w) \qquad (2)$$

where T_{PT} is a measured temperature using plate thermometer [17] and T_w is the surface temperature of the construction.

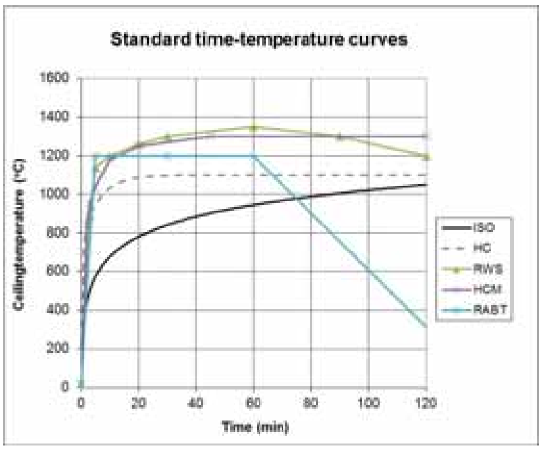


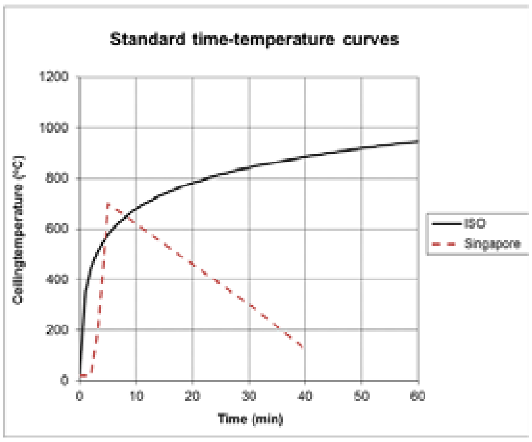
Figure 2: The most common standardized time-temperature curves for road tunnel applications.

In laboratory tests for building products or tunnel elements, the plate thermometer is generally used to control the temperature inside the furnaces in accordance to the curves presented in figure 2. Therefore, the plate thermometer is an excellent instrument to measure the heat impact or incident heat flux to the construction. As most furnaces have the same type of surface material and thickness, the plate thermometer becomes the only parameter that characterizes the thermal load to the construction. When the temperatures get relatively high, the gas temperature (measured by a thermocouple) and the plate thermometer temperature becomes very close. As nearly all the fire curves used in furnaces today are controlled by plate thermometers, and thereby gives a very good approximation of the heat impact on the tunnel construction, it is a good instrument to measure the effects of FFFS on tunnel constructions. Lemaire et al [16] used this fact to obtain a special time-temperature curve based on the measured values by the plate thermometers in the Singapore tests [10]. In figure 3 (left), a plot of the proposed time-temperature curve for the Singapore tests are shown. An interesting observation is that this curve in the early stage of the fire is following the standardize ISO curve quite well, except for a short peak after about 5 minutes into the fire. This curve is not even close to the other standardized curves used for tunnels, i.e. the HC and RWS.

Ingason and Li [18] proposed a simple equation to calculate the total HRR based on a temperature curve in a large tunnel fire under the critical velocity:

$$Q_T = 11.3 \cdot 10^{-4} \Delta T_{\max} A_p^{1/6} \sqrt{H} (H - h_{fo})^{5/3} \tag{3}$$

where Q_T is the calculated total HRR in MW based the temperature, $\Delta T_{\max}$ which is the excess maximum ceiling temperature and A_p which is the projected area of the fuel load (projection to the floor), and h_{fo} which is the height from road surface to bottom of the fuel. If we put in the Singapore temperature curve together with the ISO curve we can calculate the total HRR corresponding to these temperatures, using equation (3). We use the values from the Singapore test, H=5.2 m, h_{f0}=1.1 m, A_p=8.2 m x 2.5 m=20 m^2. The ventilation rate was about critical velocity (3 m/s), and therefore equation (3) can apply. The results are shown in figure 3 (right), and the peak total HRR is found to be about 30 MW. When looking at the HRR data from the FFFS tests from Singapore, this fits very well to the results [10]. The good correlation somehow proves the data obtained in the tests and suggests that it is realistic to assume lower HRR when using FFFS (technical trade-off).



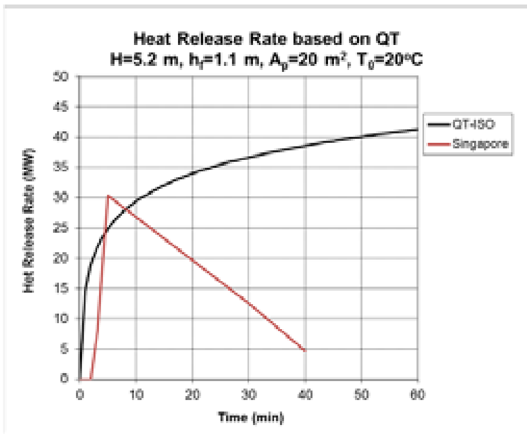


Figure 3: The Singapore time-temperature curve (left) and corresponding total HRR calculated for the Singapore tests using equation (3) (right).

As the Singapore curve appears to be a little bit odd in appearance, it is therefore proposed to use ISO curve instead. The corresponding total HRR is shown in figure 3 (right). Note that the calculated ISO HRR curve in figure 3 (right) covers most part of the test data. The figure suggests that for this type of tunnel we are expecting a total HRR lower than 45 MW within one hour. Note that the total HRR increase with tunnel height. If the tunnel height is raised to 6 m, the corresponding total HRR would be 60 MW.

A conclusion is that using the ISO curve as the design time-temperature curve for tunnels with FFFS would cover most cases. Note that all these analyses are based on the assumption that the fire suppression system can efficiently suppress or control the fire and reduce the fire size to the level that is discussed here. Apparently, the more general method is to obtain the time-temperature curve based on a reduced design fire for tunnels with FFFS.

However, for key infrastructures, e.g. immersed tunnels, the trade-off for tunnel structure protection is not recommended to apply due to the uncertainty of the fire size, and the performance of fire detection, fire suppression system and fire ventilation system in case of a fire. In other words, the ISO curve is not recommended for key infrastructures.

2.3. Evacuation

The easiest way to control the effects of reduced HRR in evacuation situation is to use one dimensional model to calculate the FED values [19] for two different conditions, one with FFFS and one without. Assuming that the production ratio of combustion products is the same, this type of comparison shows that the FED values are kept lower in fires with FFFS as the total HRR is lowered, e.g. the FED value of 1 in a 100 MW fire (without FFFS) will be obtained much faster than in a 50 MW fire (with FFFS). This can be shown by simple calculations using equations given by Purser [19] and by Ingason [20]. This type of analysis can be used to determine the distance between escape exits in tunnels with high ventilation. In a free burn fire situation, the combustion situation is much more profound than when FFFS are used. When the water is applied, the combustion conditions may change in negative way, but at the same time the total HRR is lowered. In summary, using FED analysis is the most effective way to design the distance between escape exits in FFFS fires, however, the three-dimensional effect could be important and the products due to incomplete combustion could produce negative effects which require further research.

3. CONCLUSIONS

A reliability analysis using risk assessment process should be undertaken before use of technical trade-offs. With that fulfilled, following technical trade-offs are proposed for FFFS in the design of safety systems:

- Using 60 % of the total HRR with FFFS as the convective HRR for design of the ventilation system appears to be a conservative value to apply. For the total HRR with FFFS, full scale test data could be used, or for a normal deluge water spray system operated at a water flow rate of approximately 10 mm/min, 50 % of the total HRR without FFFS could be considered as the design fire or the total HRR with FFFS. This means that for a normal deluge spray system at approximately 10 mm/min, a 100 MW free burn fire could be reduced to 50 MW (50 % of 100 MW) by the FFFS and 30 MW convective HRR (60 % of 50 MW) could be used for estimation of the critical velocity and other parameters related to the design, such as pressure loss due to fire and negative slope.
- Using ISO curve as the design time-temperature curve for tunnels with FFFS would cover most cases.
- Using one-dimensional FED analysis is the most effective way to design the distance between escape exits in tunnels with FFFS, despite that much research is still required in this filed.

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WITH HIGH SPEED TO A SAFE EMERGENCY HANDLING - VIENNA - ST. PÖLTEN TUNNEL HIGH-SPEED LINE

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ABSTRACT

In December 2012, the Austrian Federal Railways (ÖBB) put the "Vienna - St. Pölten" high-speed railway line into operation. In total, 34.8 km of the 50 km long new twin-track line were built in tunnels. In other words, approx. 70 % of the line is located in tunnels. The longest of the eight tunnels is the Wienerwald tunnel with a length of 13.4 km. The whole line is designed for a maximum speed of 250 km/h and with maximum longitudinal gradients of 8 ‰.

The planning process (which started in 1990!) and the operation start-up procedure (which took place in 2011/12) of the new line was accompanied by a number of objectives. The main objective consisted in setting new standards in tunnel safety in terms of structural issues, technical solutions and operational procedures. The essential question to be addressed was how to effectively manage an emergency at the interface of human beings and innovative technical solutions.

Keywords: tunnel safety, emergency plan, evacuation, human behaviour, emergency exercises

1. INTRODUCTION

When the new "Unterinntal" and "Vienna - St. Pölten" high-speed railway lines were taken into operation in 2012, the Austrian rail tunnel network increased by approx.70 km. Up to the year 2024, more tunnels are expected to be constructed, bringing the total length of tunnel sections to approx. 300 km (including major tunnel projects like the 33 km long Koralm tunnel or the 27 km long Semmering base tunnel).

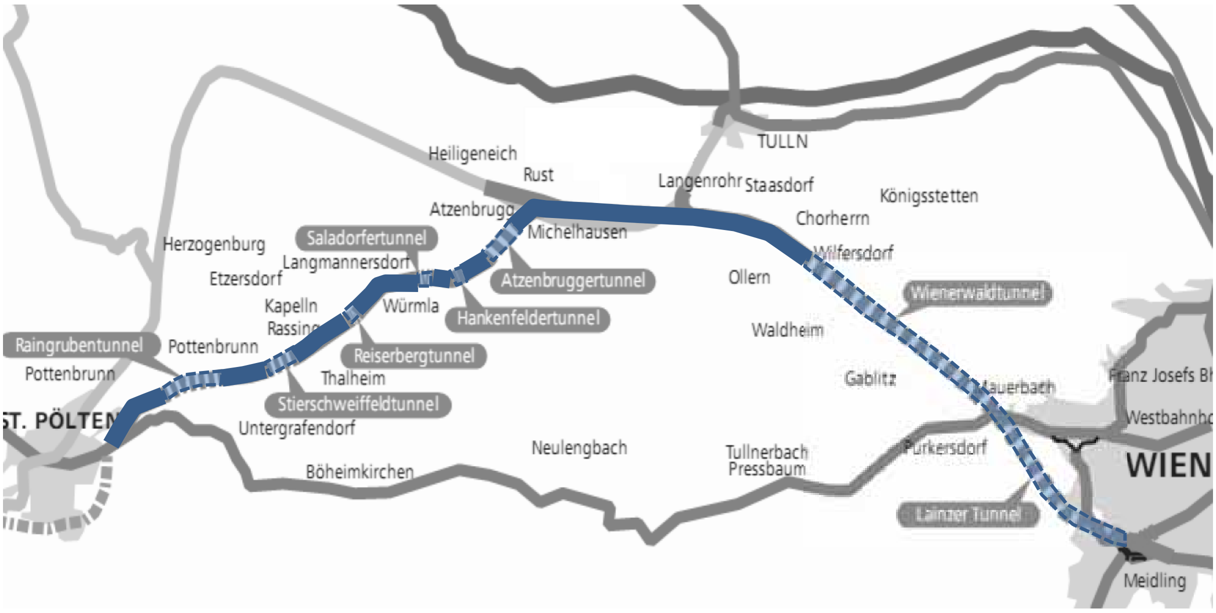

Figure 1: Scheme of the new Vienna - St. Pölten railway line

The new “Vienna - St. Pölten” railway line with a length of approx. 50 km for mixed traffic is an essential component of four-tracking the existing “Westbahn” railway line. The railway line branches off from the existing “Westbahn” line at the “Hadersdorf” junction (Vienna), runs underneath the “Wienerwald” in a 13.4 km long tunnel, subsequently passes through the southern “Tullnerfeld” area and the “Perschling” valley to the city of St. Pölten and joins the existing “Westbahn” line at the “Wagram” junction.

2. TUNNEL FACILITIES

2.1. Tunnel systems

The twin-track tubes of the new high-speed line have in total 32 vertical emergency exits, which lead directly to the surface. The shaft heights range from a minimum of 3 m to a maximum of 63 m. Shafts exceeding a height of 30 m are equipped with an emergency elevator. In the “Wienerwald” area, the tunnel system changes from a conventional twin-track tube to two single-track tubes. It features 22 cross passages at 500 m intervals, which lead to the adjacent tube. The Wienerwald tunnel was the first railway tunnel in Austria to be constructed with two single-track tubes.

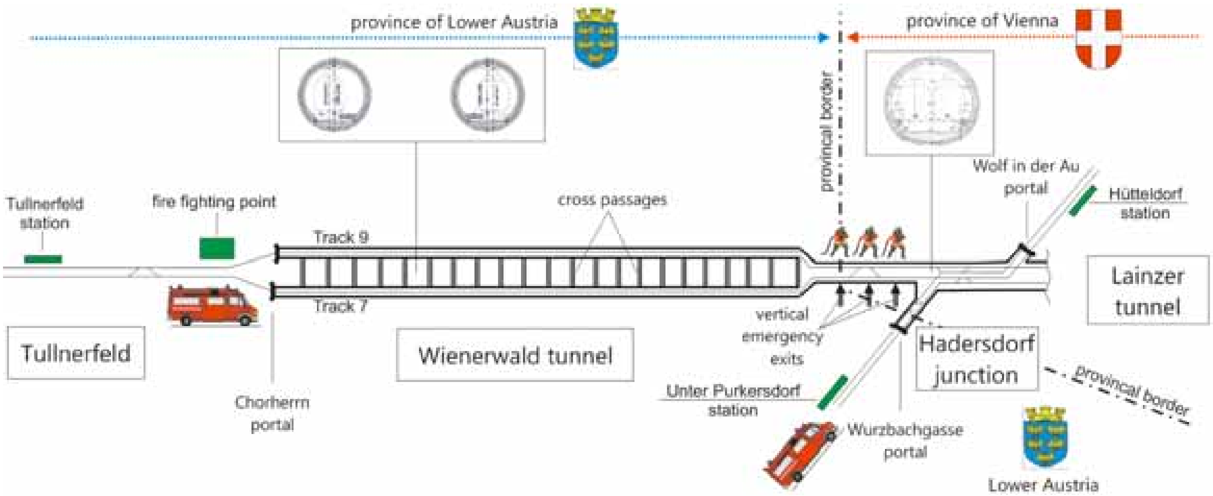

Figure 2: Change of tunnel system within the Wienerwald tunnel

2.2. Different concepts for assisted rescue

This change in tunnel system is mainly to be attributed to the different rescue strategies pursued by the fire brigades of the Austrian provinces of Vienna and Lower Austria. The professional Viennese fire brigade stressed its preference for the Wienerwald tunnel to be constructed with emergency exits, as this was in line with the municipal fire brigade’s intervention concept. The voluntary Lower Austrian fire brigade stated its preference for using its own rescue vehicles for interventions into the “Wienerwald” railway tunnel. The larger part of the tunnel (the two single-track tubes) is located in Lower Austria.

2.3. Rail tracks accessible by rubber-tired emergency vehicles

Following the design concept of the latest tunnel projects of the ÖBB, all tunnels of the new high-speed line are constructed with rail tracks which are accessible by rubber-tired vehicles and which allow fire brigades to proceed directly to the site of the emergency. Using their own vehicles and equipment inside the tunnel guarantees a safe emergency response and enables a significant gain in time, which is crucial when it comes to life or death of injured persons in the tunnel. The new line comprises a stretch of vehicle-accessible railway tracks, which is approx. 15 km in length and includes 3 turnouts (see Fig. 4).

Figure 3: Railway tunnel accessible for rubber-tired vehicles

2.4. Mechanical ventilation systems

Emergency ventilation facilities were installed in all cross passages and emergency exit shafts. In case of an emergency, these mechanical ventilation systems are taken into operation. To create a smoke-free environment, the air pressure is increased in the safe areas (emergency exit shafts, 2nd tube of the tunnel) but at the same time it builds up in front of the emergency doors. Under these emergency ventilation conditions, it is not only to be ensured that the doors have a fire resistance of at least 90 minutes and fulfill all the requirements defined for suction-pressure loads, leakage rates and opening direction (doors to open in the direction of the escape route) but it is also to be ensured that the force required to open the emergency exit doors will not exceed 100 Newton.

In addition to ventilation facilities in the cross passages and emergency exit shafts, the Wienerwald tunnel has furthermore been equipped with an emergency ventilation shaft which was positioned between the tracks before the two single-track tubes merge into the twin-track tube. In case of a fire near the single-track tube / twin-track tube interface, the ventilation shaft shall prevent smoke from entering the unaffected tubes (parallel adjacent tube or following twin-track tube).

2.5. Access to the safe area (evacuation)

Behind every emergency exit door in a tunnel, a lock is provided. This lock is equipped with another emergency exit door, which either leads to the adjacent tube (single-track) or to the emergency staircase (twin-track). In case of a tunnel fire, the safe area behind the lock is pressurized. This ensures smoke-free conditions in the safe area and keeps smoke from entering the lock, even if the doors are open.

For the emergency shafts, the area in front of the staircase was reviewed by the use of an evacuation simulation model. The evacuation model provided a detailed analysis both of the building structures and the organisational sequences involved in the evacuation of a passenger train in a tunnel. Using the model guaranteed an adequate design of the queuing space at the bottom of the staircase. It prevents escaping passengers from queuing back to the lock door.

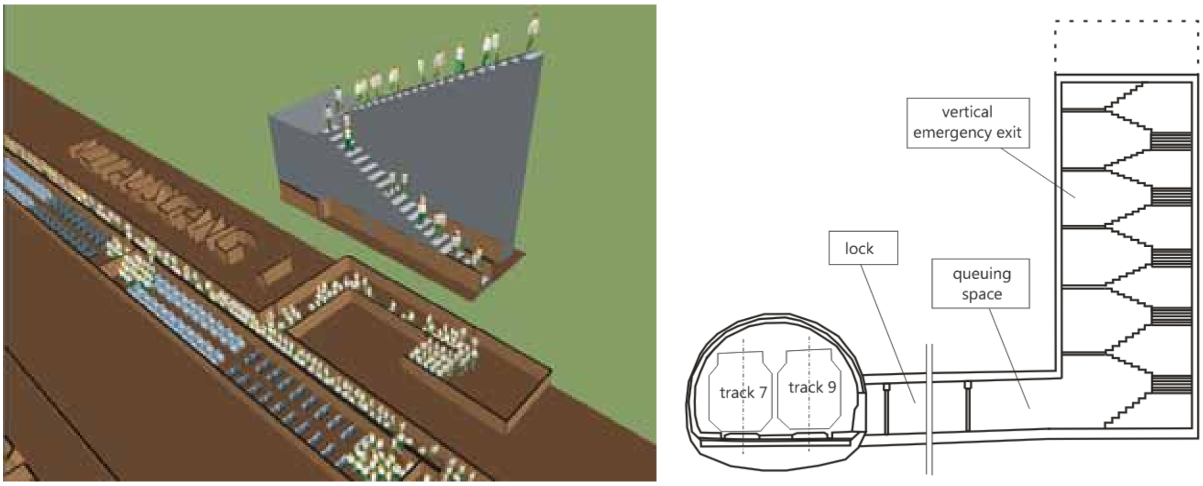

Figure 4: Evacuation simulation of vertical emergency exits

2.6. Catenary system

Prior to rescue teams entering the tunnel, a number of precisely defined requirements must be met. A vital requirement is that the catenary system must be grounded and disconnected from the power system. The complex tunnel system of the Wienerwald tunnel and the Lainzer tunnel (including 6 tunnel portals), requires a special solution to indicate whether this requirement is fulfilled. For fire brigades entering the tunnel, this information is either provided on control panels (including a key lock) or on display panels (only for notification). Control panels, which are installed at the portals, are not only equipped with a display system, which indicates the status of the catenary system, but are also equipped with a lock system to ensure that the catenary system cannot be reconnected. Only if the control panel shows "catenary system disconnected and grounded" (illuminated yellow arrows pointing towards each other), can the commanding officer of the fire brigade turn around the key in the lock. Subsequently a symbol signals "catenary system cannot be reconnected" (illuminated green lock). Now the commanding officer can remove the key from the control panel, which guarantees a safe emergency response for the fire fighters as long as he holds on to the key. The display panel cannot be operated by hand and only serves to provide information to forces approaching the vertical emergency exits. After the emergency response campaign, the commanding officer of the fire brigade returns the key to the commanding officer of the ÖBB.

The main advantage of the new disconnecting and signalling system is that time is gained in the process of visualisation and communication between the commanding officers. The new electrical system requires less communication in case of an emergency in the tunnel and replaces the old mechanical system used for grounding (earthing rods).

control panel - catenary system not disconnected and not grounded, and also not secured against reconnection

display panel - catenary system disconnected and grounded, but not secured against reconnection

display panel - catenary system disconnected and grounded, and secured against reconnection

Figure 5: System signalling the status of the catenary system

2.7. Interoperable train control system ETCS L2

In Austria, the declared goal is to continuously reduce the probability of train accidents. For this reason, the entire new railway line is equipped with the newest interoperable train control system called ETCS L2 (European Train Control System Level 2). The ETCS L2 has an on-board radio system allowing the on-board computer to communicate with the control centre. The train detection equipment sends the train’s position to the control centre. The control centre, which receives information on the position of all trains on the line, allocates the new train movement authority to the train. To ensure safe railway operations, the on-board computer continuously determines the train’s position and checks whether the current speed of the train corresponds to the distance travelled. In case of significant deviations from normal conditions, the train’s speed is controlled automatically.

3. TUNNEL SAFETY DOCUMENTATION

Building the new railway line was an enormous constructional challenge. Putting it into operation led to many organisational challenges. One challenge was to bring together the different structures of the individual alarm control centres. Jurisdictional boundaries or interfaces in alerting procedures had to be clarified between all the parties involved like the ÖBB, the fire brigade, the police, the ambulance and the municipal disaster authorities. Emergency response plans and checklists were prepared in close consultation with the rescue services to support the respective officers-in-charge in case of an emergency.

All issues, which are relevant to the handling of an emergency in these tunnels, are collected in the “tunnel safety documentation”, which focuses on tunnel-specific hazard analyses to determine the appropriate rescue concept. The crucial aspect is that people trying to escape from the site of an accident should be able to reach a safe area in an adequate period of time (evacuation). In addition, a tailored portfolio of tunnel safety measures should be available to the rescue forces to enable them to support the assisted rescue and the fire-fighting campaign. The tunnel safety documentation comprises detailed information on all physical tunnel structures as well as a manual for all operational actions for standardized emergency scenarios.

4. EMERGENCY EXERCISES

4.1. The Programme

Prior to taking a new tunnel into operation, the tunnel system must be checked by simulating rescue campaigns and performing fire drills. By establishing a systematically structured exercise programme, a new standard was set for new high-speed railway lines.

To implement the exercise programme, five different expert teams were formed, each consisting of members of the ÖBB, the district headquarters of the fire departments, the ambulance, the police and the relevant district authorities. The programme began with joint inspections to obtain the necessary site-, object- and system-related knowledge. Several training sessions followed focusing on different priorities, such as tunnel equipment, lines of communication, allocation of responsibilities, and cooperation of emergency services. Trainings focusing on operational tactics were only held after the team members had acquired the necessary system knowledge and had been briefed on the organisational framework conditions. The performance of emergency exercises followed the strategy of starting with simple rescue scenarios, gradually proceeding to more complex, multi-scale exercise scenarios involving various emergency services. After each exercise, debriefings were held. The experiences gained were documented in detail to be considered in subsequent exercises. The findings were furthermore recorded in the “tunnel safety documentation”.

The completed training programme was as follows:

- 15 instruction courses [site-, object- and system-related knowledge]
- 11 emergency response exercises [tactical approach, safe handling of equipment]
- 3 staff exercises [communication, allocation of responsibilities]
- 4 disaster drills [cooperation between all parties involved]

The exercises were performed to meet the following objectives:

- Promote the motivation and cooperation of parties involved
- Gain confidence in the management of emergencies after the occurrence of an incident/accident
- Ensure a structured organisation of the exercise
- Ensure a smooth performance of the exercise
- Assess and document knowledge gained during the exercise

Figure 6: Simulation of a burning train (left) and a derailment with lost cargo (right)

4.2. Interesting findings identified during the exercises

One exercise took place at the transition zone from the twin-track tube to the two single-track tubes in the Wienerwald tunnel. The passengers were evacuated in the direction of the two single-track tubes. On the way to the emergency exit, the passengers stayed on the side of the escape walkway, on which they had left the train. They did not cross the tracks, although the emergency lighting ended on this side and continued on the opposite side of the emergency walkway. It seems that people leaving the scene of an incident or accident are afraid of crossing the tracks. It was furthermore observed that they waited in front of the emergency exit door and did not proceed into the lock area of the cross passage and into the adjacent tube.

In case of extensive smoke development in the tunnel, the colour of the escape lighting (which should indicate the route to the emergency exit) is similar to the colour of a fire. Due to this similarity in appearance, especially in a smoke-filled tunnel, the orange-yellow colour does not seem to be a good choice to mark the emergency exit in a tunnel and for psychological reasons it is hence considered to be changed to white.

Some of the exit signs were very dirty resulting in a reduced visibility in comparison to the concrete background. During maintenance works, special attention should thus be placed on cleaning the escape route signs at regular intervals.

With deep rescue shafts, walking up the emergency stairway to the surface, can be very challenging both physically and psychologically. This applies to all people walking up the staircase, but especially to elderly and impaired people. Numbering the steps to indicate the distance to the surface seems to be very important to evacuees, who long for certainty and psychological support.

Fire fighters and evacuees (some of them injured) met in the emergency staircase. Due to the width of the stairways (2 m) they could easily pass each other. But the acting performance of some of those participating in the exercise was so convincing that many of the fire fighters came to their rescue, helping “injured” and “exhausted” evacuees to a safe area at the surface, where they were looked after by the rescue services, instead of heading straight down to the tunnel to fight the fire.

At a different exercise scenario, a freight train derailed in the tunnel losing some of its cargo. The lost cargo consisting of tree trunks lay on one of the tracks. As the rail tracks could be accessed by rubber-tired vehicles, the obstacles on the tracks could be easily bypassed by the emergency vehicles. Rubber-tired vehicles were found to be more flexible than track-bound vehicles and thus proved to be advantageous under emergency conditions.

In addition rolling pallets, which are located at the emergency exits and at the fire-fighting points near the portals, were found to be very helpful, not only for the transport of equipment and the removal of lost cargo but also for assisted rescue operations (evacuation of people). Without this simple technical device, transport activities turned out to be very exhausting for the rescue services.

The exercises have shown that in case of an emergency, several voluntary fire brigades with several commanding officers are involved in the ensuing rescue campaign. A clear assignment of responsibilities (lines of communication, search for appropriate contact persons) is much more difficult, if there is more than one contact person for the different emergency services involved. The alarm and operation plan of the rescue forces must clearly identify and show the hierarchy of responsibilities among the different fire brigades.

Figure 7: Roller pallets (left) and numbering of staircase steps (right)

5. COMMISSIONING PROCESS

5.1. Timetable

It is only after all regulatory requirements have been met, that the required operating permit will be issued by the Federal Ministry for Transport, Innovation and Technology based on inspection documents and approval certificates. The timetable for the commissioning of the new Vienna - St. Pölten high speed line was as follows:

Table 1: Steps to obtain the operating permit for the Vienna – St. Pölten high-speed line

2009 - 2010	Completion of structural works
Mar. – Apr. 2012	Completion of infrastructure equipment installation
Apr. 2012	Acceptance tests in compliance with authority regulations
Mar. 2012	Acceptance tests and operation start-up of Tullnerfeld transformer substation
Mar. 2012	Completion of Tullnerfeld railway station
Apr. - May 2012	Start of courses for fire brigades (rescue services, police) to offer them the opportunity to familiarise themselves with the tunnel and the infrastructure equipment
Apr. - Aug. 2012	Start of test runs on the new railway line
Apr. - Sept. 2012	Staff exercises and training sessions for the fire brigades
Aug. 2012	Technical and functional acceptance test for operating speeds > 160 km/h
Sept. 2012	Trial runs gradually increasing the running speed from 160 km/h to 275 km/h (250 km/h plus 10%)
Sept. 2012	Performance tests for operating speeds > 250 km/h, verification of computation assumptions and theoretical computation results
Oct. 2012	Innovations and improvements for the rail traffic sector
Sept. - Nov. 2012	Operation start-up of the new train control system ETCS
Sept. - Nov. 2012	Final emergency exercises (large-scale disaster drills) involving all emergency services (fire brigade, rescue services, police, etc) as well as the authorities
Dec. 2012	Issuance of the operating permit by the Federal Ministry of Transport Innovation and Technology (BMVIT)
09. Dec. 2012	Opening of the new Vienna – St. Pölten high-speed railway line

5.2. Conclusion

When it comes to meeting the requirements to obtain the necessary operating permit, every large-scale railway infrastructure project needs intense cooperation between project management, signalling and control management, and emergency services. For that matter, the following aspects are of vital importance:

- For railway lines with many different tunnels, transparent harmonised guidelines for emergency services approaching the tunnel in case of an emergency (access by vehicle and on foot) are imperative.
- There is a strong need for standardised tunnel safety facilities and measures and for standardised operation management processes to ease the handling of emergencies.
- Emergency documents (emergency response plans, check lists, etc.) should be elaborated using a standardised structure and layout and should be delivered to all parties involved in due time.
- As an important part of the permitting process, the exercise programmes need to be systematically structured and scheduled (training sessions, complex multi-scale exercises).
- A proper and disciplined communication between key personnel is the most challenging task during an emergency. Exercises covering various realistic scenarios represent the most effective means to improve and optimise emergency communication.

UPGRADING EXISTING TERN ROAD TUNNELS TO CURRENT NEEDS, TAKING THE ARLBERGTUNNEL AS AN EXAMPLE

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ABSTRACT

The operation and safety facilities of European road tunnels in the Trans-European Road Network (TERN) must meet the requirements of Directive 2004/54/EC by not later than April 2019. This regulation applies to all tunnels in the TERN with a length of more than 500 metres, whether they are in operation, under construction or under design. This directive aims at ensuring a minimum level of safety for road users by preventing events which might endanger human life, the environment and tunnel installations. Taking the Arlberg road tunnel as an example, this paper shows how an existing road tunnel may be upgraded to meet the requirements of Directive 2004/54/EC and the Austrian national guidelines RVS. The Arlberg road tunnel is the longest single-tube road tunnel in Austria, and has a relatively low traffic volume. Hence, the construction of a second tube is not really cost effective. As this tunnel is the only winter-safe link between Tyrol and Vorarlberg, the closure of the tunnel during winter needs to be avoided as far as possible.

Keywords: TERN, egress ways, operation and safety facilities, FFFS

1. INTRODUCTION

The Arlberg road tunnel, with a length of about 15.5 km, is the longest single-tube road tunnel with bi-directional traffic in Austria. The tunnel connects St. Anton in Tyrol and Langen in Vorarlberg and is the only winter-safe link between Tyrol and Vorarlberg in the Trans-European Road Network (TERN).

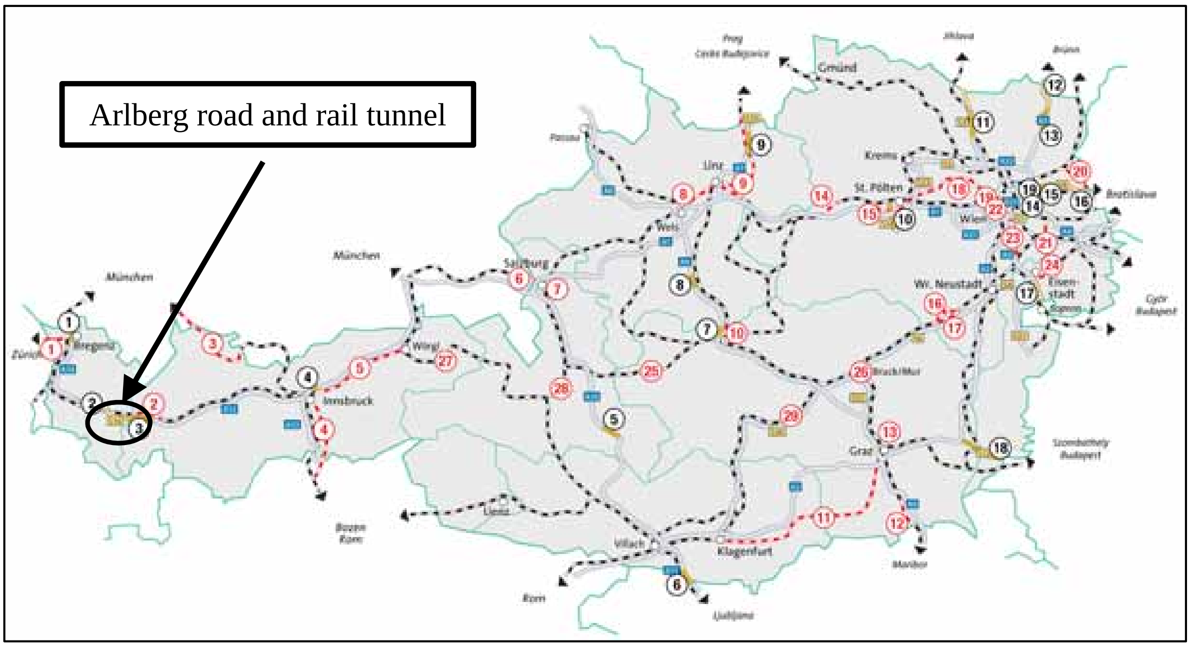


Figure 1: Location of the Arlberg road tunnel in the TERN (bmvit).

The average daily traffic volume is about 8,000 vehicles/day. The peak traffic in holiday seasons is almost twice as high. The tunnel is equipped with a full transverse ventilation system with six ventilation sections, two vertical shafts (736 m and 218 m) and two portal stations. Each section is currently ventilated by one fresh and one exhaust air fan. Figure 2 depicts the ventilation scheme, where VS1 to VS6 denote the ventilation sections, F1 to F6 and E1 to E6, denote the fresh and the exhaust air fans.

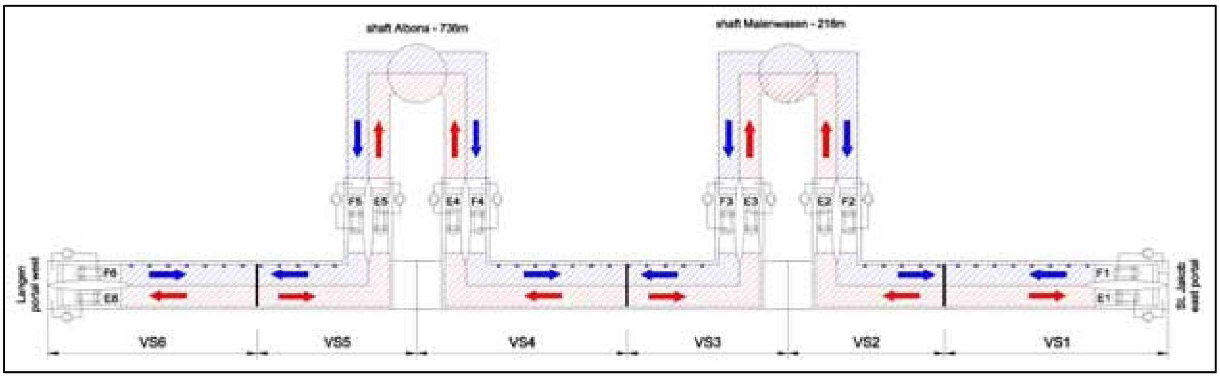


Figure 2: Sketch of the existing ventilation scheme of the Arlberg tunnel.

After 35 years in operation the Arlberg road tunnel needs to be refurbished. All the operation and safety facilities such as ventilation control system, video surveillance, alarm and radio equipment, fire detection, the road drainage and the fire-fighting water pipes need to be upgraded. In addition, 37 egress ways must be built in order to make the tunnel even safer for the road users.

In addition to the required structural refurbishment and the requirements of the RVS (Austrian guideline) [2] and the EU directive [1], the status of the existing operation and safety facilities was also investigated in order to ascertain the complete scope of refurbishment required.

Arlberg tunnel is part of the TERN. According to the EU directive [1] the distance between egress ways has to be reduced to a maximum of 500 m. The current escape galleries, which lead to the parallel railway tunnel, are located every 1,700m. An example of an existing egress way is shown in figure 3.

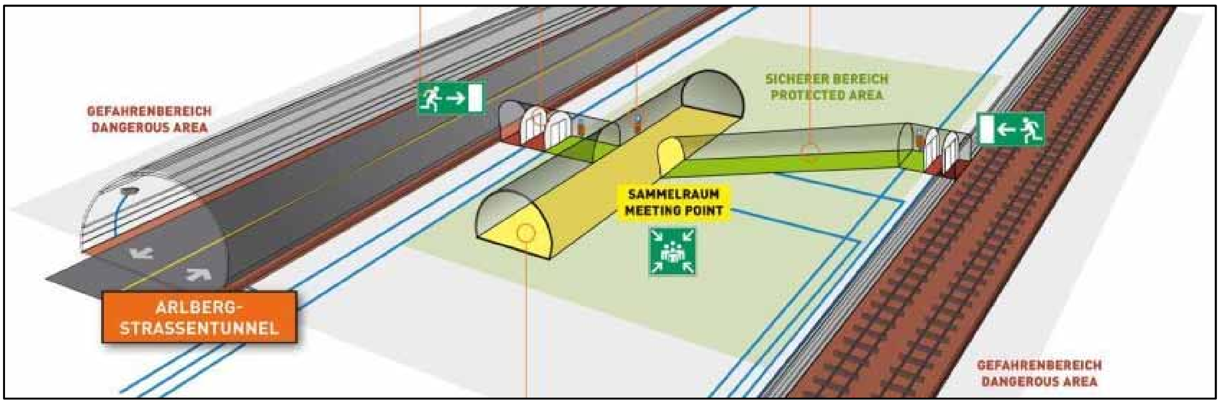


Figure 3: Example of an egress way in Arlberg road tunnel (ASFINAG).

In the course of the design process, different options were examined in order to assess which of them might best meet today's requirements. The investigation included the development and comparison of an optimized procedure with respect to construction work and site logistics, traffic operational, loss of toll income, possible traffic routing and, last but not least, construction costs.

As the distance between railway and road tunnel is never more than 300 m there is no need for further escape routes for the railway tunnel. Thus, instead of introducing further cross passages to the rail tunnel of the following solution was chosen. In future, the fresh air ducts between the existing cross passages to the railway tunnel will serve as egress ways. While this minimises construction costs, it does require additional installations for maintaining egress user safety. Figure 4 shows a sketch of the road and railway tunnel, as well as of the existing and the new egress ways.

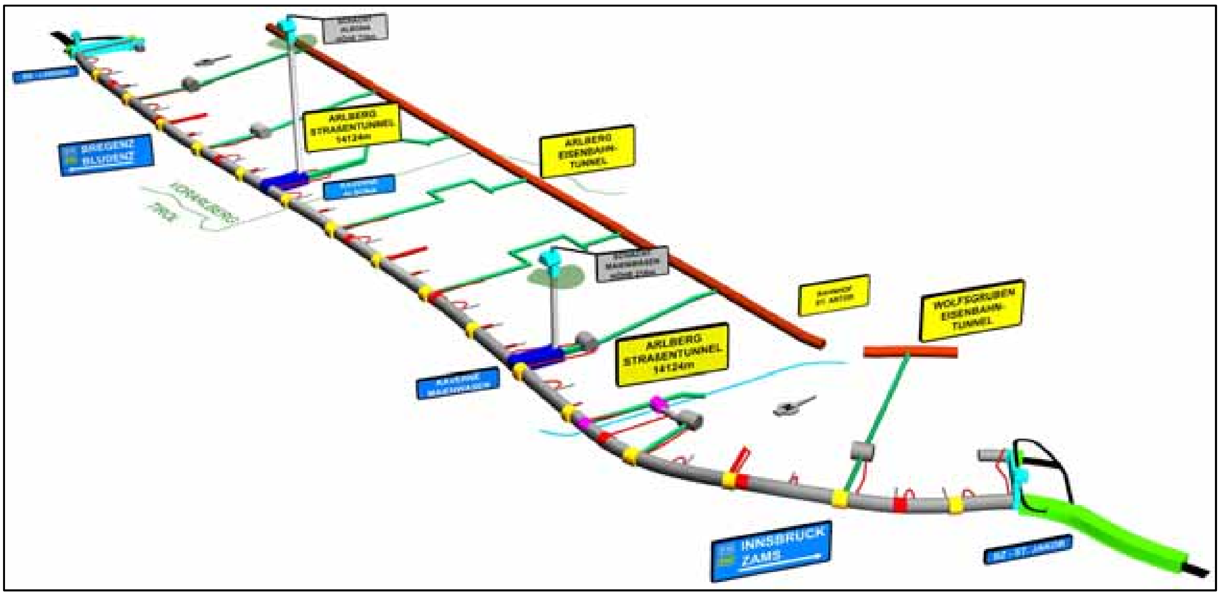


Figure 4: Sketch of the egress ways of the Arlberg tunnel (ASFINAG).

2. FEASIBILITY STUDY

In order to fulfil the relevant regulations and to find a practicable design, a feasibility study was performed. The following options were investigated:

- option 1: Total closure of the Arlberg road tunnel for the whole period of refurbishment
- option 2: Ongoing traffic operation with short closures only at certain times (e.g. night time), together with some unavoidable closures over a few days.
- option 3: Seasonal closures from the middle of April to the end of October together with convoy control during the night.
- option 4: Construction of a new single tube, with the existing tube being used as escape and rescue tunnel
- option 5: Construction of a second tube and refurbishment of the existing tunnel

2.1. Results - Assessment of the construction time

In order to keep traffic restrictions to a minimum, the refurbishment of the tunnel and further lining of the egress ways must be carried out in several temporally distinct phases. Figure 5 shows the predicted construction times of the five options.

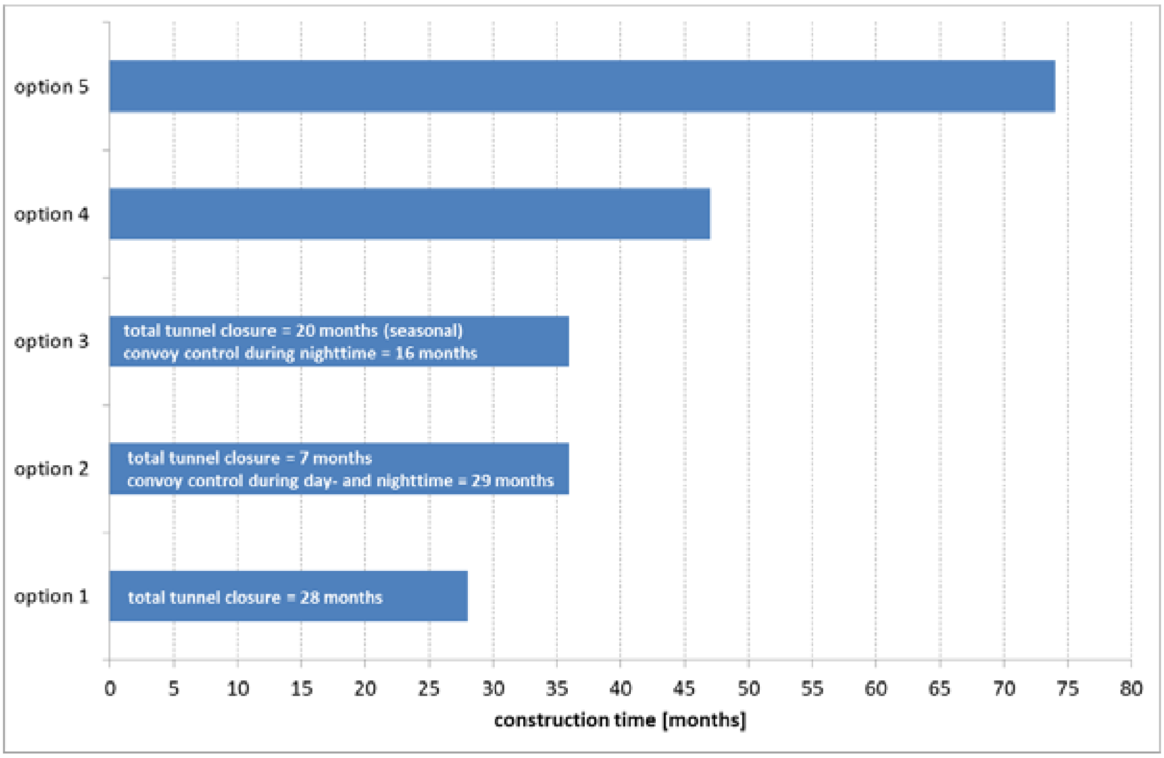


Figure 5: Construction times.

In option 3 the refurbishment of the existing tunnels will take place in 3 seasonal closures between April and the end of October. Thus, compared to option 1, the Arlberg road tunnel can be used during wintertime and the traffic burden in the city of St. Anton can be substantially reduced.

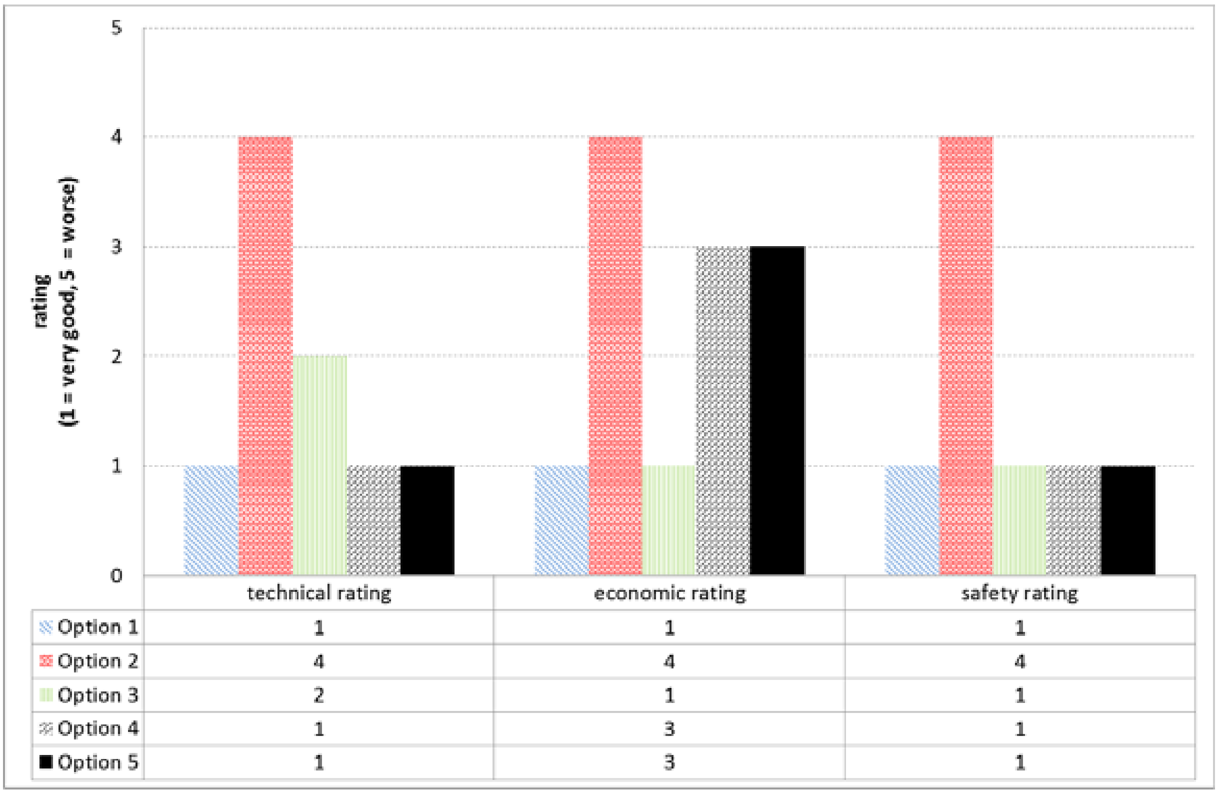
2.2. Results - Assessment of the technical and economic feasibility

<u>Option2:</u>
Option 2 can not be recommended from an economic and technical point of view. This is largely due to concerns relating to tunnel user and construction worker safety as a lot of work must be done within in the traffic room.

<u>Option 4:</u>
Option 4 was acceptable in terms of technical and safety considerations. However, compliance with the RVS and the STSG would make a larger cross-section and larger break-down bays necessary in the new tube. This would lead to significantly higher additional costs in the coming decade. In fact, the overall costs of option 4 are more than twice those of option 1 and 3. Even though traffic flow would still be possible during the whole construction period, the toll income gained would not be sufficient to compensate for the extra cost. Hence, option 4 can not be recommended from an economic point of view.

<u>Option 5:</u>
Option 5 represents the safest option for the tunnel users and is also acceptable in terms of technical considerations. In terms of economics, however, this is the most expensive option. The overall costs of option 5 are more than 2.5 times higher than the costs of option 1 und 3.

<u>Option 1 & 3:</u>
From the economic and technical point of view option 1 (total closure) is to be preferred to option 3 (seasonal closure). Seasonal closures entail lower additional costs and lower revenue loss as no provisional arrangements or multiple treatments are necessary. The construction work can also be handled with appropriate quality. The difference in the relative costs of the two options is in the range of about 10 percent.



	technical rating	economic rating	safety rating
Option 1	1	1	1
Option 2	4	4	4
Option 3	2	1	1
Option 4	1	3	1
Option 5	1	3	1

Figure 6: Rating of the five different options.

Based on the results of the feasibility study, option 3 was selected for realisation.

3. DETAILED DESIGN

3.1. Operation and Safety Facilities

Fixed Fire Fighting System (FFFS)
A FFFS will be installed throughout the tunnel. An FFFS has the potential to reduce the rates of fire growth and fire spread. In the event of a fire, this helps tunnel users and emergency services during the self-rescue phase. Other potential benefits of an FFFS are protection of tunnel assets from fire damage, and minimisation of road network interruptions during post-fire repairs.

Storage niches and break-down bays
Break-down bays and storage niches are located every 1,000 m, and provide safe parking spaces.

Audio tunnel monitoring (AKUT)
Microphones transmit data to a special database. Special software is able to differentiate between the normal sound of the traffic and unusual noises such as collisions or screeching tyres and brakes. Any alarm automatically activates the camera nearest to the sounds so that the staff in the control centre can respond immediately.

Impact absorbers
In cases of collision, impact absorbers serve to reduce the accident severity of vehicles or to direct vehicles back onto the traffic lane.

Energy
In cases of emergency, the tunnel has an autonomous energy supply (transformers, emergency generators).

Fire extinguisher points
Fire extinguisher points containing a hydrant are installed every 125m to 150 m.

High-tech tunnel monitoring
A range of high-tech systems such as video image evaluation and fire detectors ensure rapid response to any accident. The opening of doors is monitored via the use of door contacts. Emergency signals – SOS or fire – can be activated by manual and automatic alarm.

Information systems
To ensure that drivers are kept fully informed about traffic conditions a range of information systems such as loudspeakers, information boards, radio announcements and signs are available.

Intelligent light systems

Brightness sensors ensure that optimum lighting is available to drivers at all times. The brighter it is outside the tunnel, the brighter it will be in the entrance portal zone. This makes it easier for tunnel users to adapt to the illumination level.

Emergency phone systems
Emergency phones with illuminated compartments are located approximately every 125 m in the tunnels.

Traffic
The tunnel is fitted with CCTV which transmits images to the tunnel control centre. Sensors in the tunnels provide additional information on traffic levels, visibility or air conditions. In the event of a disruption, traffic can be quickly and adequately managed by the tunnel operators. All HGVs and buses over 7.5 tonnes maximum permissible weight (MPW) pass through the thermal scanner on a dedicated lane before entering the tunnel. The system measures the outer skin of the vehicle using laser scanners in order to create a 3D image. Two infrared cameras additionally record the temperature from both sides. Critical points, such as tyres, wheel bearings, the engine area and exhaust systems are precisely localised. Special software combines and analyses all the data. In the event of overheating, the vehicle is taken off the track to cool down or to allow for troubleshooting. After the problem has been dealt with it is returned to the thermal portal.

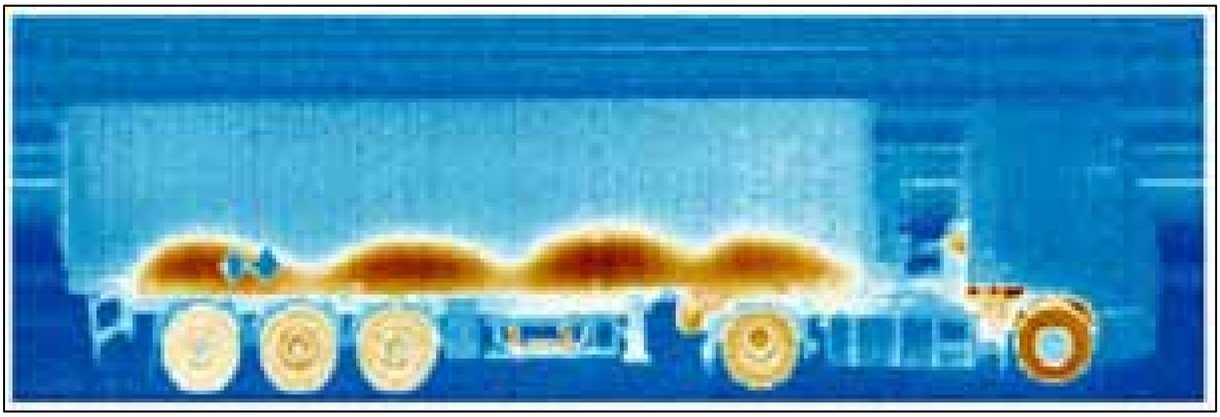


Figure 7: Thermal imaging cameras - external temperature of the vehicle (ASFINAG).

3.2. Egress ways

As described above the distance between railway and road tunnel is quite large. In order to minimize construction costs it was decided that the fresh air ducts be used as egress ways. To enable handicapped people to use the egress ways, instead of stairways, ramps with a gradient not exceeding 10% will be constructed. Figures 8 and 9 depict the new egress ways.

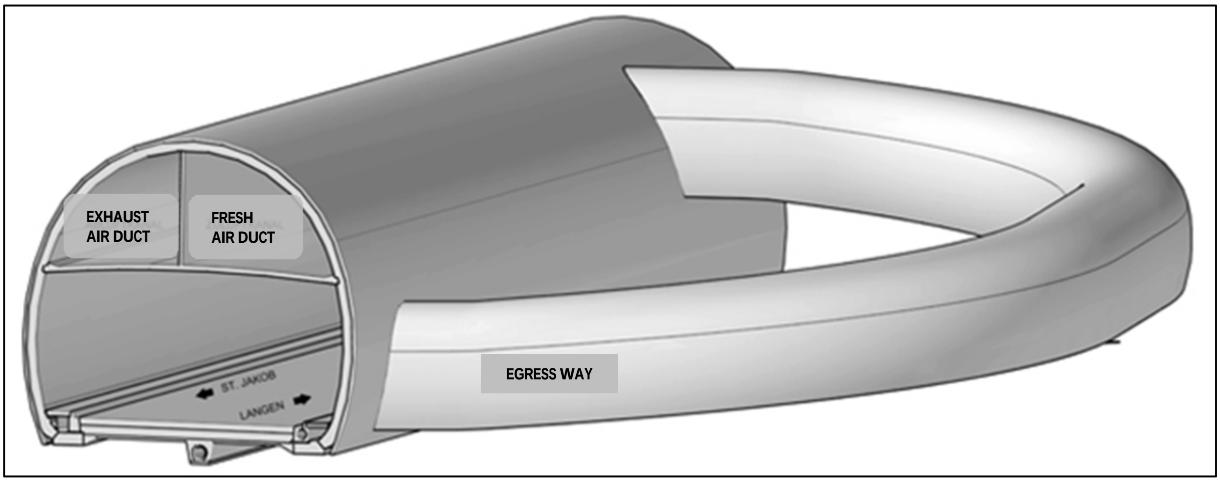


Figure 8: Scheme of the new egress way (ASFINAG).

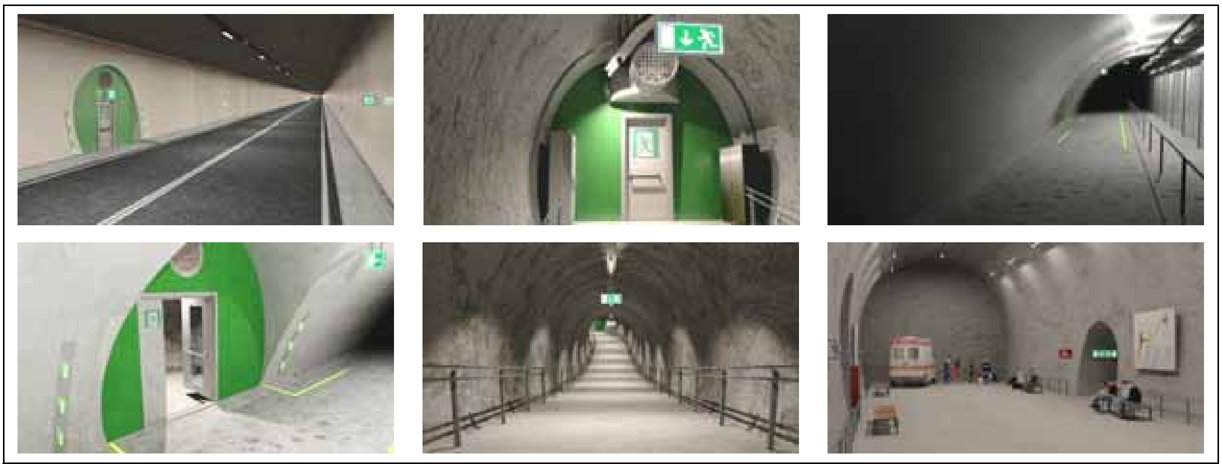


Figure 9: Images of the new egress ways (ASFINAG).

3.3. Fire ventilation

The main issue in fire ventilation lies in the problem of confining smoke to the region of the extraction damper. As the Arlberg tunnel represents a weather barrier the meteorological pressure differences between the two portals are quite high. They amount to 254 Pa, the 95th percentile of the half-hour mean values of the pressure differences. Hence massive electro-mechanical installations in the form of jet fans or air injection nozzles are needed in order to maintain pressure gradients. A cost-benefit analysis indicated that usage of the existing fresh air fans for air injection is appropriate. This requires the installation of fresh air injection dampers (FAID) and sealing doors within the fresh air duct. Figure 10 depicts the scheme of the upgraded ventilation system with the FAIDs and additional jet fans (JF1 to JF3) for smoke control. Figure 11 depicts the cross-section of the tunnel at the place of the jet-fans. The advantage of this system is that existing fans can be used and structural adaptations inside the tunnel can be reduced to a minimum. The drawback of FAIDs is that each additional device raises the flow of air into the tunnel. The increase in momentum (thrust) brought into the tunnel is accompanied by an increase of the volume flow rate. Hence the air/smoke velocity inside the tunnel also increases. Use of a simple jet fan, in contrast, would only produce the required thrust in the traffic room. In order to overcome the problem of increasing volume flow rates, air extraction in other ventilation sections has to be utilised to achieve the required pressure balance (push – pull system). Such a concept was originally implemented in Austria in 2002, using a full closed loop control system for the 10 km long Plabutsch tunnel [3]. At that time, however, vertical air injection and extraction was employed without using the momentum of the injected air. Systems with FAIDs have since been applied successfully in Austria in several long road tunnels [4]. What is new in the Arlberg tunnel, is the parallel usage of multiple FAIDs and jet fans as well as air extraction in sections other than in the fire section.

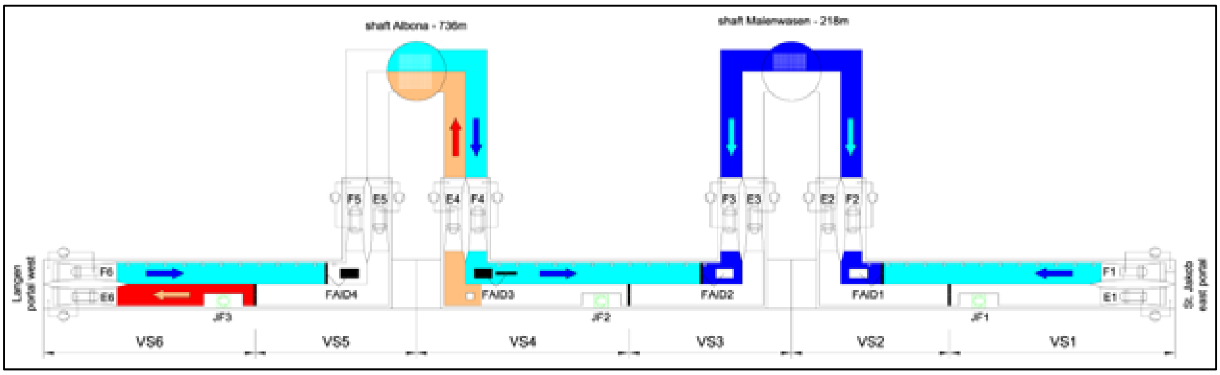


Figure 10: Sketch of the new ventilation scheme of the Arlberg tunnel.

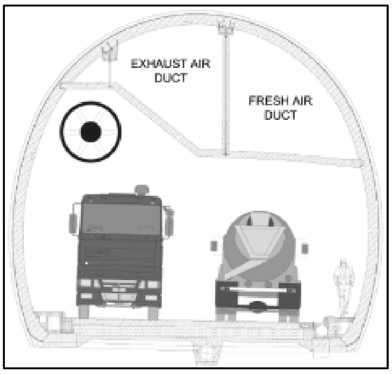


Figure 11: Sketch of the cross section in the region of jet fan JF1/2/3.

Figure 12 shows a scenario for a 30 MW fire in ventilation section VS6. Close to the fire location a mass flow of 144 kg/s smoke/air is to be extracted. In order to achieve a nearly symmetrical flow from both portals towards the extraction location the usage of the FAID 1 and FAID 2 as well as of the jet fans JF1 and JF2 is needed. In addition air extraction is required in section VS6. In this particular case, various exhaust air and fresh air supply fans as well as the jet fans are needed at the same time in order to reach the required ventilation goal. The remaining fresh air fans are needed to vent the escape route via the fresh air duct. Figure 13 shows the velocity distribution inside the tunnel resulting from fan activation in this scenario. As can be seen, symmetrical air flow from both sides of the incident location towards the extraction point can be achieved.

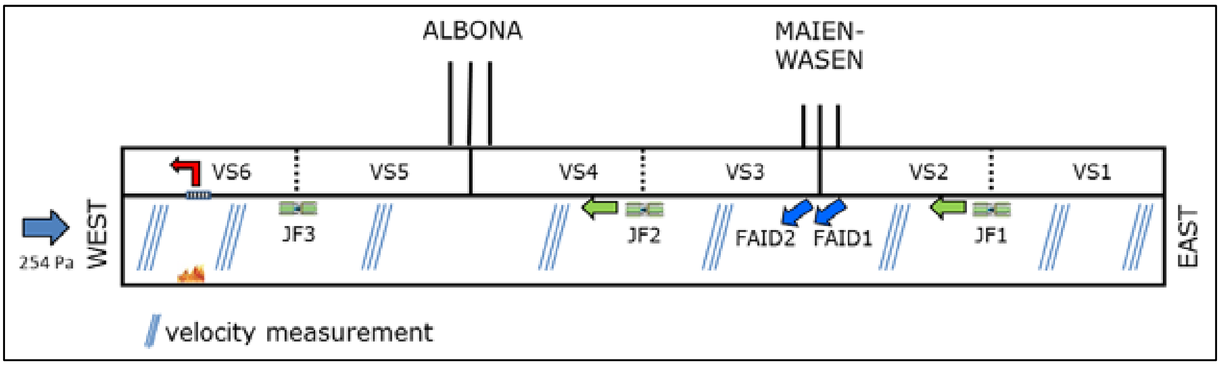


Figure 12: Fire ventilation for an incident in ventilation section VS6.

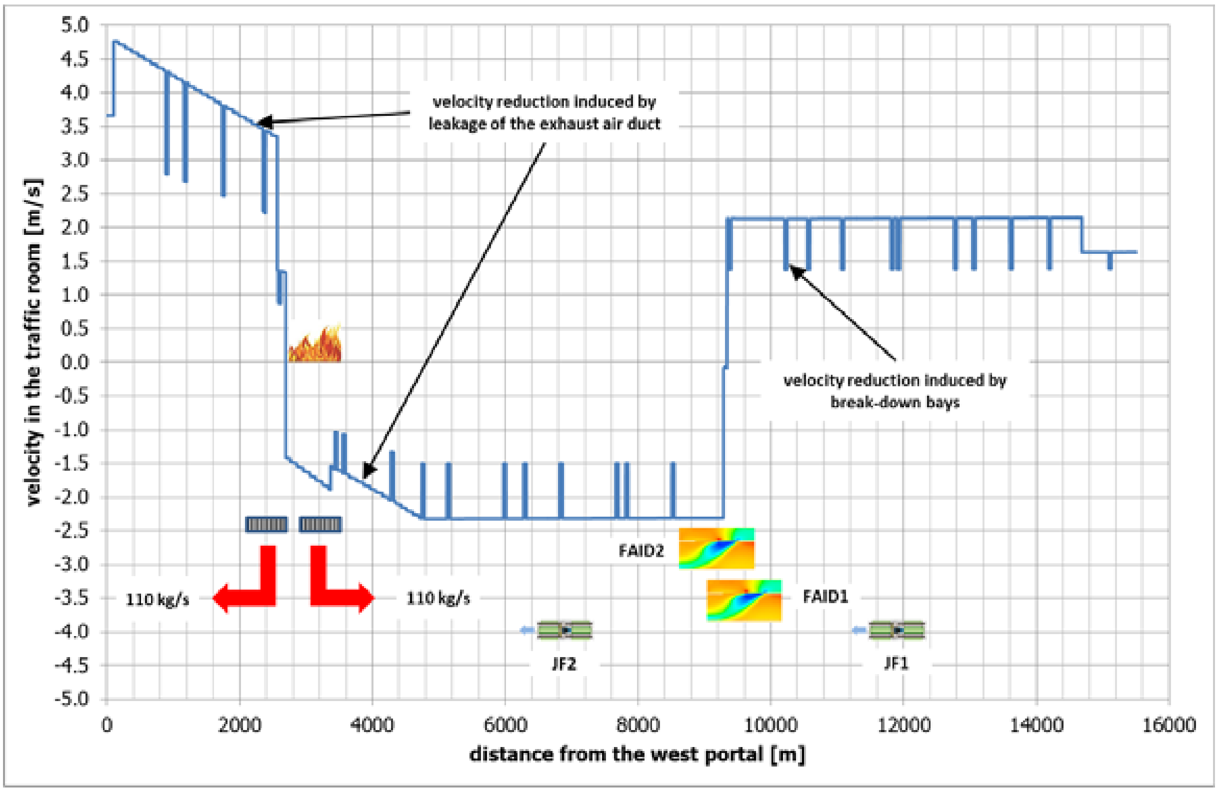


Figure 13: Air velocity distribution for an incident in ventilation section VS6.

The ventilation system chosen for the Arlberg tunnel utilises as much existing equipment as possible and thus helps avoid new construction of major civil works that would otherwise be necessary in order to achieve current safety requirements. It represents a compromise between the requirements of cost efficiency, the time available for system refurbishing and upgrading, and technical feasibility. The tunnel is quite long, hence the air masses that need to be moved in the case of a fire are relatively large. As a result of the high level of inertia, the control behaviour of the flow is expected to be relatively slow. However, the equipment available to control the velocity inside the tunnel (FAID and air extraction) is powerful enough to cope. Sufficient time for adjusting the software parameters as well as for testing the whole system will be required. This has to be followed by a dense schedule of system tests in order to minimise the risks of producing an overly complex, or unwieldy ventilation system.

3.4. Structural fire protection – fixed fire fighting systems

To protect the intermediate ceiling - and thus the fresh air duct which serves as an emergency escape - against high temperatures a high pressure water mist system will be installed in the traffic room of the Arlberg road tunnel. Aqueous Film Forming Foam (AFFF) is used to coat fuel, preventing its contact with oxygen, and thus resulting in suppression of combustion. The high pressure water mist system enables the water mist to penetrate into a fire in liquid form and result in cooling due to evaporation at specific locations. High pressure water mist also effectively fills up the protected space and provides superior cooling, hence protecting surrounding equipment and structures.

<u>Design parameters for the FFFS:</u>

- Liquid pool fire: 200 MW
- Operation time: 120 Minutes
- Aqueous Film Forming Foam: 1 % - 3 %
- Basic design parameters: RVS 09.01.45 [5] and RVS 09.02.51 [6]

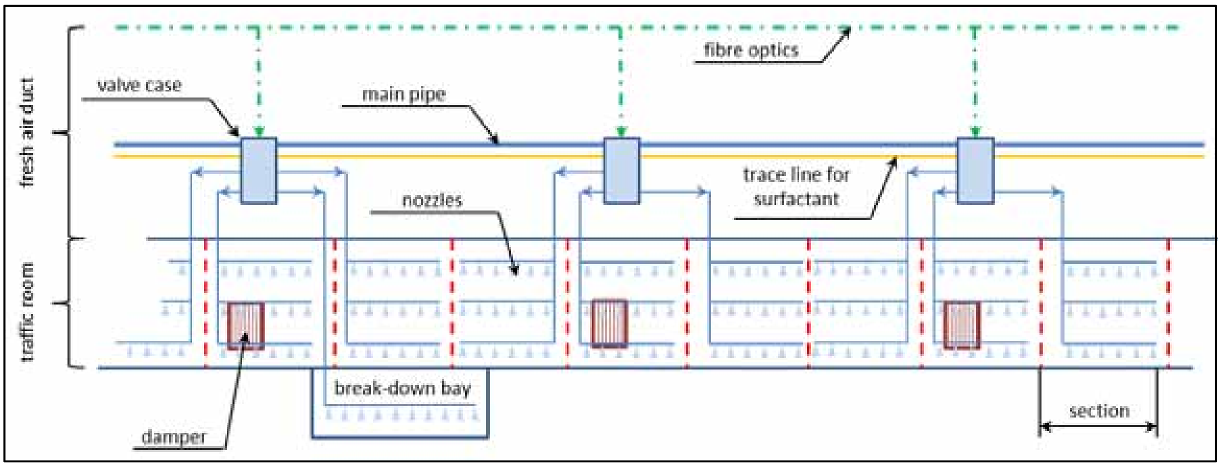


Figure 14: Scheme of the high pressure water mist system.

4. CONCLUSION

The Arlberg road tunnel will be refurbished within the period autumn 2014 to autumn 2017. A feasibility study including 5 options for upgrading the tunnel was performed. The feasibility study showed that the construction of a second tube for unidirectional traffic (option 5) or the construction of a new bi-directional tube - using the existing tube as escape and rescue tunnel (option 4) - is not suitable due to the low traffic volume and the length of the tunnel. Option 1 requires too many tunnel closures and the loss of toll income is too high. Option 2 was not found to be acceptable due to the high safety risks arising during the construction time.

Therefore option 3 was selected for realisation. This option has a relatively short construction time and is also to be recommended from an economic and technical point of view.

The Arlberg road tunnel has a full transverse ventilation system. In order to minimize construction costs the fresh air duct will be used as an egress way. Construction of long cross-passages to the parallel railway tunnel can thus be avoided. In the case of fire tunnel users can reach the fresh air duct (safe area) via ramps from the traffic room. From the fresh air duct the egress ways lead to existing collecting rooms, from where the tunnel users can be evacuated through the railway tunnel.

In order to protect the fresh air duct against high temperature, fixed fire fighting systems will be installed in the traffic room. In addition, complete replacement of all the safety equipment is to be carried out.

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CONTROL OF THE TUNNEL-VENTILATION SYSTEM IN THE NORTHERN LINK (NORRA LÄNKEN) IN STOCKHOLM

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ABSTRACT

The Swedish Transport Administration (in Swedish, Trafikverket) needed to establish a good approach on the methodology to describe the functionality and also the demands for the operation and control of the tunnel ventilation in a new and complex road tunnel. Therefore, in the Call for Tender the technical description of the tunnel-ventilation control had to be in such a format that it could be used as a software application for the system integrator. There are some difficulties you had to be aware of in this kind of contracts. The main contractor for installations in a traffic tunnel had to handle approx. 10 different technical systems. Can we really expect the contractor to be an expert or find experts on everything, especially when this tunnel project is so particular?

1. BACKGROUND

Trafikverket makes contracts with functional requirements in major projects for installations. One major issue is to find the right technical knowledge and also at lowest cost to handle this type of tasks for a system integrator. The Norra Länken is a very complex tunnel system in Stockholm city.

Here are some basic data of Norra Länken:

- Motorway twin-bore tunnel 2x4500 m.
- The tunnel includes underground on- and off ramps
- For safety and practical reasons he tunnel is divided in 15 independent operating sections.
- The tunnel is designed for a 100 MW fire
- Longitudinal ventilation with jet fans: approx: 150 jet fans
- Jet fans with fixed speed. Some jet fans have adjustable speed and some of those are reversible
- Air-supply stations: 2 (with jet fans)
- Exhaust air stations: 3 (with jet fans)
- Dimensioned for queue and traffic congestion
- Fixed Fire Fighting System (FFFS)
- Very onerous requirements on the environmental ventilation: on internal air-quality and on minimising the impact of vitiated tunnel air to the environment at the portal zones
- DCS, Control system (ABB 800Xa) with approx. 11300 objects.

Layout of the Ventilation system and Sensors

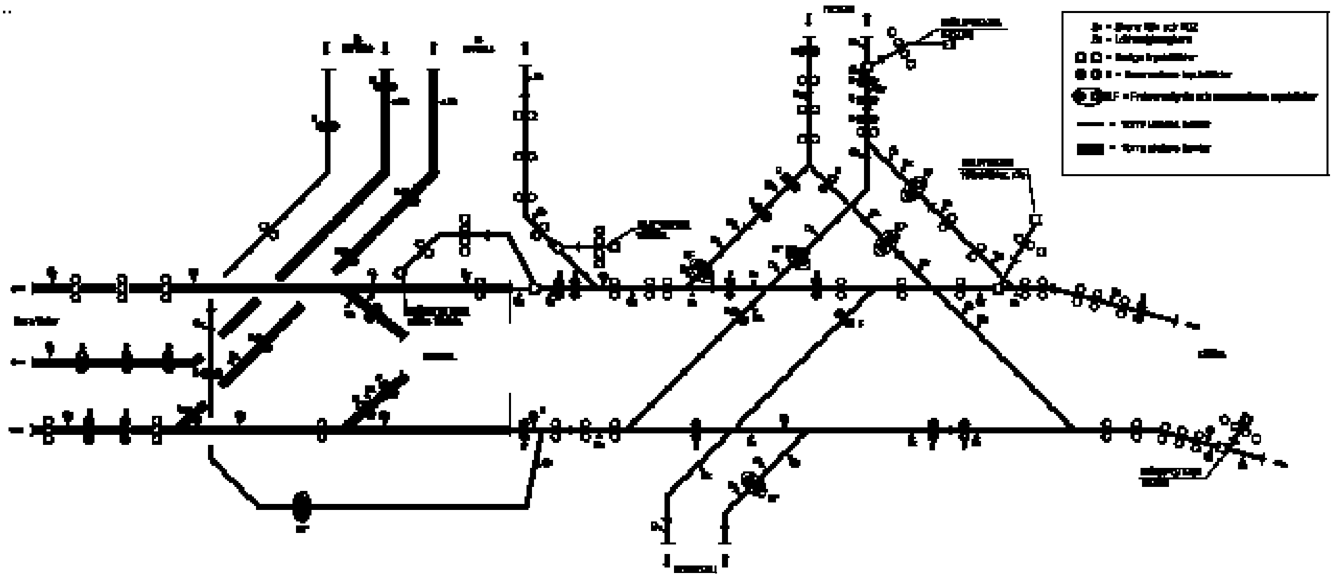

Figure 1: Norra Länken layout of the tunnel-ventilation system showing fans and sensors.

We have to bare in mind that neither the contractors nor the Client has got extensive experience in complicated solutions for tunnel-ventilation. Moreover, the contractor can't be expected to make all simulations and make the strategic thinking for fire-ventilation and environmental-ventilation. This is the responsibility of the Client, Trafikverket.

2. WORK PROCESS

Our task was to produce documentation so good that it could be used as basic data for software application for the system integrator.

There are different approaches of documentation to accomplish that.

- Text description for all jet fans and sensors
- Excel documents showing all jet fans and sensors
- Graphical function drawings
- Graphical layout of the tunnel-systems with all information included for fans, air velocity, etc. Combined with a text document describing type object and demands.

<u>Text description</u>

This is the most common way to describe different technical systems and objects in process applications.

The document normally requires a description of each object for its alarms, interlocking, parameters and normal operation for one type object or a complete system.

So if you should use it as a document for a software programmer for a control system, it had to be very detailed and correct in its descriptions.

Matrix layout with Excel

This kind of documents shows all fans in different locations and how they should operate in different operating modes.
As for the Text Description, a text document is still required for a more detailed description of each object for its alarms, interlocking, parameters and normal operation.
Also in this case, if you should use it as a document for a software programmer for a control system, it has to be a very detailed and with correct descriptions.

Graphical Function drawings

(Power-plant documentation according to VGB-standard. VGB is the European technical association for power and heat generation)
This is a very detailed documentation and it describes how the software for the control system should be done. It always starts with an overview. Here the function is described with graphics function blocks in an overview style (Figure 2).

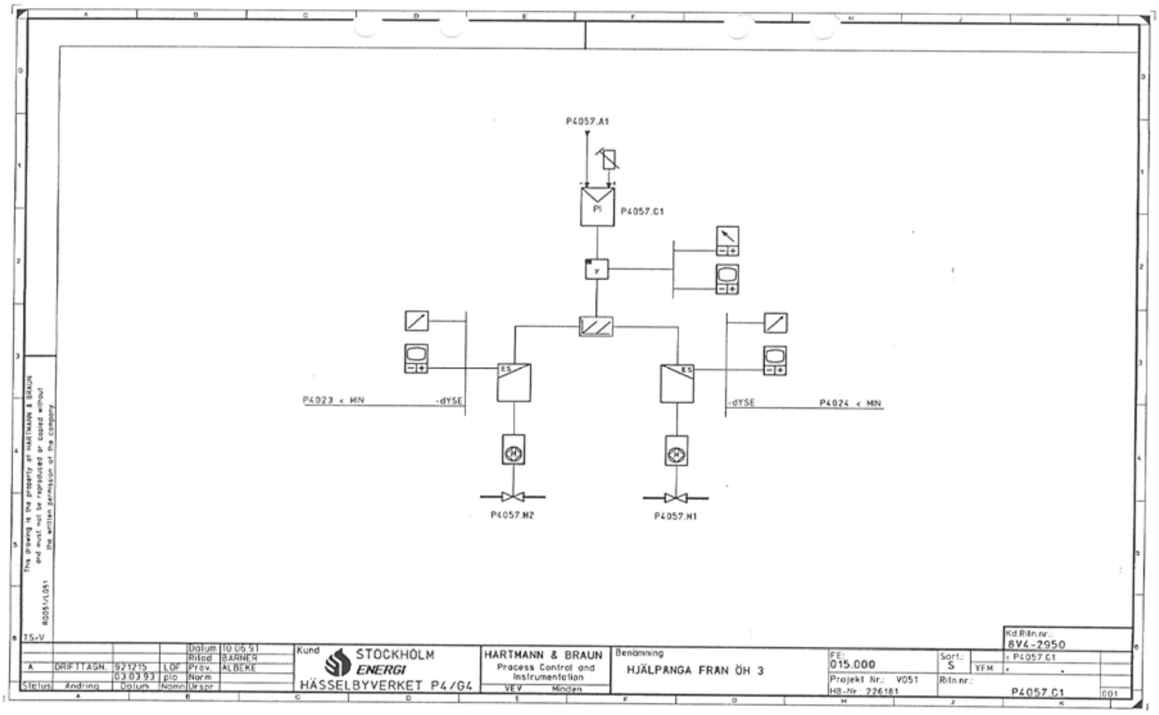

Figure 2: Example of an overview with graphics function blocks according to VGB-standard.

Then in the next example, it is described in a more detailed style (Figure 3). This is a drawing with graphics function blocks. Here, a software-programmer has all the information available to make a software application for this object. As you can see, it tells you that this controller is in a process picture with graphic display and alarms. It also shows that it has hardware in the desk for parameters as set-point and it shows the actual value there. Then it shows all graphic elements for this function. All texts are already there and even the hardware position in the cubicle and the name of the software program. In this case, you don't have to be an expert programmer to realise this function. In the working process, the programmer selects the graphic functions blocks from a software library and connects them to make a software application. In order to produce this kind of document, it takes a lot of skill and even then, you have to be an expert on your technical system.

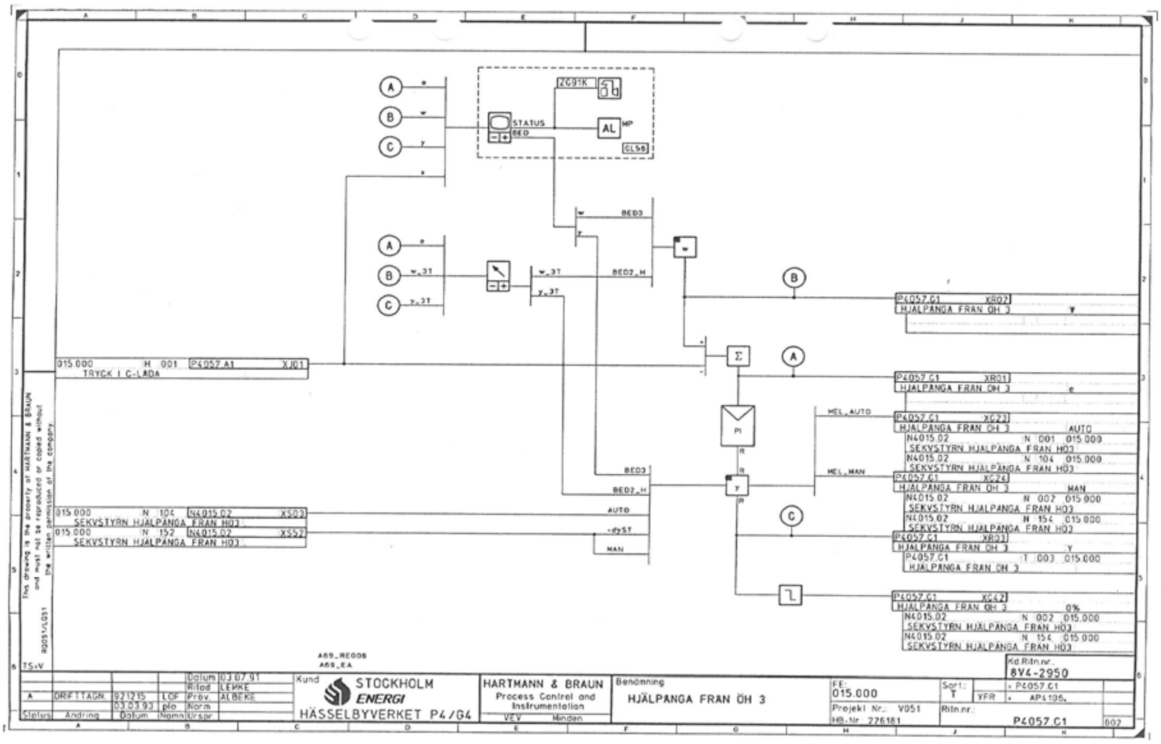

Figure 3: Example of an detailed schedule with graphics function blocks.

3. ALTERNATIVE APPROACH

1. Because of the functional demand structure in our contract, there were some basic rules we wanted to impose Provide functional demands and let the contractor make the construction and have the responsibility.
2. Provide a technical description for the tunnel ventilation-system with its alarms, interlocking, parameters and normal operation.
3. Provide a graphical layout of the tunnel-systems with all information included for all fire cases and for ventilation (in-tunnel air quality).

Trafikverket selected the Graphical Layout of the tunnel-systems made in Excel. The document called the governance principles for smoke ventilation. The reason for this was to make it so good that it could be used as basic data for software applications and it can also be used in the testing phase for an easy verification of the control strategy. It shows in this overview format all fans and air-ventilation stations. It gives information on how the tunnel is divided into different ventilation areas and the names of the different tunnels. Each drawing shows a fire scenario in a specific location and how the control system shall control each jet fan. All values are made from simulations runs. There are also text describing general rules and principles. For the reader, the colour marking helps understanding what happens under different scenarios. Different modes of operation for the jet fans are clearly indicated.

The Graphical Layout of the tunnel system consists of two parts: one is for the fire-ventilation that has three different ventilation modes (also known as strategies).

- Minimal Fire-ventilation with an air velocity of approx. 1-2 m/s
- Fire-ventilation with an air velocity of approx. 2-3 m/s
- Forced Fire-ventilation i.e. maximum possible air velocity

This is a static control of jet fans but some connected ramps have an active control of jet fans with frequency converters for ensuring a certain flow maintaining a back pressure.

This documentation contains approx. 120 such layouts

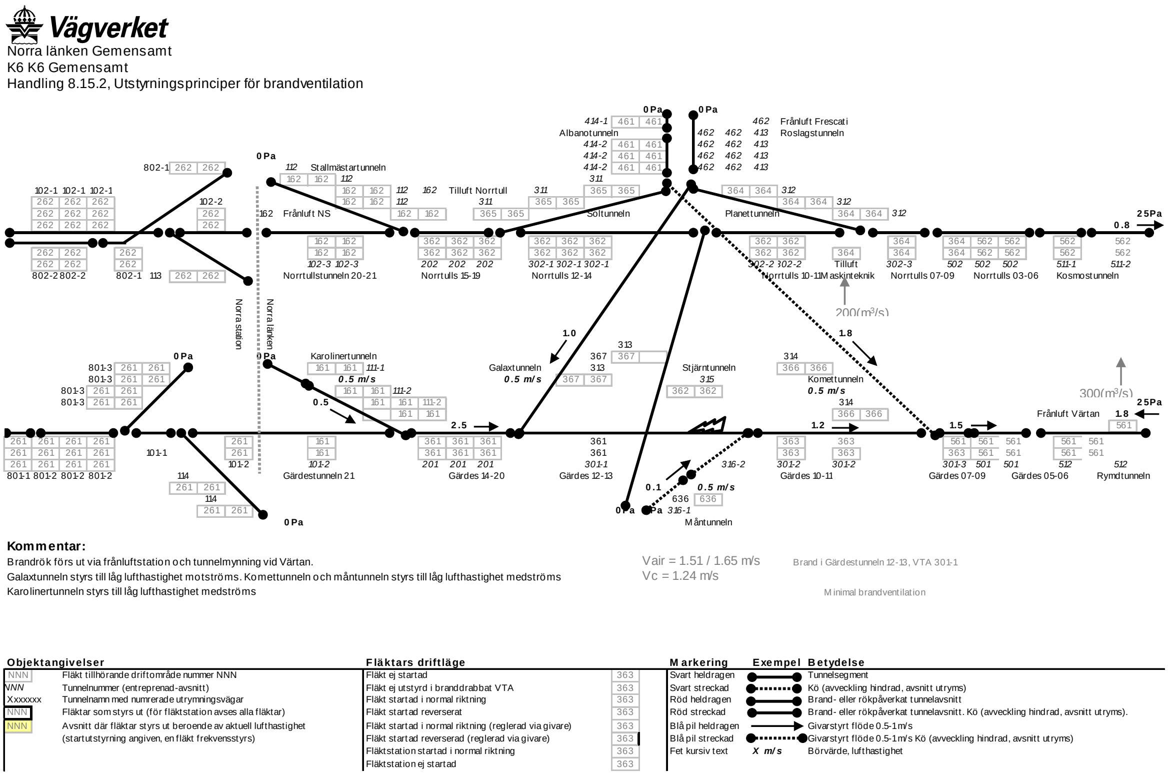

Figure 4: Example of the control principles for Fire ventilation

The second part consists of the environmental ventilation and the different control chains. During normal operation, the environmental ventilation has two objectives:

- Internal environmental ventilation (in-tunnel air quality)
- External environmental ventilation (impact on ambient air quality)

It has the same basic layout ad for the fire ventilation and describes the different ventilation areas depending on which control chain is in operation. This is an active control of jet fans and air- supply and exhaust-stations.

The documentation for this contains approx. 30 such layouts.

Text description

The main text description consists of a document that describes the ventilation strategy with different operation modes; Minimal fire-ventilation, Fire-ventilation and Forced fire-ventilation. It also describes monitoring of jet fans i.e. running time, start counter, safety functions, interlocking and fan redundancy.

The next part describes the environmental ventilation and the different control chains, for Internal environmental ventilation (in-tunnel air quality) and External environmental ventilation (impact on ambient air quality.

4. SECOND OPINION

Trafikverket wanted an external review, so we contacted Dr Rune Brandt from HBI Haerter in Switzerland to scrutinize all documentation. Dr Rune Brandt gave us some valuable recommendations and we made changes mainly in the layout of environmental ventilation. Subsequently, all documentation was included in the contract for installations in Norra Länken in 2010.

The Norra Länken project will start commissioning during 2014 according to those documents.

AUTOMATIC RESPONSES WHEN SOMETHING HAPPENS: WHAT SHOULD BE IMPLEMENTED IN THE FUTURE

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ABSTRACT

Most road traffic centrals are reluctant to the use of automatic response in tunnels. They claim it disturb traffic unnecessary, give wrong reaction, is dangerous, and many more reasons. But mainly, it is to may false alarms!

The truth is, in many cases it will improve safety, reduce wrong decisions, act faster, but it will cause closed tunnel more often, but only for few minutes.

This paper will consider benefits with automatic response, and demands to system, if you are using automatic response.

Key words: testing of tunnels, demands to consultant, design of ITS systems in tunnels

1. INTRODUCTION

The Road Traffic Center in Bergen is responsible for supervising nearly 250 tunnels, and the number is increasing. To have a cost effective Road Traffic Center, it is necessary to keep the number of people on duty as low as safely possible. One of the conditions to be able to maintain safety with few operators is to increase automatic responses to given safety and traffic-related events. Automatic responses also increase the level of safety for managing various errors, as well. Before the fire in the Seljestad tunnel, in 1999, nothing was managed by automatic responses, except normal ventilation. This fire showed us that we needed more automatic responses. In the same time, the fire in the Gudvangen tunnel showed that automatic response, and predefined actions might cause more people to be exposed to smoke.

2. PHILOSOPHY

In many cases it is critical to close a tunnel fast and the consequences of using 1 or 2 minutes extra cannot be neglected. When an operator receives a fire alarm, he is supposed to check out the alarm to decide if it is real or false.

In the possess industry and oil platforms, we have learned that they cannot safely expect reaction times on less than 90 seconds. → they are afraid to shut down production. In the same way, the operators for a tunnel will resist to close the tunnel, in case it was not necessary.

During this time many vehicles may enter the tunnel, and if it is a real fire, the people entering the tunnel during this time are exposed to an unnecessary danger. If the tunnel is closed they are prevented from entering, although a queue may build up for several minutes.

Based on this, the road traffic central in Bergen, has decided that the philosophy should be *think and open,* not *think and close.* These are two very different approaches to the same problem. The road traffic central in Oslo use the opposite, think and close.

Fire ventilation in longitudinal ventilated tunnels

The main philosophy has been to ensure fast access for the fire brigade, to put out the fire as soon as possible. In the considerations, the assumption has been that this will cause more people to be exposed to smoke, but we expect them to survive. The fire in the Gudvangen tunnel showed this. If they had waited, ore not changed the direction of the ventilation, far less people would have been caught in the smoke. The road traffic central had no information about how many people it was on either side. The fire was 3,5km in from one side and 8 from the other side. The tunnel do not have any ITV due to that it is a low traffic tunnel. The road traffic central followed instructions. And the result was as planned! No secondary deaths, but 73 people to the hospital for treatment of smoke poisoning.

But the fire has restarted the discussion about what do during a fire!

If you want to use an automatic response, you MUST have a predefined action.

In Norway only very few tunnels has installed systems for fire detection. Most of the low traffic tunnels do not have ITV, or any kind of detection exept for traffic caused pollution I the tunnel. According to the EU regulations, these tunnels do not need ITV.

3. SYSTEMS DEMAND AN AUTOMATIC RESPONSE

If you implement automatic actions based on what you measure in a tunnel, your tolerance for false alarms is drastically reduced. There is no longer an operator filtering the alarms. When we treat removing a fire extinguisher as confirming a fire, we do not have many false alarms.

We have many long, low traffic tunnels in Norway, where the consequences of starting the fire ventilation system are unnecessarily expensive. But with good systems constructed to avoid false fire alarms, in the last 4-5 years we have allowed fire ventilation systems to start automatically together with an automatic tunnel closing, based on the removal of a fire extinguisher.

Many tunnels used to be closed automatically based on pollution levels in the tunnel, but this was removed due to frequent errors from gas monitors. Today, however, these systems are being installed in some new tunnels again, and will probably be installed in more tunnels.

The main problem here is still zero point drift and the maintenance of the gas sensors.

In the Knappe tunnel in Bergen we originally wanted to close the left lane and specific tunnel section when the video analysis detected a wrong-way driver. The implementation of this was delayed, due to many false alarms. Without automatic response, the time necessary to confirm wrong way driving and, close left lane is too long.

Several “close encounters” forced the road traffic central to implement automatic response to wrong way driving. But now it is based on two successive cameras. This combination does not give false alarms, but the reaction is delayed compared to detection on one camerea, with approximately 20 seconds. This is a drastically improvement compared to manual reaction.

4. AUTOMATIC RESPONSES

A main rule for all PLC systems must be: *An automatic response should always be performed as close to the physical process as practically possible.* This is the theorem on which we build all PLC systems. It creates very modular and stable systems where large sections are independent of the levels above them. The discussions arise concerning practical issues, where different designers and system integrators have many different approaches.

When working with instructions for the operators, we decided that some procedures could be replaced with automatic responses in the PLC systems. When a fire extinguisher was removed from its location, the operator was supposed to close the tunnel and start the fire ventilation system. When this is performed by an operator he will always think and look for confirmation before closing the tunnel. This instruction was replaced with an automatic response. Now, before the operator can react, the tunnel will be closed and the fire ventilation system will be up and running. The instruction for the operator is now reduced to "call the fire brigade". If the tunnel is equipped with a camera, he will of course have a "pop up camera view" of the actual area. AFTER he has called the fire brigade, he is supposed to start looking for other information that might confirm if there is an actual fire or not. *By doing it this way, we have changed the modus from "think and close" to "think and open*". In many tunnels with medium traffic, it really doesn't matter if people have to wait for 5 minutes. In a high traffic tunnel, several vehicles would have entered the tunnel during the decision time, which would represent an unnecessary risk. If it is a high traffic tunnel, it will probably have cameras and thereby quick confirmation of the actual status. In a complex tunnel system with junctions there are also different ways of starting the ventilation system, depending on where the fire is. By definition the fire is assumed to be in the area of the fire extinguisher first removed and the fire ventilation system will then start accordingly. Adjustments can of course be done from the Road Traffic Center. The merging of systems has made it possible to add a command to the "on screen" camera picture for "fire at this location" (see Figure 3). This command will start the fire ventilation system for that area, and stop traffic moving toward the fire at all possible points in the tunnel. "One decision – one button" means fewer operator errors.

The ventilation during normal traffic has of course always been automatic, with the possibility for the operator to override the system.

And of course, if you install modern fire detection systems, and use a combination of smoke and heat for detection of a fire, you will also know where the fire is. The problem are again that few of this systems are stable enough to be used for automatic response, they either give several false alarms, or no alarm.

4.1. Automatic response for traffic incidents

Many operators and people working with traffic management, will claim that it is not possible to have automatic response for traffic incidents. Impossible or not possible are word that never should be used.

It is more difficult to predefine action for traffic incidents. Look at stopped vehicle. Is it possible to have automatic response for closing lane, and reducing speed limit due to at stopped vehicle?

Standard ITV detection systems might give you which lane a stopped vehicle is in. The problem arises when it is between lanes.

Most vehicles stop in the right lane or emergency lane. In a highway tunnel with two lanes in each direction it should be possible to categorize a stopped vehicle I three categories.

1-left lane, 2-not sure, 3-right lane

For the number two action, the operator will have to decide what to do, as today. But for the others, automatic closing of lane should be easy to define. In all cases the speed limits and warning signs should come on by automatic response.

Again, the demands for accuracy, and tolerance of false alarms are very low. I do not know of any systems based on video detection with sufficient quality for automatic response. Perhaps radar detection will be good enough for this.

4.2. Construction of automatic systems

4.3. Basic Design

When you choose to use automatic response systems you are vulnerable to false alarms. This forces you to change the construction of certain components in the system.

Let us look at a cabinet for fire extinguishers.

Old systems: The cabinet is mounted on the tunnel wall and is subjected to vibrations caused by high/low pressure from heavy duty vehicles. There are mechanical switches for detecting an open door and the removal of a fire extinguisher. This results in false alarms for fire extinguishers being removed when large trucks pass by. As long as the switch is new the problem does not exist, but as time goes by this becomes a problem, as *maintenance is always short of funding*! By changing the alarm to "door open" and "fire extinguisher removed" at the same time, the number of false alarms is drastically reduced. This could be done by changes in the software, but this is still not good enough for automatic response systems.

New systems: Mechanical switches have been replaced with inductive sensors, where the steel canister has to be moved 20 mm before an alarm situation is detected. This has been installed in nearly all tunnels in the western region of Norway. Only in one tunnel has I learned of false alarms concerning this. Here it was due to installation, not according to contract. The supplier had used inductive sensors with gap distance 12 mm. This caused false alarms in the cabinet outside the tunnel, when the snow plow passed, at the caused the cabinet to shake.

If the PLC system is constructed the wrong way, you can still have false alarms when you lose power to the station.

Automatic systems require careful construction of the system. What will you do when a fuse is out or you lose power to the cabinet for the fire extinguisher? Close the tunnel? Or just keep an extra eye on the tunnel until it is fixed? It is not popular to close a tunnel just because a few cabinets with fire extinguishers are not being monitored. Closing a tunnel might even have a higher risk of causing secondary accidents. (If you have everything on one fuse, shame on you!)

4.4. Where to use automatic responses

4.4.1. Start-of-Fire Procedure

Today only the removal of a fire extinguisher will trigger an automatic start-of-fire procedure. We regard the removal of a fire extinguisher as a "confirmed" fire until a "no fire exists" is confirmed. This means that the theft of a fire extinguisher will close the tunnel, and start the ventilation as if the fire is in the area of the removed fire extinguisher. This procedure may only be stopped by a manual command, either from an emergency control panel or from the Road Traffic Center. The Road Traffic Center has many different ways of changing fire procedures or stopping them.

4.4.2. Wrong-Way Driver

If we have a trusted system for the detection of a wrong-way driver, we will be able to have the left lane closed in less than 20 seconds. This reduces the risk of accidents during these situations. Camera detection does have some limits, and other systems are preferable.

When using image analysis we had one situation where we had an alarm due to a fly crawling across the camera lens in wrong direction. Don't expect that it is possible to eliminate all false alarms!

4.4.3. Pollution – High Gas Concentration

No one should intentionally construct a system where they would have to read pollution levels and manually set the levels for ventilation. But, unfortunately, we have built many tunnels where the closing of the tunnel due to high levels of pollution must be done manually based on an alarm from the tunnel. The main problem is a lack of accuracy and neglected maintenance. To close a tunnel based on 0.75 ppm NO_2 ±0.4 ppm is not something we feel comfortable about. And this is the warranted accuracy for the best electrochemical sensors. To use NO, and close with a level of 6.75±1.5 ppm is far better. But since the NO_2 levels as compared to NO levels are not constant, you still need to measure NO_2, especially in long tunnels.

4.4.3.1. Other Situations for Automatic Responses

All tunnels longer than 500m are supposed to have a radio system for FM radio as well as the channels used by emergency personnel. The possibility for speaking to people in cars via FM radio is nearly never used. No one has been able to provide regulations on what to say when. Different people in fire brigades, police, and health care services are unable to agree on standard messages during different kinds of accidents.

If we were able to define what to say when, it would be possible to have predefined messages in the tunnel, which could by triggered by automatic or manual response systems.

4.4.3.2. Automatic Reduction of Speed Limits During Queue Situations

Many tunnels will have a queue situation during rush hour or during accidents. A queue stretching halfway through the inside of a highway tunnel is a situation no one likes, but it is unavoidable unless you close the tunnel during rush hour.

It is easy to reduce the risk by automatically reducing speed limits based on speed measurements in the tunnel. Here a few too many speed reductions, do not pose a major problem

5. SPECIFICATIONS FOR NEW TUNNELS

When you write the specification for an automatic system, you have to consider, and specify with great detail how the system should work. DO NOT EXPECT the system integrator to know how it should work.

It is now very important that the demands for the software are strict, and well planned. Any combination of input, where the output is not specified might cause a dangerous situation in real life.

All demands must be possible to identify and verify. Any demand that cannot be verified is worthless.

This detailed specification of how the software must work is time consuming, and difficult. Most consultants will be afraid of being sued, and thereby try to avoid giving specific instructions. This in combination with few consultants who know software and traffic makes them even more reluctant.

Byers will also try to say, it must work, and stop there. Their problem is when the system integrator asks, where do contract say it must work that way? The road administration must then order a changer. Even when the supplier accept, it as his responsibility, it will often be time consuming to change the software, and the opening of the tunnel will be delayed.

Remember, if you cannot tell the software engineer how it should work, how can you then expect him to understand how it should work? He is good at writing software, not traffic safety!

6. TESTING

Since what you build in a tunnel is a safety system, you should write the entire specification in a way, which makes it easy to test.

The Norwegian public road administration has specified several levels for testing, but they are still, in my opinion, taking to light on Factory Acceptance Test, and parts testing before systems are finished. But they have specified System integrators performance test, which has do be done as a complete test for sensor to automatic response to road traffic central. This test consists of testing all objects in the tunnel. For every object the system integrator must sign that it works from end to end.

After this is delivered, then the road administration starts their test, the Site Acceptance Test. If it shows that the previous test is false, they can demand that the system integrator test everything again. And when SAT is accepted, User Acceptance test start, and now it is the road traffic central testing the system. They are looking closely to stability. To test this they test all kinds of combination of commands.

Many a tunnel has worked fine, when you go from a normal situation – to situation 1 or x and back to normal. Trouble often arises, when you change from situation 1 to situation 2 and so on. Now the lack of specifications becomes visible. Combinations of commands not thought of, might give very dangerous situations in a highway system with traffic.

These results, when discovered at the end of the project will normally cause delayed opening of the tunnel.

7. CONCLUSION

If you want to reduce the risk of delayed opening, and extra bills at the end of the project, you must use more time for specifications, and make it easy for yourself when you are going to test the systems. A detailed specification like this will always contain some errors. The benefit is that you often discover them early in the project, so the consequence is reduced, compared to when you just say, "It should work". In the last case you will discover the errors during SAT.

SAFETY INTEGRATED. HOW MUCH SAFETY LIES WITHIN TUNNEL AUTOMATION?

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ABSTRACT

In automation technology, fail-safe control components have been long enforced. Ensuring the safety of human, machine and equipment has led to a wide product range of safety components at any considerable manufacturer of control components. Thereby, functional safety is able to cover a further aspect in addition to the availability of control systems. Compliance with the applicable standards is a prerequisite to realize a secure machine or facility.

In tunnel automation, consideration of the availability of the control system has been proven and led to a high standard for automation solutions. Fail-safe control components are able to add to the automation solution, besides availability, also the component of functional safety, and even in the case of error to increase the quality of execution of the control task and, thus, contribute significantly to risk reduction.

This paper seeks to provide insight into safety engineering from the perspective of automation and to highlight possibilities of tunnel automation applications.

Keywords: tunnel automation, high-available, safety integrated, safety

1. INTRODUCTION

„Ensuring safety in automated processes is not only a question of human obligation, but also of economic reason."- Werner von Siemens 1880

An old quote that, even in today's time, hasn't lost of its topicality. Especially in tunnels, safety is top priority.
Through risk analysis of tunnel systems, measures can be defined that help increase the safety in the tunnel concerning each particular application. These measures determine the way of ventilation systems, possibilities of hazardous transportation, etc. The inclusion of the automation system, which implies the components allowing a safe operation of the tunnel, is usually not considered.
A robust automation system with a high-availability configuration is a prerequisite to ensure safe operation and to offer, in case of fire, the highest possible protection for human beings and the tunnel itself. However, it is vital to note that "zero risk" is not feasible. As shown in Figure 1, risk can be reduced to an acceptable level by applying appropriate measures and, in the final step, also via a safety system (Failsafe Control).

Within the first step, structural measures should be a priority. These are adequately described in various standards and guidelines.
Nevertheless, it should not be forgotten that control technology contributes significantly to the operation and safety of the tunnel.

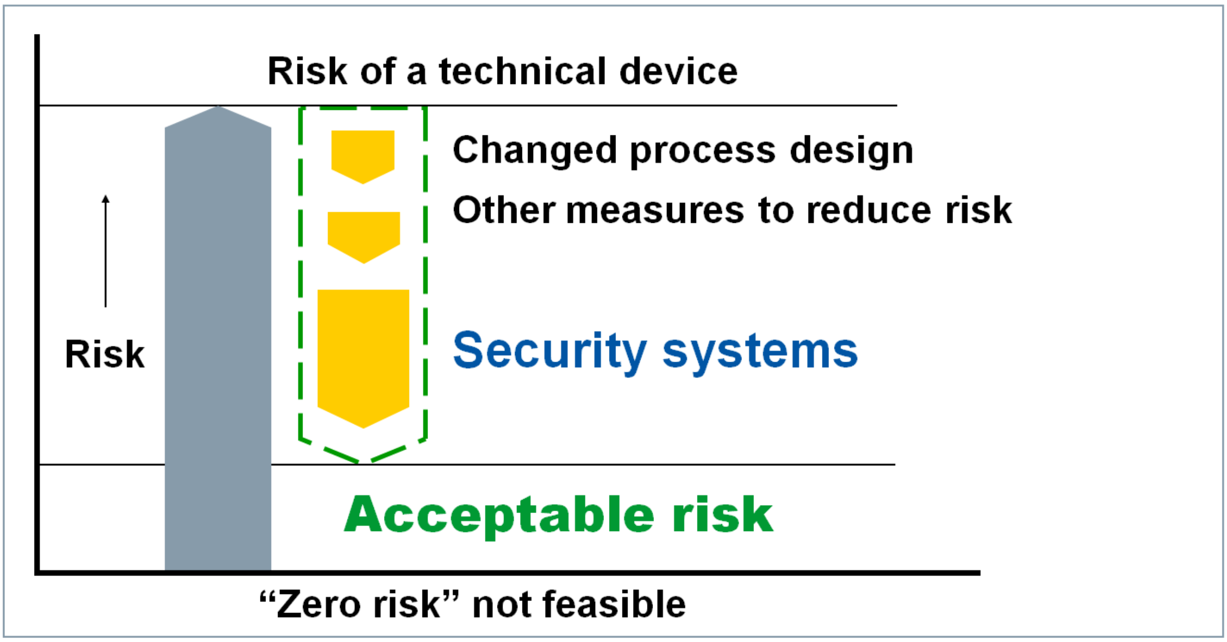


Figure 1: Risk of a technical device

Modern control technology regulates complex ventilation programs, manages the flow of information within the tunnel, takes control of traffic programs and guidance systems and, thus, forms the backbone of all technical equipment in the tunnel.

2. SAFETY FROM THE PERSPECTIVE OF AUTOMATION TECHNOLOGY – THE BASICS AND DEFINITIONS

Particularly in tunnels, special attention needs to be paid to availability, functional safety and functional integrity. Availability and functional safety can be guaranteed through the system design and the selection of suitable control components.
Functional integrity of the control system should be given when the automation system could be directly exposed to the effects of fire within the tunnel (mostly not the case when spatial separation).

2.1. Availability

Availability is the probability of a system being operable at a predetermined time. It can be increased by the use of high-availability modules, which extend the MTBF (Mean Time Between Failure) of a system by a large factor. [1]

2.2. Functional Safety

Functional safety describes the part of the system's safety, which is challenged by a 100% function of the safety-related system and the external devices for risk reduction. Once the system detects an error, it leads to a safe-defined state of the application or the machine / facility. [2]

2.3. Functional Integrity

The functional integrity (fire resistance) of a component is part of a substance's reaction to fire. It is measured by the duration for which a component keeps its function in the case of fire. Depending on the prescribed duration of function maintenance, E30 / E90 (integrity at least 30 / 90 minutes) is required for the wiring systems (cables and ducts). [3]

2.4. Norms and Guidelines

For control systems to meet the safety requirements and thus offer functional safety (Safety Integrated), they must principally be designed accordingly to the basic standard IEC 61508.

- IEC 61508
  Regarded as a fundamental standard and the basis for safety standardization. It covers all areas in which safety-related protection is realized by electrical, electronic, or (memory-) programmable systems. [4]

The way in which systems need to be safety-related designed, is treated in the standard IEC 61511 and IEC 62061.

- IEC 61511
  Functional safety for processes, sector-specific standard for the process industry [5]
- IEC 62061
  Safety of machinery – functional safety of electrical, electronic and programmable controllers of machines and equipment [2]

Regarding the minimum requirements for safety in tunnels of the road network one must consider for Europe the directive 2004/54/EC and for respective member states corresponding guidelines for implementation. Exemplary, Germany RABT (guidelines for the equipment and operation of road tunnels) and Austria RVS (directives and regulations for highways) are being considered in terms of availability and functional safety of automation.

- RVS: The RVS prescribes explicitly the consideration of the system redundancy within the control system depending on the risk level. Functional safety of the automation system is not being covered by this directive. [6]
- RABT: The RABT also describes the redundancy of control systems and bus systems. Regarding functional safety of the control system, no description is being provided. [7]

Therefore, control manufacturers and installers of the equipment need to obey the directives in order to fulfill the safety requirements.
In the above guidelines for tunnel equipment inclusion of the availability is given, however a consideration in terms of functional safety is not yet explicitly stated.

3. TECHNICAL SOLUTIONS

What are the possibilities for designing a fail-safe control system and which advantages can the system provide?

3.1. Design variations for Failsafe Controllers

Considering a purely fail-safe system, four construction alternatives arise as shown in Figure 2. Looking at the cost analysis, flexibility, ease of programming, maintenance and commissioning, the structure would prevail with only one SPS and mixed I/O system (Figure 2, variant 4).

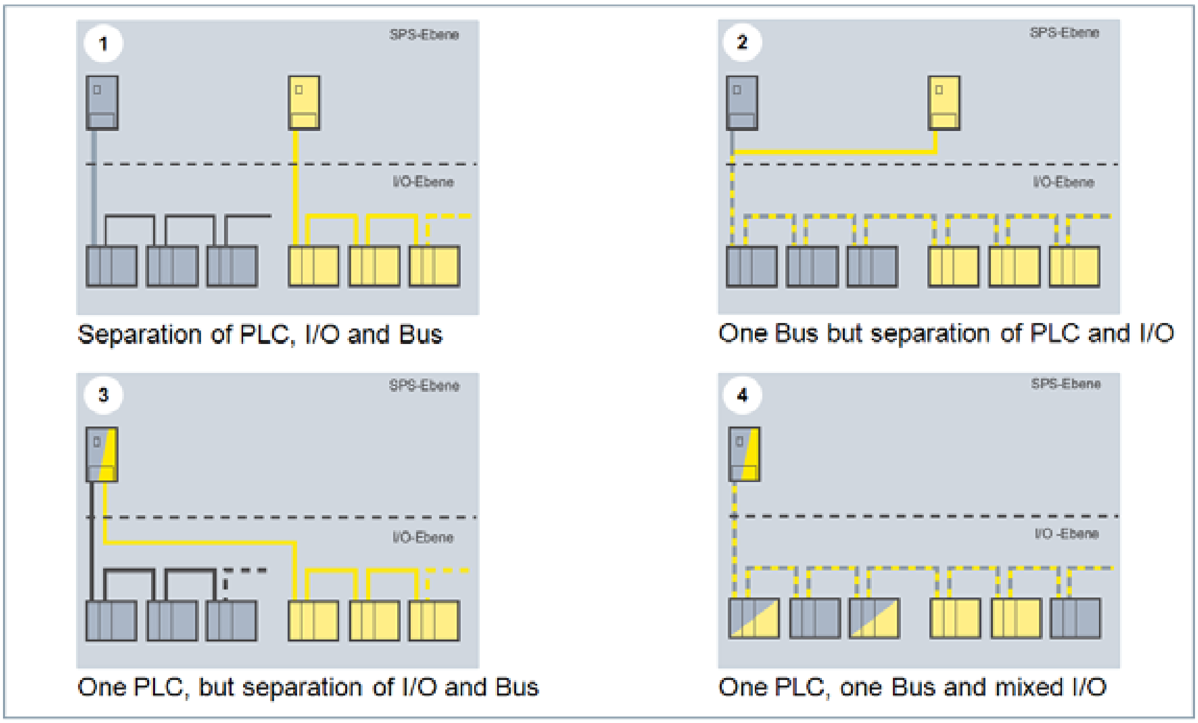


Figure 2: Fail-safe design variations (yellow components are fail-safe modules)

For the bus system, it is recommended to use a standardized and possibly widespread system, which is also able to allow fail-safe communication. Since its introduction in 1989, PROFIBUS has become the world's leading field bus system for the automation of machines and plants.
In addition to PROFIBUS, the Ethernet based PROFINET also counts to the world's most widespread bus systems. Both bus systems are supported by the PI organization (PROFIBUS und PROFINET International), which is the world's largest automation community.

Relevant guidelines mentioned in chapter 2.4 define primarily a high-available system. Logically, in the case of an additional fail-safe structure, a system can be chosen, which supports a high-available configuration where components can run fail-safe as needed. A basic requirement is that the PLC (programmable logic controller) runs high-available and fail-safe. Thus selected system architecture, as shown in Figure 3, can be designed as a fail-safe high-available system via a skillful selection of additional fail-safe modules, inexpensively and without changing the system architecture.

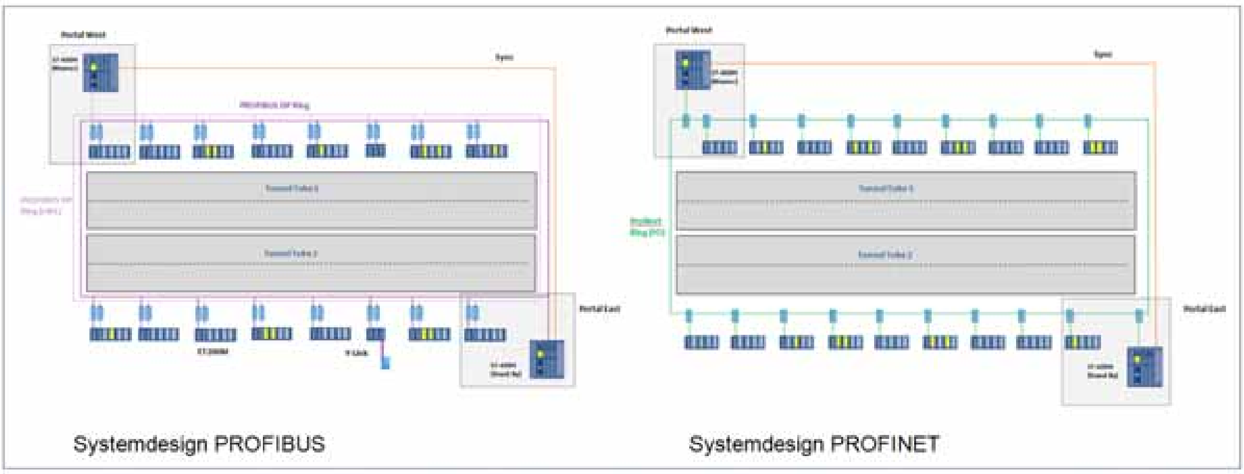
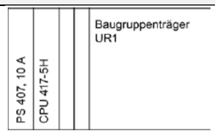
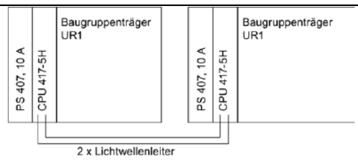
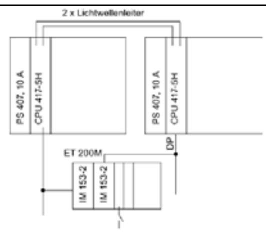
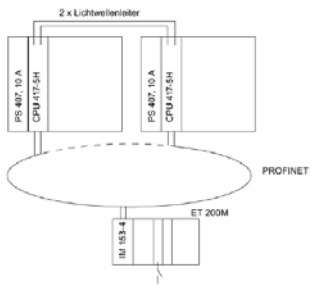


Figure 3: Construction types of high available fail-safe controls

3.2. Availability and functional safety of high-available fail-safe systems

The MTBF (Meantime between Failure) value is relevant for the availability of a module. The MTBF represents a statistical mean for the average time between two random failures during the normal period of use [8]. Table 1 displays the effect of a high-availability setup on the MTBF value. Concerning the control system, a Siemens S7-CPU417-5H was used for this calculation. This type of control is already applied in tunnels worldwide and due to its hardware-based PLC architecture (no PC based control) it comes with high robustness (MTBF 23 years). Hence, in case of a high-availability configuration, the MTBF value can be increased by the factor 38. Involving the control system periphery into the system's observation, an additional significant increase of the overall system can be achieved.

Table 1: Characteristics of high-availability automation systems [9**]**

PLC Layout		**MTBF Factor**
Fault-tolerant PLC in stand-alone mode (e.g. CPU 417–5H)		1
Redundant PLC 417–5H in divided rack, CCF = 2%		approx. 20
Redundant PLC 417–5H in two separate racks, CCF = 1 %		approx. 38
System Layout		**MTBF Factor**
One-sided distributed I/Os		1
Switched distributed I/O, PROFIBUS DP, CCF = 2 %		approx. 15
Switched distributed I/O, PROFINET, CCF = 2 %		approx. 10

Once the system is being expanded by including the aspect of functional safety, it is recommen-ded to consider the SIL (Safety Integrity Level) for the control system.

The Safety Integrity Level is, among others, a performance criterion, which describes the probability of failure of the SIS (Safety Instrumented System) in case of an incident. A higher SIL should therefore lead to a higher functional safety.

Consequently, the MTBF time can be increased significantly by a high-available system. Additionally, if the automation system is fail-safe the risk of a "wrong" executed switching action, in case of failure, can be reduced (Table 2). If an error occurs, the system is able to switch over into the safe mode where, in our case of a tunnel, ventilation, lighting or fire dampers can be controlled so that a safe operation is still possible. In order to guarantee this service, control components must be approved for the determined SIL level.

Table 2: Safety Integrity Level: Probability of failure on demand [5]

Safety Integrity Level	Probability of failure on demand (PFD) per year (Demand mode of operation)	Risk Reduction Factor = 1/PFD
SIL 4	>=10^{-5} to < 10^{-4}	100000 to 10000
SIL 3	>=10^{-4} to < 10^{-3}	10000 to 1000
SIL 2	>=10^{-3} to < 10^{-2}	1000 to 100
SIL 1	>=10^{-2} to < 10^{-1}	100 to 10

When considering fail-safe control modules, emphasis is not only placed on the system being able to switch off „safely", but a major feature is the safe operation in case of an error. And this safe operation plays an important role when looking at structures, such as tunnels, where the safety of a great amount of people is mandatory.

4. Risk Assessment Process

In order to perform risk assessment, a risk analysis must be carried out first (determination of limits of the machine / system and identification of hazards).
Then in the next step, the Safety Integrity Level can be defined via risk assessment. [10]

4.1. Risk Assessment

In order to elicit the required level of functional safety in a plant, it is vital to act according to the norms IEC 61511 or IEC 62061. Figure 4 shows a decision matrix executed based on the norm IEC 61511, which leads to the executed SIL level.

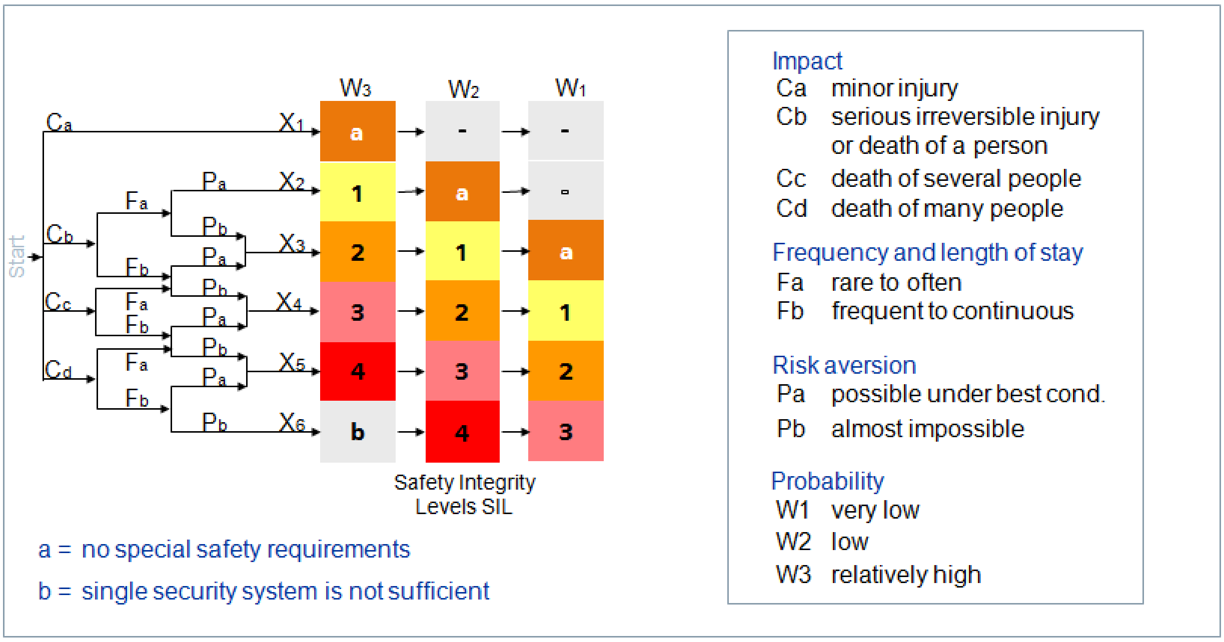


Figure 4: Determination SIL regarding IEC 61511 [5]

For an exemplary determination, following assumptions are made:

- Failure of a safety device may lead to the death of several or many people.
- The frequency and duration of stay in the danger zone is often to permanently.
- Risk aversion is possible under certain conditions.
- Probability of occurrence is very low.

Cc → FB → PA → W1 → SIL1 (Death of several people possible)
Cd → FB → PA → W1 → SIL2 (Death of many people possible)

The above mentioned assumptions are chosen to apply particularly for a tunnel. Consequently, consideration of the SIL Level arises as an additional safety criterion for a control system in the tunnel.

5. EXAMPLES

Examples for already running tunnel systems with highly available, fail-safe systems:

France - Tunnel Croix Rousse
Highly available and fail-safe control system (SIL3) / in operation
Germany - Tunnel München Mittlerer Ring Ost
Highly available and fail-safe control system (SIL3) / in operation
Belgium - Liefkenshoektunnel
Highly available and fail-safe control system (SIL2) / currently commissioned
United Kingdom - Dartford Road Tunnel and Bridge
Highly available and fail-safe control system (SIL2) / in operation

The provided examples show the determination of the SIL level for subsystems such as ventilation, lighting, control, etc. via a safety-related evaluation where the control hardware was designed accordingly.

6. CONCLUSION

First and foremost, it is important to distinguish between availability and functional safety. Availability is, as shown in many directives, a major topic. Functional safety is, however, often not taken into account, but should find its way to tunnel automation due to its proliferation and state of technology.

Posing the question of how much safety lies within tunnel automation, one needs to answer that emphasis is put on availability, but the idea of safety controllers and functional safety has only, so far, prevailed in some countries.

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MONITORING CENTRES - A DEVELOPMENTAL JOURNEY INTO THE NEXT DECADE

Anton Waltl (ASTL) and Peter Reiter (AX)

ABSTRACT

Control centres for traffic monitoring are the heart of each operation unit of a road network. All the electronically provided input comes together at one location and the persons on duty have to be provided by the most important information concerning traffic on the road network to be monitored. Although much information and data is handled and stored in the SCADA system, it is task of the system to bring abnormal traffic and operation situations to the awareness of the operators. This concerns all information which is required to run the network smoothly and to provide a safe journey for the users of the network.

The technical development in data transfer and communication technology allowed for an integration of huge parts of road networks including many critical infrastructure parts, like road tunnels. Hence the demands on such control centres have changed during the last decades dramatically. Nowadays the operation of a road network relies strongly on automatic support provided by the systems.

Keywords: Road tunnels, monitoring centres, SCADA systems

1. INTRODUCTION

Tunnel monitoring centres have evolved over the past 20 years from primarily performing system monitoring to currently processing traffic monitoring tasks. The original mosaic display with static system images and the display of operating notifications have been replaced by projection screens consisting of individual monitors. The resulting display flexibility has been primarily used for displaying video images from traffic monitoring.

Figure 1: Tunnel control station Plabutsch Tunnel 1987

The requirement to monitor the function and plausibility of automatic processes was the original purpose for displaying system images. The performance capability of simple controls was insufficient for complex processes such as a fire and therefore still required manual controls. Functional and plausibility control via machines only became possible with the rapid advances in automation. Further progress in video image analysis constituted the next step towards depicting a practice-oriented number of live images from the traffic systems since traffic irregularities were automatically detected in the background and a notification was subsequently displayed with video image intrusion on the control console.

However, the currently available hardware potential is not utilised sufficiently. In fact, advancements in monitoring technology seem to be at a standstill for years.

2. CURRENT INSTALLATIONS

Due to budgetary constraints, a low-cost, small control console, which incorporates all the functions of a large monitoring centre, had to be constructed for the traffic control station Liezen, which acts as Monitoring Centre North (ÜZ-North) for huge parts of the road network of northern region of Styria. Among other things, the plan included designing a projection screen that was as flexible as possible and could be sufficiently equipped with cost-efficient standard LCDs, which provided the possibility for utilising OLED display screens at least in the second generation without the need for further technical restructuring work.

Figure 2: Projection screen construction ÜZ-Nord 2011

All subsystems, such as emergency services, video, avalanche warning and tunnel guidance devices etc., had to be completely integrated into the guidance system in order to ensure full flexibility. This is also the most prominent distinctive feature in comparison to the technical state of current control console technology. The standard has even regressed in some areas such as for real-time identification.

Figure 3: Input monitors at the control station WELS 2003

Due to this currently unique integration of all subsystems (which even includes the house intercom and gate control system), operators no longer have to differentiate between old integrated systems. The guidance system performs command executions in the background.

For the first time, all audio signals have been integrated into the guidance system with a network-compatible mixer console in order to provide automatic switching or automatic volume control according to prior signals such as emergency service, telephone etc.

Figure 4: Screen input via touch panels or mouse and keyboard 2011

During the course of constructing the station ÜZ-Nord, a completely new emergency call system with standard telecontrol protocol including IEC 104 and the standardised SIP protocol (without add-on) for voice transmission was realised. For the first time, the video packages for the tunnel systems via the network have also been standardised with H264. Actual commands can be entered via touch panels for all external and internal controls.

All systems, including workstation computers, have been expanded redundantly in order to ensure operational safety. Only the external telephone centre building and the early warning system for icy conditions were not integrated into the system upon request of the operator.

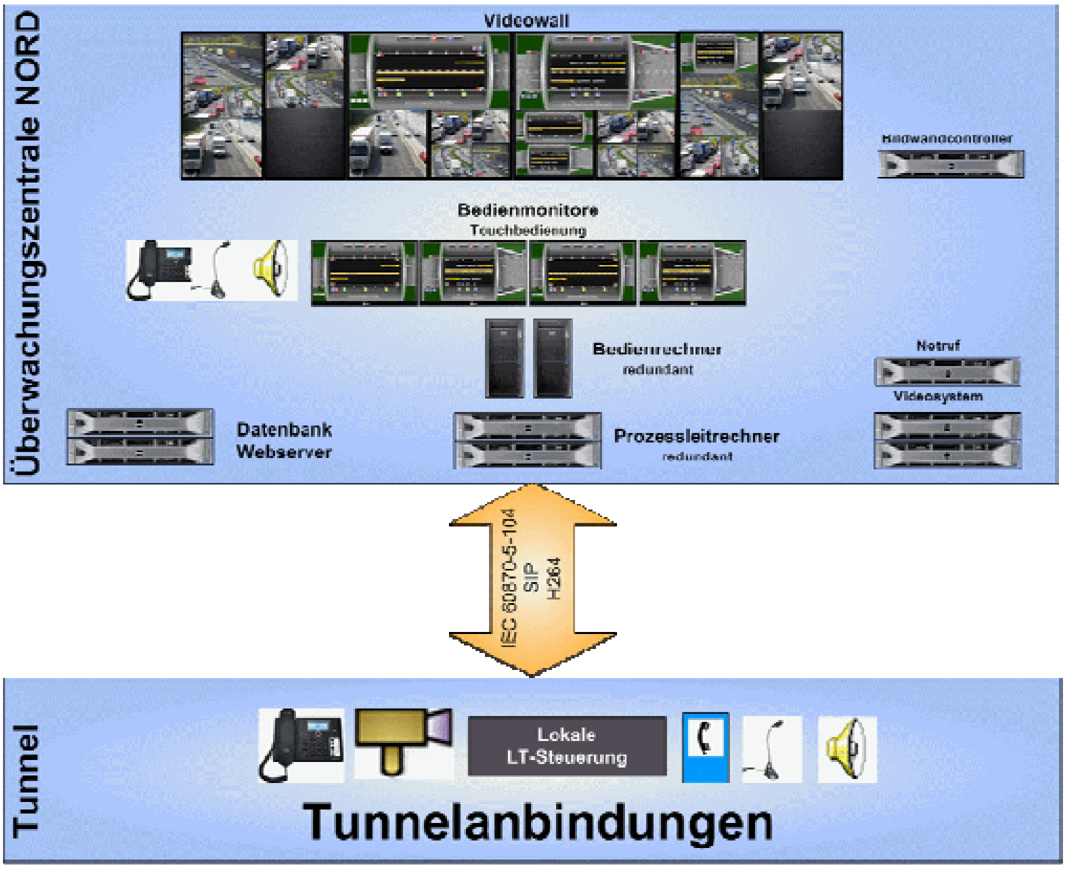

Figure 5: System overview ÜZ-Nord

These new technologies achieved a cost reduction for the control console or console system, which amounted to approximately 0.5 million euros. The little available space could be optimally used due to the optimal utilisation of the available technical hardware and software.

Manufacturer-specific problems have been kept out of the system by using standard protocols. The operator does not notice any difference between old and newly constructed tunnel systems.

The requirement was to ensure that each function for control and guidance of all tunnel systems could be loaded and controlled from anywhere in the monitoring area via a network-integrated notebook on-site or service control console in accordance with authorisation. Additionally, video images from all available traffic cameras can be loaded onto the notebook. These TV images are also available to the respectively responsible external road maintenance depots.

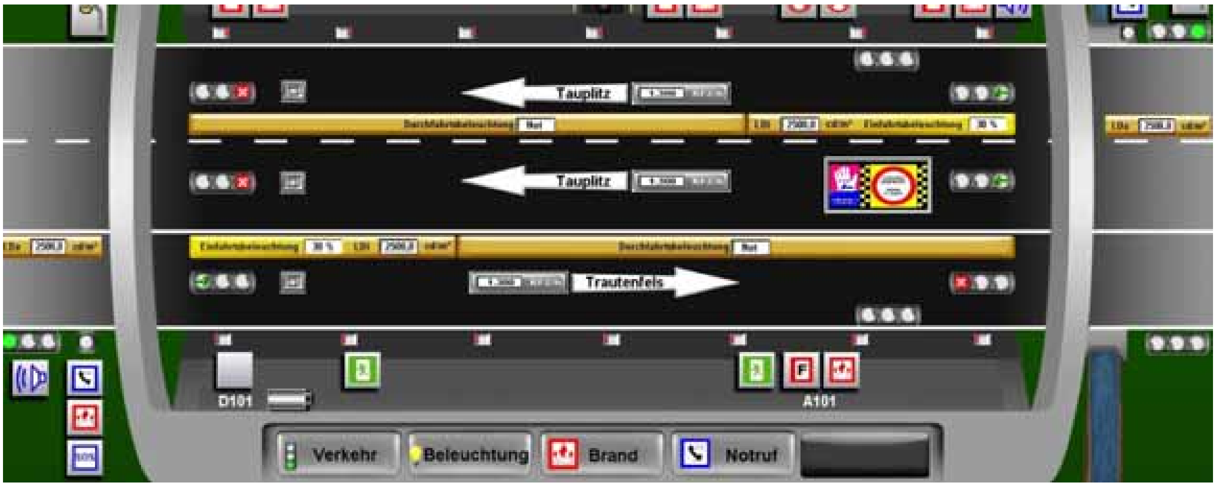

Figure 6: Tunnel control and display level on the input screen

This also constitutes the first step towards so-called Internet and/or desk control consoles. Operation no longer requires hundreds of background images since the active image elements can be added, removed or combined according to the requirements of tunnel subsystems. For the first time, bands instead of images have been used for the visualisation, which fully realise all advantages by combining layer, pan and zoom technology.

Thus, all framework conditions, such as cost optimisation, full-content display and uniform control of all subsystems, have been fulfilled. This, however, does not imply that a new technical standard has already been achieved. It has, however, provided proof that a full integration of all tunnel system parts is possible with little expenditure resulting in the establishment of an advanced monitoring centre.

Figure 7: Monitoring centre Nord 2011

Thus, the basis for cost optimisation including operating costs has been established, and the cornerstone for a new control console technology for tunnel monitoring has been laid.

First and foremost, we take the situation of the operators into consideration, which greatly contributes to the safety on the streets. Appropriate hardware and functions must be made available to the operators. Of course, acquisition costs and operational management must also be taken into account.

3. CURRENT AND FUTURE TECHNOLOGY

Currently, the following SCADA tools are available or will establish themselves in the near future:

<u>Human-machine communication:</u>

The most relevant part for the operator is the connection between control operations and the associated actions within the system.

<u>Hardware reduction:</u>

Large workstations with an enormous amount of equipment will no longer be necessary and become less important in the near future. Operators will process tasks on relatively small, location-independent workstations.

Technical systems are already available for directly utilising the latest developments.

<u>Standardisation of communication protocols:</u>

By now we also have a data world that covers the largest share of information with standardised protocols. Of course, further specific protocols will be required depending on the application, but these do not concern the operator. The operator will be independent of various communications and system parts and have consistent control over the same activities.

<u>Location-independent system control:</u>

Network connections with an appropriate bandwidth are available everywhere and no longer constitute a public limitation. All required services have advanced significantly and are fully available via the network.

Figure 8: Micro control console as notebook control console with tunnel remote control

<u>Mini consoles:</u>

New hardware components shrink the necessary workstation space to an unprecedented size. The development of OLED monitors is the decisive achievement in this area. The compression of computing power also contributes significantly to these advancements.

Based on these achievements, the workstation can develop into a compact unit that is no longer bound to local conditions. The workstation consists of only one monitor (8K/77") and two upstream touch-capable 24" input devices. Headphones are used for language services, which frees up the operators' hands for other work.

In an 8K resolution of a new OLED screen 70 video images could be displayed at full 4CIF resolution at the same time. Due to the compact arrangement is thus the representation ability much higher than in a conventional screen with rear projectors!

Voice and gesture control will not play an important role and should be disregarded on account of safety considerations.

The video wall functions are directly integrated into the visualisation, and all subsystems are also fully integrated.

What would such a control station look like?

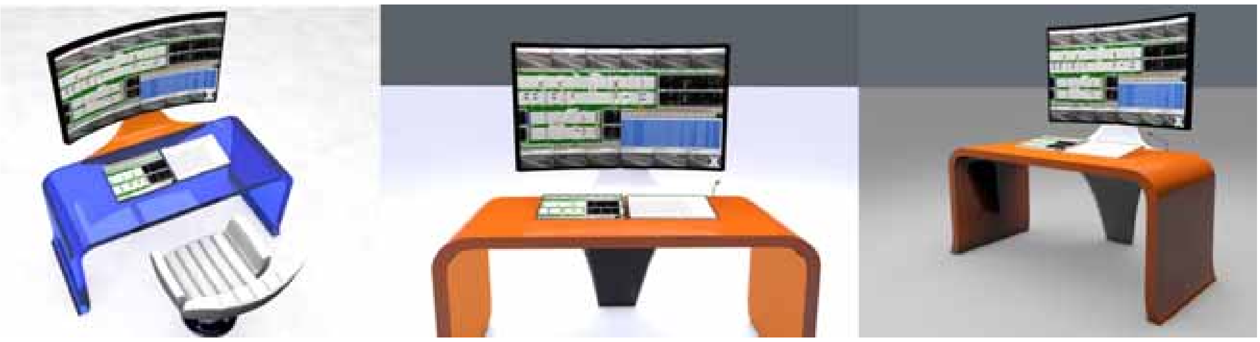

Figure 9: Structure plan and 3D illustration of a control station

What advantages will the new control console technology provide?

1.) Operational simplicity, advanced training and safety for all systems
First and foremost, operational simplicity must be mentioned here.
The operator can assemble the surface himself. The system in the background ensures a consistent and uniform operation for various system functions. Training and induction times for operators are reduced to a minimum. Improper interventions can be avoided for the most part.
2.) No investment costs for large spaces, light shading and air-conditioning for display devices
Halls for control consoles will no longer be necessary due to these new technologies. Desk control consoles can be used in a normal office environment.
3.) Availability like never before
Desk control consoles can be equipped with redundancies and spare or parallel work stations.
4.) Cost savings
In a cost comparison, a total savings of 60% of the current cost of control consoles was calculated.

REAL-TIME ESTIMATION OF HEAT RELEASE RATES IN TUNNEL FIRES

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ABSTRACT

A method of estimating heat release rates in tunnel fires in real time is introduced. The method takes advantage of the ability of linear temperature sensors to provide reliable measurements of evolving temperature histories at numerous locations along a tunnel. The possibility of knowing the heat release rate will open up many new opportunities for responding to fires in tunnels, especially in remote tunnels that are operated automatically. The principle underlying the method is presented and its effectiveness is demonstrated using pool fire tests in a full-scale tunnel. At the current stage of development, a number of factors limit the accuracy of the method, but on-going developments will improve its capability. In the meantime, the current simple implementation offers a significant advance on existing practice.

Key words: tunnel fire, temperature measurement, heat release rate, on-line prediction

NOMENCLATURE

A	: cross sectional area of heated air/smoke	[m^2]
Cp	: specific heat capacity of heated air/smoke	[J/kg.K]
$E\{t\}$	: total energy receive by air up to the time t	[J]
E_{fire}	: total combustible energy	[J]
i	: individual sensor along linear heat sensor cable	[-]
k	: an instant in time	[s]
$-m,n$	: values of i at (or beyond) ends of the region of influence of the fire	[-]
Q_{HRR}	: heat release rate from the fire	[W]
t	: time	[s]
Δt	: time interval	[s]
T	: increase in temperature since fire began	[K]
T_i	: local value of T at location i	[K]
T_{sum}	: spatial sum of T_i - see Eq.(7)	[K]
$\hat{T}_{sum}$	: maximum value of T_{sum}	[K]
V	: volume of heated air/smoke	[m^3]
x	: distance along tunnel	[m]

Greek characters

α	: proportion of fire heat received by air/smoke	[-]
ρ	: density of heated air/smoke	[kg/m^3]

1. INTRODUCTION

The continual improvement of fire safety is a principal agenda in road tunnels. Many experimental, theoretical and conceptual studies have been conducted to this end and many international conferences have been wholly or partly devoted to it. Some advances are made possible through improved understanding of phenomena related to fire and smoke whereas others arise from increased understanding of softer issues such as human behavior. This paper introduces a potential advance arising from an increasing ability to measure evolving conditions in tunnels and to interpret them in real time.

At the time when a fire initially starts, very little information is available to the persons (or computer) that must respond to it. There will inevitably be some initial delay as information gradually becomes available. In a huge majority of cases, the incident turns out to be a relatively minor hiccup, but at the outset, this outcome is not assured and the "worst case" potential scenario is orders of magnitude more serious. As a consequence of this ignorance and uncertainty – and also other factors – it is common to respond initially in a non-specific manner and to tailor this (up or down) as the situation evolves. Typically, the response may be characterized in three phases, namely (i) self-rescue, (ii) assisted rescue and (iii) infrastructure protection. This paper is of greatest relevance during the first of these phases, although it is also relevant at later stages, especially in remote tunnels with little or no direct involvement from human operators.

The most appropriate response to a fire is strongly dependent on the accuracy of information about (i) the fire location, (ii) the fire power. Herein, attention is focused primarily on remote tunnels with dominantly longitudinal ventilation and with no visual surveillance equipment. There are thousands of such simple tunnels [1]. Until relatively recently, the accuracy with which the two key pieces of information (location and size) could be obtained reliably has been poor. As a consequence, pre-determined automatic response systems have necessarily been designed to lowest common factors in the range of possible scenarios. Today, however, the ready availability of linear heat detectors [2] makes it possible to determine the location of a fire accurately - and even to detect whether the fire source is stationary or moving. The principal purpose of this paper is to demonstrate that linear sensors can also be used to estimate the fire *power*. That is, the sensors can yield both the location and the size of a fire, thereby enabling a major improvement in the one-size-fits-all form of automatic initial response.

1.1. Influence of Fire Size on Optimum Ventilation Response

The importance of the fire power and its influence on the most appropriate ventilation response has been demonstrated on numerous occasions - in actual incidents, in tunnel commissioning trials and in dedicated tests. Among the latter, particular reference is widely made to full-scale experiments conducted by EUREKA at Norway Repparfjord Tunnel in 1990 to 1992 to investigate the basic nature of vehicle fire phenomena in road tunnels [3]. Detailed measurements were made of parameters such as the available thermal energy and the evolution of temperatures, heat release rate and smoke generation in various ventilation regimes. Typically, citations of work such as this are made in papers discussing the most appropriate ventilation response to the outbreak of fire. Usually, however, little attention is paid to the manner in which the fire size – and especially the heat release rate - will be identified before selecting between ventilation responses that depend upon it. Implicitly, it is acknowledged that this information will be available, at best, only in a qualitative form. This paper demonstrates that it is becoming possible to obtain the information quantitatively. To date, this can be done only within a factor of about two. In due course, this uncertainty might reduce, but even a factor of two is a huge improvement over factors of, say, 10 or 20 that have been tolerated to date.

2. HEAT RELEASE RATE AND STRATIFICATION

For the purposes of his paper, the most important conclusions from tests such as the EUREKA programme are:

- The available fire energy depends strongly on the number and type of vehicles involved (e.g.**Table 1**).
- The heat release rate (HRR) varies with the number and type of vehicles and also with the ventilation regime. It can vary strongly in time (e.g. **Figure 1** and **Table 2**).
- With suitable ventilation regimes, air heated in a fire can remain in a stratified form for large distances from the fire. This has important consequences, especially during the early self-rescue stage of a fire.

The first two of these conclusions illustrate the need for real-time information about the current states of a fire during an actual incident. The third is important for the particular methodology introduced herein. In particular, it is assumed that, during the early stages of a fire, (i) stratification exists, (ii) it is stable, (iii) it does not vary strongly in time, and (iv) its cross-sectional dimensions do not vary strongly with distance from the fire.

Table 1: Approximate energy of combustible materials of vehicle (EUREKA fire tests[3])

Type of vehicle	Energy content [MJ]
Private car	6,000
Plastic car	7,000
Public bus	41,000
TIR fire load	65,000
Heavy goods vehicle	88,000

Table 2: Typical maximum heat release rates in vehicle fires (PIARC W5[4])

Type of vehicle	Max. Q_{HRR} [MW]
1 small passenger car	2.5
1 large passenger car	5
2-3 passenger cars	8
1 van	15
1 bus	20
1 lorry with burning goods	20-30

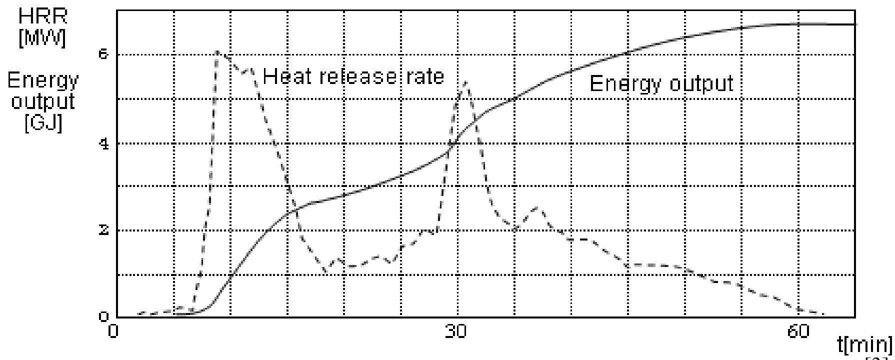


Figure 1: Heat release rate of plastic car fire (EUREKA fire tests [3])

2.1. Linear temperature sensors

Linear temperature sensors are long lengths of cable in which discrete temperature sensors are embedded at regular intervals. Each of the discrete sensors monitors the local temperature and the information is typically transmitted to an automatic display or control system. The important information is the *change* in temperature since some previous state and this is used to infer the presence or otherwise of heat sources. When a tunnel fire occurs, it is detected by multiple sensors and this provides a degree of robustness in the measuring system. Moreover, it enables the evolving extent of the fire to be detected as well as its amplitude. **Figure 2** illustrates the detail that can be obtained in the case of a fire in a road tunnel. It shows multiple temperature histories from individual sensors in a linear temperature cable. The sensors recording the largest temperatures are those closest to the fire and the remainder are at successively greater distances from it.

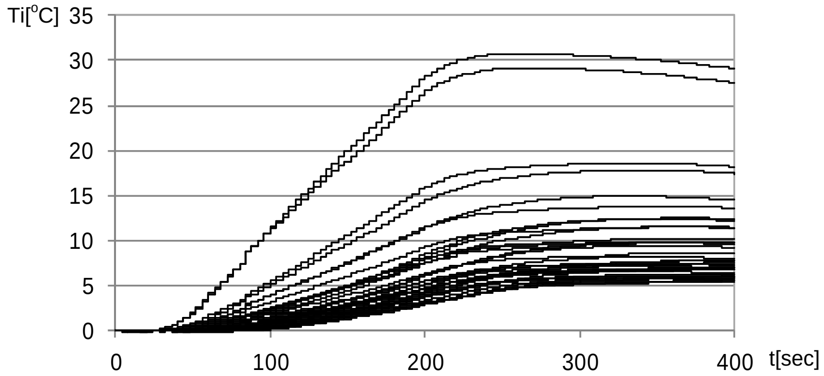


Figure 2: Temperature histories from multiple sensors

The particular measurements shown in the Figure were obtained during a pool-fire test in which the heat release rate increased to a maximum and then remained approximately constant. As a consequence, it is possible to distinguish easily between the individual curves and hence to infer some important characteristics. First, the close family resemblance of the signals from the various sensors demonstrates that each performs similarly and that variations in their scaling factors are sufficiently small to be unimportant for practical purposes. Second, there is a pronounced reduction in sustained temperature with increasing distance from the fire. Since this persists long after quasi-steady conditions have evolved, it is clear that the heated stratified air/smoke cooled as it propagated along the tunnel. Attention is drawn to this behavior because it has important consequences for the innovative methodology introduced below. At this preliminary stage of the analytical development, heat loss from the smoke to the environment is deemed to be negligible. This limits the direct applicability of the methodology in its present form, but that is not a matter for particular concern because realistic methods of addressing the matter are already known. They simply have not yet been developed to a level suitable for inclusion in a preliminary paper.

3. REAL-TIME ESTIMATION OF EVOLVING HEAT RELEASE RATE

3.1. Principle

The principle on which this paper is based is beautifully simple. Until relatively recently, however, it would have been impossible to make use of it in practical tunnel operation. The increasing reliability of linear temperature sensors changes the position radically. In a nutshell, the idea stems from the simple fact that a large proportion of the heat released by a fire remains in the air for a considerable time. The affected air is likely to be convected along the tunnel (possibly in both directions, especially in the case of back-layering), but its temperature will decay only slowly during this propagation. Accordingly, the total energy in the whole mass of air will tend to increase during the early lifetime of the fire. Therefore, by measuring the air temperature over a large distance, it will be possible to estimate (i) the total energy released since the outbreak of fire and (ii) the instantaneous heat release rate, $Q_{\mathrm{HRR}}\{t\}$.

This behavior is illustrated in **Figure 3** which shows measured temperature rises along a 70 m^2 test tunnel at successive times during three pool fires defined in **Table 3**. The fires were located at $x = 0$ and were initiated at the instant $t = 0$. The measurements were obtained using a linear temperature sensor cable, which was hung underneath a cable rack attached to the tunnel ceiling. The sensor cable had embedded temperature sensors every 4m along its length.

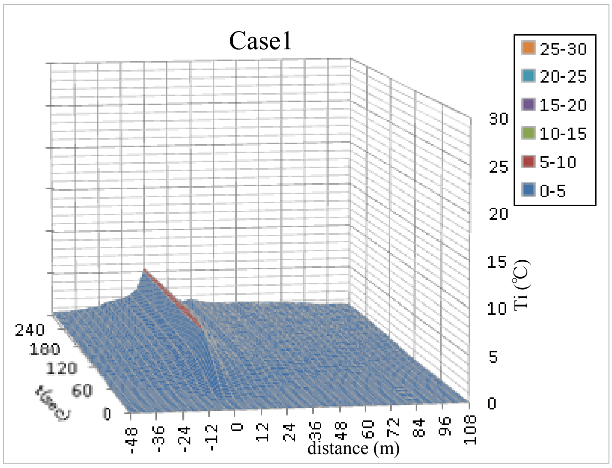
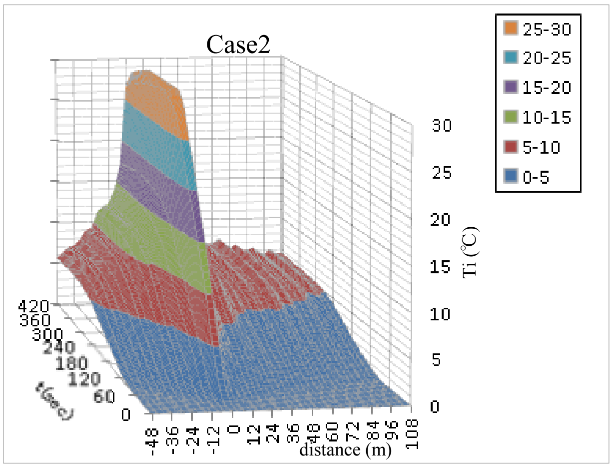


Table 3: Fire Test Cases

Case	Fire scale	Wind Speed	Total Energy *E*
1	0.5 m^2, 1L (N-Heptane)	0m/s	30.7MJ
2	1 m^2, 12L (N-Heptane)	0m/s	370MJ
3	1 m^2,12L (N-Heptane)	2m/s	370MJ



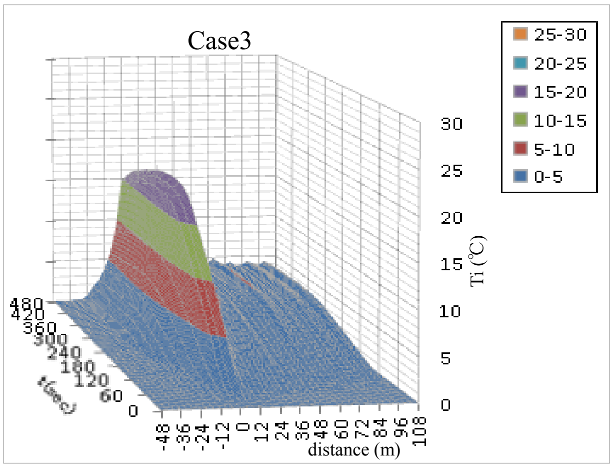


Figure 3: Temperature increases in Space and Time, $T\{x,t\}$

The influence of the fire size (1 litre or 12 litre) and the forced air-flow velocity (0 m/s or 2 m/s) can be seen clearly. It can also be seen that the intensity of the fires initially increased gradually and then remained approximately constant. Furthermore, the decay in temperature with increasing distance from the fire, although significant, is not dominant. These cases are therefore useful for illustrating the proposed methodology.

3.2. Theoretical basis

Let $E\{t\}$ denote the total energy received by the air from the fire in the time t since its outbreak. Neglecting heat loss and any influence on kinetic energy, the total may be approximated as

$$E \cong \int_V C_p \rho T dV \tag{1}$$

where C_p denotes the specific heat capacity at constant pressure, ρ is the air density, T is the *increase* in temperature and the volume V is chosen so that the integral is evaluated over the whole region of affected air.

The heat release rate Q_{HRR} at any instant is related to the rate of increase of E by

$$Q_{HRR} \cong \alpha \frac{dE}{dt} \tag{2}$$

where α is an empirical coefficient determined primarily by the proportion of heat that is received by the air. Typically this is between about 50% and 80% and the remainder of the heat is radiated to the surroundings such as the tunnel wall and the burning vehicles themselves. In the present application, the coefficient α also allows for heat loss from the air as it propagates along the tunnel.

For present purposes, it is useful to develop Eq.(1) into a form that can be used conveniently in association with experimental measurements. The total received energy is first expressed as

$$E \cong \int_V C_p \rho T dV = \int_{-L1}^{L2} C_p \rho A T dx \qquad (3)$$

where A denotes the local cross-section of heated air (typically a stratified region in the upper portion of the tunnel cross section), x denotes distance along the tunnel and all of the affected air is within the region $-L_1 < x < L_2$.

Eq.(3) can be discretized in the form

$$E \cong \int_{-L1}^{L2} C_p \rho A T dx \cong \sum_{-m}^{n} C_p (\rho A T)_i \Delta x \qquad (4)$$

where $-m \leq i \leq n$ denotes a series of elements of equal length Δx along the tunnel. The summation may be approximated by

$$E \cong \sum_{-m}^{n} C_p (\rho A T)_i \Delta x \cong C_p \overline{\rho A} \Delta x \sum_{-m}^{n} T_i \qquad (5)$$

where $\overline{\rho A}$ denotes the mean value of the product ρA over the region.

When a linear temperature sensor is used to measure the temperature at multiple locations along a tunnel and at discrete time steps since the outbreak of a fire, Eq.(6) enables the total absorbed heat up to a typical instant $t = k$ to be estimated rapidly and simply. That is, real-time estimates can be made of the cumulative heat release and the evolving heat release rate. E.g.

$$E(k) \cong C_p \overline{\rho A} \Delta x T_{sum}\{k\} \qquad (6)$$

where

$$T_{sum}\{k\} = \sum_{-\mathrm{m}}^{\mathrm{n}} T_i\{k\} \qquad (7)$$

$T_i\{k\}$ is the measured temperature increase at the location i and instant k.

3.3. Interpretation of Practical Measurements

Figure 4 shows the evolution of the sum $T_{sum}\{k\}$ measured by the linear sensors in the three test cases described above. In each case, the sum increases to a maximum and then reduces slightly. Possible causes of the reductions are discussed below. For the time being, however, attention is focused on the preceding rises and on the limiting values.

It is noted that the inferred heat release rates are proportional to rates of change of $T_{sum}\{k\}$ and instantaneous rates of change of the raw experimental data inevitably vary strongly. **Table 4** shows the maximum values of the measured curves, denoted by $\hat{T}_{sum}$,

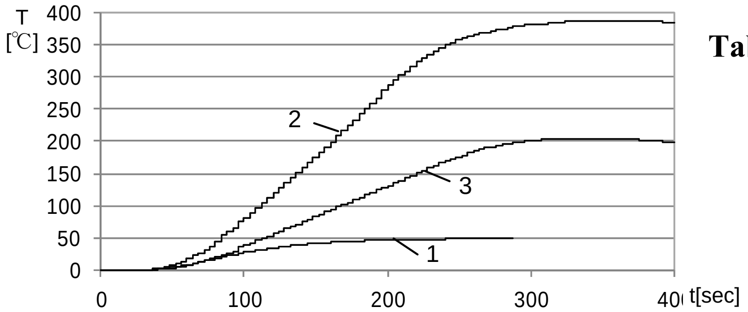


Figure 4: Evolution of the measured $T_{sum}\{k\}$

Table 4: Maximum Value of $T_{sum}\{k\}$

Case	$\hat{T}_{sum}$
1	49 °C
2	387 °C
3	206 °C

One of these curves (Case 2) is reproduced in **Figure 5** and is shown together with its time-derivative – i.e. rates-of-change of the measured value $T_{sum}\{k\}$, estimated numerically using

$$\frac{d[T_{sum}\{k\}]}{dt} \cong \frac{T_{sum}\{k\} - T_{sum}\{k-1\}}{\Delta t} \qquad (8)$$

The unevenness of the gradient is a consequence of the method using the raw data. In principle, any suitable alternative method could have been used. The relatively coarse method chosen for the purposes of this paper has the advantage of reminding readers that the real data will not exhibit clear monotonic behavior. This is an example of the sort of issue that is always exhibited by real measurements. It is especially important in the present case because the desired information relates to *rates of change* of measurements, not merely to absolute values.

Figure 6 shows the measured rates-of-change curves for each of the three test cases. Only the periods of increasing $T_{sum}\{k\}$ are shown. The subsequent periods of decreasing $T_{sum}\{k\}$ correspond to times when the heat release rate to air from the fire had become smaller than the rate of heat loss from the stratified air/smoke.

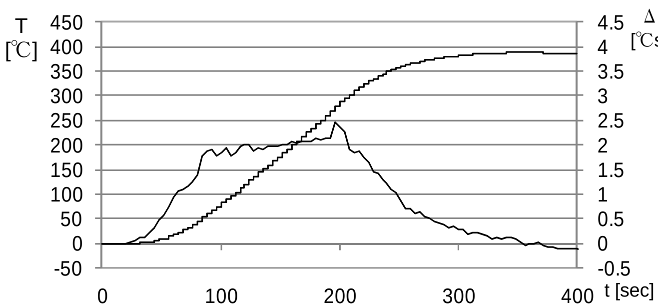


Figure 5: Evolution of $T_{sum}\{k\}$ and its rate of change

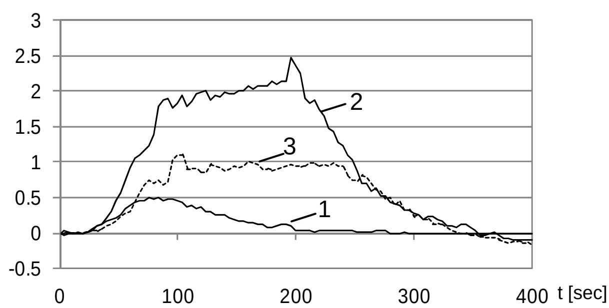


Figure 6: Rates of change of $T_{sum}\{k\}$ (Cases 1,2,3)

3.4. Information Inferred from Full-Scale Tests

Up to this point, all of the measurements and the interpretation thereof are representative of proposed use of the methodology in practical applications. In the case of dedicated full-scale tests, however, it is possible to develop the assessment in greater detail because additional information is available. Such development is valuable because it can provide a measure of confidence of the validity of the proposed methodology.

The particular piece of information that is especially valuable in the present case is the total fire energy in each of the pool fires. Neglecting heat losses, the maximum value of the temperature sum should correspond the period after the whole of the combustible material has been exhausted. That is, it should satisfy

$$E_{Fire} \cong \frac{1}{\alpha} C_p \overline{\rho A} \Delta x \hat{T}_{sum} \qquad (9)$$

Therefore, using the known value of E_{Fire} and the measured value of $\hat{T}_{sum}$, it is possible to infer values of the product $\overline{\rho A}/\alpha$ and to compare then with the actual conditions in the tunnel. Values of $\overline{\rho A}/\alpha$ inferred in this manner are listed in **Table 5**.

The inferred values can be assessed in a qualitative manner by comparing them with reasonable expectations of conditions in the tunnels. However, it is also possible to use them in a quantitative manner. This is illustrated in **Figure 7**, which shows the same data as **Figure 6**, but scaled in accordance with the inferred values of $\overline{\rho A}/\alpha$ to give the estimated evolution of the heat release rate, using:

$$Q_{HRR}\{k\} \cong \frac{1}{\alpha} C_p \overline{\rho A} \Delta x \frac{d[T_{sum}\{k\}]}{dt} \tag{10}$$

By inspection, the curves for the two largest fires are closely similar. This is exactly what would be expected in practice because the two fire loads are the same. The different outcomes obtained in the (unscaled) **Figure 6** arise because of the different forced wind speeds in the two cases. This is therefore a strong indication that the proposed methodology is soundly based.

Table 5: Coefficient $\frac{1}{\alpha} C_p \overline{\rho A} \Delta x$

Case	$C_p \overline{\rho A} \Delta x/\alpha$
1	0.61
2	0.95
3	1.8

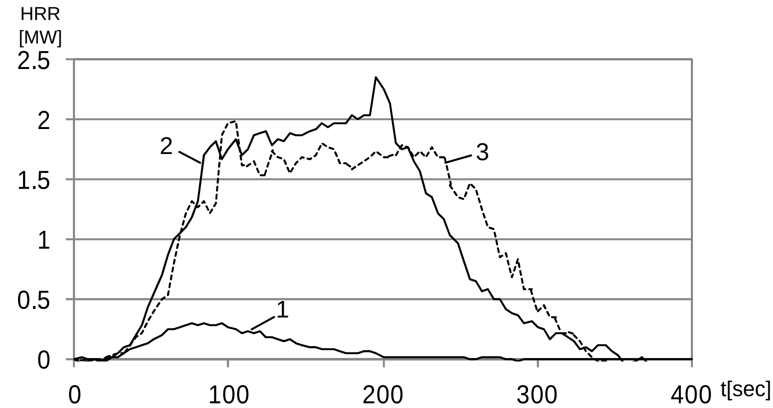


Figure 7: Evolution of the inferred heat release rate

4. UNCERTAINTIES AND APPROXIMATIONS

Notwithstanding the encouraging progress demonstrated above, there remains a need for further development to mitigate the influence of several factors that limit the applicability of the method. Particular attention is drawn to the following issues.

4.1. The parameter α

In the above development, the value of the parameter α is inherently unknown. This is an important limitation, but it is not an insurmountable obstacle. For instance, as indicated above, the parameter α is usually within the range $0.5 < \alpha < 0.8$. Accordingly, in the absence of fuller information, a reasonable approximation for practical purposes would be $\alpha \approx 0.65$. The error arising from this approximation would be well within acceptable limits.

4.2. The parameter $\overline{\rho A}$

In the above development, the parameter α appears as a ratio with the product $\overline{\rho A}$, which is itself unknown in general. However, reasonable estimates for the product could be deduced empirically from tables showing typical stratification in fires of known heat release rate in the presence of known ventilation velocities. This information could be used interactively with the above methodology. Ideally, the actual airspeed would be deduced from airflow sensors in the tunnel. Failing that, however, use could be made of the propagation rate of the heated air – as measured by the temperature sensors.

The accuracy of estimates obtained with the aid of velocity sensors will be influenced by the rate of flow. With very small velocities [eg 5], the thickness of the heated stratified layer will vary (in time and space) more strongly than when a significant air velocity exists.

4.3. Adiabatic flow

In the above development, it is assumed that heat transfer to the tunnel wall may be neglected. This is a reasonable approximation whilst the extent of the smoke spread is not great, but it could become important at large times. Indeed, there is some evidence of this in the measurements presented in **Figure 2**. This is an issue that could be addressed with reasonable confidence and with quite small overhead in the analytical interpretation of the measurements. The influence of radiation, convection and conduction could all be allowed for with sufficient accuracy to infer suitable correction factors.

4.4. Finite tunnel length

In the above development, it is assumed that the temperature sensors extend over the whole extent of the smoke region. This would not be true, however, if the smoke reached the end of the tunnel or some other outlet. In that case, it would be necessary to make an appropriate allowance for smoke that has left the measurement region. One way to do this would be to estimate the "effective length" of the exhausted smoke – i.e. the length of tunnel that it would have been occupied if the tunnel had been longer.

5. CONCLUSIONS

In existing practice, the response to a fire in a tunnel has to be designed and implemented in the absence of knowledge of the actual heat release rate from the fire. This constraint has been regarded as inevitable, but that is no longer the case. A method of determining the heat release rate in real time has been presented herein and has been validated by reference to controlled tests in a full-scale tunnel. The availability of such real-time information has the potential to influence the method of ventilation control and many other aspects of the response to a fire incident in a tunnel. Specific conclusions from the paper include:

1. Linear temperature sensors are already used for fire detection purposes. They are capable of providing much more detailed information than is needed for this purpose alone. In particular, they can provide details of temperature change in space and time.
2. Use can be made of this capability to estimate the average temperature increase in all air/smoke that has been affected by a fire.
3. By estimating the size of the thermally stratified, heated air/smoke layer, it is possible to estimate the total energy received by air from a fire up to any particular instant.
4. This, in turn, enables an estimate to be made of the total energy emitted by the fire up to the current instant.
5. The rate of change of the total energy is a measure of the heat release rate from the fire. The methodology yields this value at each instant during the fire.
6. The methodology has not yet been developed to its full potential. A number of limitations exist that will be relaxed in future. These limitations, and others of a more permanent nature, have been discussed in the paper.

6. REFERENCES

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PROVISIONS FOR RELIABLE AND EFFECTIVE SMOKE DETECTION IN ROAD TUNNELS

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ABSTRACT

Over the past years new technology has been provided to improve fire detection in road tunnels. One example is the trend to complement traditional linear heat detectors (LHD) with smoke detectors (SD). With this diversification one would expect a faster and more reliable detection. This approach is verifiably successful in shorter tunnels with or without longitudinal ventilation systems, where the simple detection of the fire is the primary goal. However in longer tunnels with smoke extraction ventilation systems, the detection system must also provide the fire location, which is a challenge for smoke detection systems. Due to the longitudinal air flow and/or the smoke-emitting vehicles travelling through the tunnel, smoke can be spread and remain over long distances and this alone makes it very difficult to reliably locate the fire source with a degree of accuracy. A wrong detection of the fire location with the corresponding ventilation scenario can produce a very undesirable situation for the tunnel users, even worse than without ventilation.

This paper covers the following topics: 1) Discussion of smoke detection, 2) The necessity to differentiate between stationary and moving smoke sources, 3) Well proven algorithm(s) to make this determination, 4) Methods to test and verify the correct functioning of the detection system, especially the smoke detection, 5) Real examples.

Keywords: road tunnels, ventilation design, fire detection, smoke detection, reliability

1. INTRODUCTION

In the case of a fire incident in a road tunnel, fast and reliable fire detection is essential to alert the emergency services and to trigger the tunnel safety systems to provide the tunnel users with favourable conditions for self-rescue.

Considering that the majority of fires (one out of about 10 to 100) are small with low or even no heat power, smoke detection is often faster than LHD and therefore smoke detection has been promoted as a complementary system in addition to LHD. In Switzerland almost all recently opened new or refurbished tunnels are equipped with SD and LHD.

Although there have been several years of positive experience with smoke detection and expectations have been satisfied, there have been some problems and questions have arisen.

2. FIRE DETECTION

2.1. Objective for fire detection

The two objectives of a fire detection system are to alert the emergency services and to activate the tunnel equipment into fire operation mode. For some equipment the fire location is not required, for others it is essential for its correct functioning (Table 1).

It is obvious that fire detection without localization is much easier than to define the fire location. Some installations, especially the tunnel ventilation, need the fire location and one must be aware of the fact that for tunnel ventilation with extraction systems, a wrong detection of the fire location can easily result in a very undesirable situation, worse than without any detection or ventilation. Longitudinal ventilation is more tolerant regarding this aspect (Figure 1).

Table 1: Important installations which change operation mode in case of fire
● = important, ○ = optional, - = not relevant

	only fire detection	fire location detection
Lighting	●	-
Tunnel Ventilation		
Longitudinal ventilation	●	○
Smoke exhaust ventilation	●	●
Escape gallery ventilation	●	-
Traffic control / Signalling	●	○
CCTV	●	○
Others (HVAC, control centre, …)	●	-

Requirements for the fire detection system include fast and reliable detection with a low false alarm rate. These requirements are contradictory and must therefore be carefully weighted for individual situations, considering for example if the control centre is manned or not.

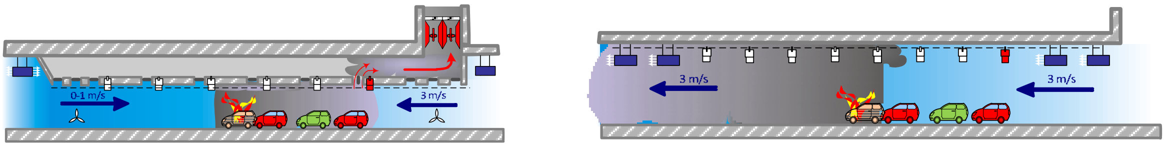


Figure 1: Result of wrong fire location detection: exhaust ventilation (left) and longitudinal ventilation (right)

2.2. Systems for fire detection

The most important systems and commonly used are LHD, SD, visibility measurement devices and video detection. Other systems such as flame, gas or radiation detectors or even acoustic systems are available but are very rarely used.

If SD is installed it is normally combined with LHD, except in very short tunnels. If no SD is installed, the visibility measurement devices are often used for “smoke detection”. Because of the rather long distances between the devices and their limited measurement range, it is usually just implemented as a pre-alarm system without automatic ventilation reaction.

2.3. Function smoke detection

Smoke detection sensors use the scattered light principle with a measurement range of typically 0 to 10 E/m. Systems are either of the in-situ or extractive type. False alarms caused by fog (near portal) can be avoided by heating up the extracted air.

The devices are self-checking and usually require maintenance annually.

2.4. Advantages / Disadvantages

The largest benefit could be achieved with the combined use of SD and LHD. Redundancy is provided with the two different systems, further redundancy (e.g. two LHD) is not required.

The main advantage of SD is the fast and reliable detection of small fire events, typically turbo-charger or engine fires. The most important disadvantage of SD is the problem of fire localization.

2.5. Guidelines

Many country’s guidelines require automatic fire detection systems, mostly specified as LHD. As a pre-alarm system, smoke detection is often additionally used (visibility measurement devices), even though it is not especially required by the guidelines. A specific request for smoke detection can be found in the Swiss fire detection guideline [1] (N.B. In Switzerland there are many tunnels which have no control staff; they operate totally automatically). The corresponding function of the ventilation system in the case of a specific fire alarm is defined in [2]. The most important Swiss requirements can be summarized as follows:

- Tunnel with safety installations and/or mechanical ventilation must be equipped with automatic fire detection system. The fire detection system must be able to detect the following fires:
    - Stationary fires with high heat release rate (HRR) (>5MW)
    - Stationary fires with low HRR (< 5MW)
    - Moving fires with low HRR
- These requirements are normally achieved by using LHD and SD every 100m – 300m.
- By using LHD and SD no further redundancy is required.
- For the ventilation the following alarm types are required:
    (1) LHD pre alarm
    (2) LHD main alarm with fire location
    (3) moving smoke alarm
    (4) stationary smoke alarm
- Smoke detection evaluation algorithm must consider two smoke concentration values (k = 10mE/m and 30mE/m) and the air velocity in the tunnel.
- The first detection system that detects a stationary fire (2 or 4) is valid and cannot be overridden by another system except manual input.
- No active ventilation reaction for either a pre-alarm or a moving fire
- No automatic reset.
- Detection time

3. TEMPERATURE AND SMOKE PROPAGATION IN ROAD TUNNEL FIRES

Increased temperature and/or the presence of smoke are typical indicators of a fire. Both indicators have very different behaviours in terms of temporal and spacial development which are described in the following sections.

3.1. Temperature

The temporal temperature development can be very different as many real fires have shown. Most fires develop slowly with no or very limited fire power during the first 5 to 10 minutes with hardly any measurable temperature increase. Nevertheless some fires, especially fires with fatalities, had rather quicker fire development.

The longitudinal temperature profile is influenced by the heat transport phenomena and is dependent on several parameters. Although there are dependencies the temperature profile for a stationary tunnel fire always looks very similar, with a temperature peak at the fire location and a steep temperature decrease on both sides. This is because the radiation heat is limited to the region close to the fire and convection heat transport is reduced by the cooling effect of the tunnel walls.

In the case of a moving fire source the temperature increase is normally low (below the threshold value) because the fire power of moving fires is typically low. In the cases of small fires the driver is either not aware of the fire or drives on despite the fire. In the case of large fires, the driver will either choose to stop or be forced to do so.

A reported scenario which can be misleading is a temperature increase away from the fire source caused by the exhaust pipes of trucks which blow the hot engine exhaust gases onto the tunnel ceiling (and the LHD).

3.2. Smoke

Tunnel fire events (cold and hot fires) are always associated with smoke production from the very beginning. Even if the smoke production rate for hot fires is somehow coupled with the fire power and the fire power development can be very slow, the amount of smoke produced is quickly sufficient to be detected.

In contrast to the temperature profile, smoke is passive particles which are transported by air movement and the absolute amount does not normally get reduced (unless a sprinkler system is used). Hence the smoke concentration is not limited to the fire source but propagates through the whole tunnel. Some examples of how the smoke can propagate along the tunnel in different scenarios are shown in Figure 2 to Figure 5.

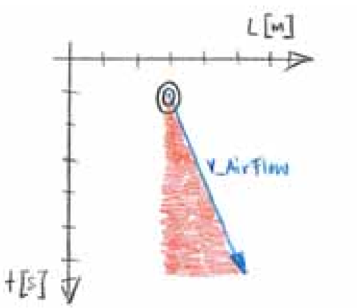


Figure 2: Air flow →, Fire stationary, constant smoke production

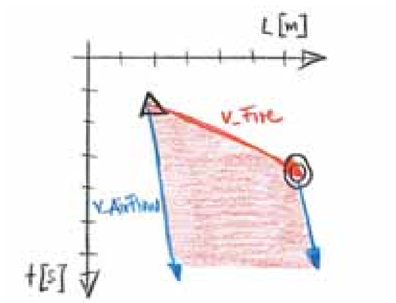


Figure 3: Air flow →, Fire moving →, constant smoke production

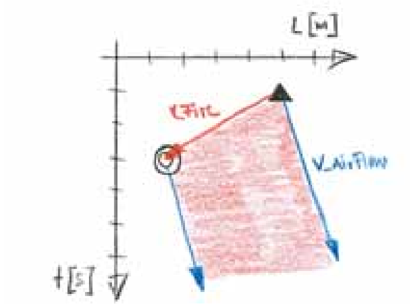


Figure 4: Air flow →, Fire moving ←, constant smoke production

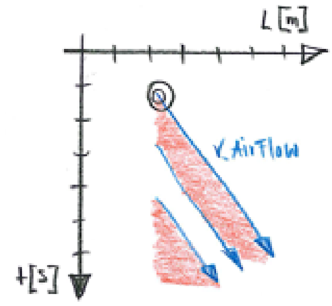


Figure 5: Air flow →, Fire stationary, inconstant smoke production

4. DETECTION OF THE FIRE LOCATION

As required by the guidelines and motivated by further considerations it is required that the smoke detection system can locate the fire location as soon as it is stationary. The resulting problem is the smoke propagation in the tunnel, mainly caused by smoke emitting vehicles travelling through the tunnel before they stop and also by natural air flow. To handle this situation it is essential that the smoke detection system analyses the smoke development from the very beginning.

Figure 6 shows a typical smoke detection plot. By examining the plot it is quite obvious that it must have been a moving smoke source on the first half of the plot (sloped red line) and became stationary later (vertical red line). If one considers that the smoke detection system captures and evaluates the data ongoing and not the whole plot at once, the task is much more challenging. Besides the evaluation must be fast and reliable and be independent of the various smoke propagation scenarios shown above.

An example of a proven and tested algorithm to distinguish between a moving and a stationary smoke source on the basis of single SD is presented in the next section.

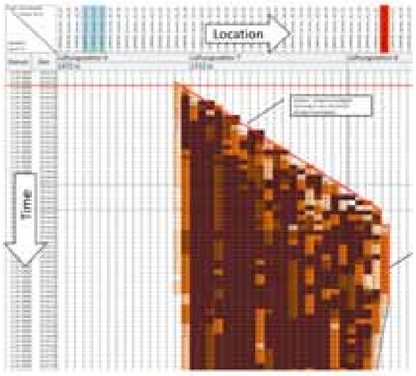


Figure 6: Smoke detection plot from a turbo-charger fire in the Gotthard road tunnel [3]

4.1. Algorithm

The described algorithm requires the following data for the evaluation:

- 3 discrete values of the smoke concentration: SV0 < 10mE/m < SV1 < 30mE/m < SV2
- Longitudinal air velocity in the tunnel
- Distance between the SDs (predefined value)
- Not available SDs

Stationary smoke alarm will be triggered if the criteria of A or B or C are satisfied:

A
1) 1 SD with SV2 for > 60s **and**
2) All other SDs with SV0

➔ Fire location = location of the activated SD with SV2

B
1) At least two activated SD, at least 1 SD with SV2 **and**
2) Smoke propagation direction(1) equal to air flow direction **and**
3) Smoke propagation velocity(1) smaller or similar to air flow velocity

➔ Fire location = second to last activated(1) SD

C
1) At least two activated SD, at least 1 SD with SV2 **and**
2) Last activated(1) SD longer than 60s (SV1 or SV2)

➔ Fire location = location of the last-activated(1) SD

(1) considerring only SD within the monitoring frame (MF).

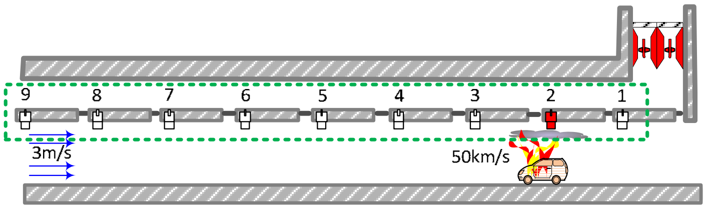
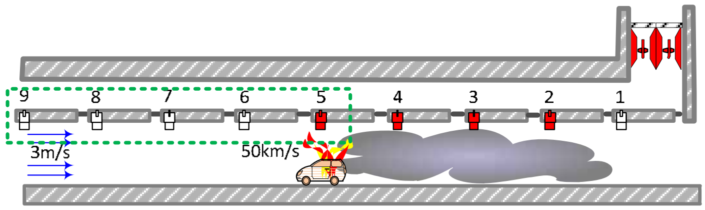
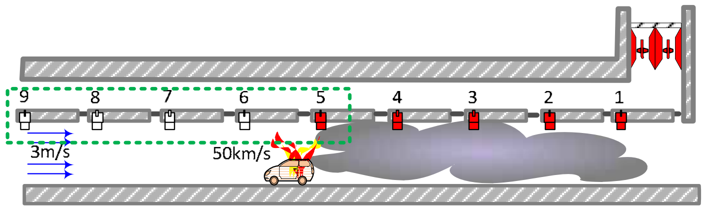
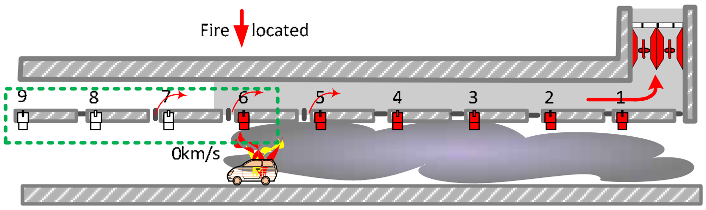
The monitoring frame (MF) includes a) all SD as long as just one SD is activated, b) all SD from the last activated SD in the direction of the smoke movement.

In all cases with 3 or more activated SD (SV1 or SV2) and if one of the A, B or C triggers is not satisfied it indicates a moving smoke alarm.

4.2. Example

Table 2 shows an illustrative example of how the algorithm works.

Table 2: Moving smoke source travelling against the natural air flow (Case C), SDs in red = activated, green dotted box = monitoring frame

Time		
t0		Fire breaks out, SD 1 is immediately activated, A (60s required), B (2 SD required), C (2 SD required) or moving smoke (3 SD required) not satisfied.
t0 + 30s		SD 3,4 and 5 activated in short intervals, A (no other SD required), B (smoke direction = air flow) and C (last SD not for 60s) not satisfied. Moving smoke alarm is triggered (≥ 3 SD activated).
t0 + 40s		SD 1 is activated due to smoke propagation. A (no other SD required), B (SD 1 is not in in MF) and C (last SD not for 60s) not satisfied. Moving smoke alarm is still on.
t0 + 120s		Fire is no more moving (t0 + 50s), SD 6 is activated (t0 + 60s), after 60s criteria C is satisfied. Fire location is defined near SD 6, exhaust system switches on and corresponding dampers open.

5. VENTILATION REACTION

Once a fire has been detected the decision must be made whether a ventilation reaction is appropriate or not and, if yes, what should the ventilation do. Three possible and used concepts are described and analysed in Table 3.

Table 3: Concepts of ventilation strategies in case of smoke detection alarm

1) Variable exhaust location	
As soon as one SD has activated, the ventilation system switches on and locally extracts in the region of the activated SD. The extraction location will be continuously alternated in a way that the extraction is in the region of the highest smoke concentration. This procedure goes for so long as the LHD is not activated. As soon as the LHD is activated the implied location from the SD gets superseded and the extraction location is defined by the LHD and	+ Simple algorithm, because no moving / stationary fire evaluation is required + Immediate ventilation reaction and smoke extraction. - Danger that dampers do not correctly close: reduced efficiency or even hazardous situation - Uncontrolled smoke propagation can be the result - Negative reaction on exhaust ventilators and longitudinal air control - Steady communication between SD- and ventilation system required

no longer changes its location.	- No clearly defined fire location is problematic for fire fighters (exhaust location) and other safety facilities which require a fire location
2) Linear extraction (moving fire) → local extraction (stationary fire)	
As soon as moving fire alarm is activated the ventilation system switches on and with linear extraction. As soon as stationary fire is detected (LHD / SD) the ventilation changes to local extraction with fixed exhaust location (except manual input).	+ Immediate ventilation reaction after moving fire detection + Clear boundary between detection and ventilation - If dampers afterwards do not correctly close it results in reduced ventilation efficiency or even a hazardous situation - Complex algorithm to evaluate moving / stationary fire - Influence on the air flow and the detection algorithm
3) No extraction (moving fire) → local extraction (stationary fire)	
Only when a stationary fire is detected (LHD / SD) is the ventilation switched on with local extraction and fixed exhaust location (except manual input).	+ Robust, reliable and proven + Clear boundary between detection and ventilation + Clear and controllable air flow situation in the tunnel - Complex algorithm for evaluation of moving / stationary fire -> intense testing required - Theoretically slower than concept A

Real smoke tests have shown that concept Nr. 1 can get into an uncontrollable state and cannot be recommended for use. The benefit of early linear extraction with concept Nr. 2 must be considered with the several disadvantages and, normally, concept Nr. 2 cannot be justified. As a result of several tests proving the approach the recommended concept is Nr. 3.

6. OTHER ASPECTS

6.1. Portal to Portal Smoke Recirculation

SDs are typically installed at some distance from the portals. For unidirectional tunnels, when the fire is located between the last SD and the exit portal, a critical scenario could result as shown in Figure 7 just due to smoke recirculation. The solution is to install the last SD near the exit portal and to consider this case in the algorithm (active SDs in both tunnel tubes).

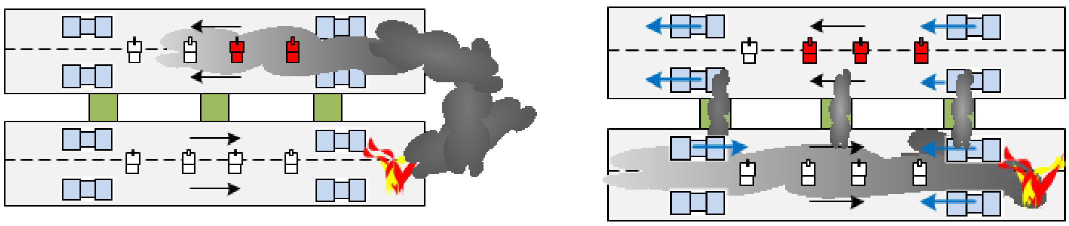


Figure 7: Wrong fire location detection due to portal to portal recirculation

6.2. Priority LHD vs. SD

Should the LHD have a higher priority than smoke detection? As discussed previously, the LHD is more suited to detect the fire location. However it is not recommended to prioritise LHD. The reasoning is the fact that, after a fire breaks out, the tunnel begins to congest and the heat from the exhaust pipes of trucks or other heating processes could activate the LHD far away from the fire that had potentially previously been detected by the SD.

It is recommended to give equal priority to LHD and SD, which means, the first activation (stationary fire) is relevant and defines the ventilation reaction.

6.3. False alarms due to fog or dust

Fog (typically due to condensation) or dust (typically due to road salt) can result in undesirable activation of SDs. The problem with fog can be eliminated by heating up the air sample; this is recommended for SD close to the portal. The dust problem is mostly limited to winter periods and can be reduced by using alternative de-icing products (liquid), regular tunnel cleaning and filters solutions for the SD. Extraction systems may have an advantage in relation to this.

6.4. Combination of smoke detectors with dampers

Mechanically installing the SD sensor into the damper is an often used approach. Although numerous interfaces need to be clarified it is an appropriate option. Not recommended is the communication via the damper control unit or a direct control of the damper from the SD. A separation between sensors and operating equipment is the basis of all safety systems.

6.5. Temperature measurement via smoke detectors

Smoke sensors provide a function to measure the temperature and theoretically could take over the function of the LHD.

Because of the discrete sensor locations every 100 to 300m and the less reliable measurement principle it is not recommended to use the SD temperature measurement instead of LHD.

6.6. Separate PLC vs. Ventilation control for SD algorithm evaluation

For the evaluation algorithm the smoke concentration values of all SD (SV0, SV1 and SV2) and the air velocity is required at frequent time intervals. As the air velocity data comes from the ventilation control it is tempting to include the SD algorithm evaluation on the ventilation PLC. The counter-arguments are that the SD evaluation is relatively complex and inflates the already large ventilation control unnecessarily. Once more it would combine a sensor with an equipment facility and the ventilation control would become a fire detection facility and would need to broadcast the fire alarm to the other safety facilities.

7. TESTS

With real smoke tests numerous malfunctions of the fire/smoke detection system have often been discovered, notably in the tunnel commissioning tests. Experience has clearly shown that tests only on a software simulated basis are not sufficient. The smoke tests provided have been carried out with smoke generator (temperature resistant smoke) arranged on a trailer, to create moving fires.

8. CONCLUSIONS

Smoke detection is an effective detection system for road tunnels, especially combined with LHD. Particularly for tunnels with smoke extraction systems, where the fire location is essential, special provisions are required for a reliable smoke detection system. Before a smoke detection system is put into operation appropriate testing is necessary, including real smoke tests.

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A UNIQUE TECHNOLOGY FOR EARLY FIRE DETECTION IN TUNNEL ENVIRONMENTS

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ABSTRACT

This paper outlines the challenges involved in the design and implementation of an efficient and safe system for detection of fire incidents in tunnels. It furthermore outlines the possibilities of Multiple Gas Detection technology (MGD) as solution to improve safety in tunnels.

1. INTRODUCTION

"Technologies of nature", and in particular the sense organs, have always excited scientists and technological utopias and have stimulated visionary concepts. Modern sensor technologies in conjunction with intelligent software make possible an objective evaluation of sensory perceptions and thus create the basis for equipment containing "sense organs". Systems responding to acoustic, thermal or optical stimulations have long since established themselves in industrial applications. Now the "Electronic Nose" has been developed according to principles of nature and is ready for industrial application. However, in comparison to the human model the Electronic Nose has highly enlarged capabilities. The human sense of smell is subject to external influences and can therefore provide only subjective odour structures. In addition there are gases, which the human nose cannot detect. The recognition of such substances, however, plays a special role in the assessment of situations and processes.

1.1. How it all began

The development of the Electronic Nose was initiated by the space industry, where a broadband control of the inhaled air inside space vehicles is required. RST Rostock developed the intelligent sensor system SamSGS for the EUROMIR 95 mission and the German mission MIR 97. Successfully deployed in both missions the system has proven its long-term stability on the space station MIR since 1995.

Having acquired the core competence for intelligent multi-sensor systems, *RST* and ***FIREFLY AB*** has brought the specific space system to infrastructure/tunnel maturity: ***FIREFLY*** offers the SENTIO system as a modular sensor system for various applications in security technology and environmental monitoring. This system not only recognizes odours, fragrances and other volatile substances in an objective and rapid manner, but detects also gases, which the human nose will not perceive or which contain Intolerable substances.

1.2. The MGD technology

The core element of SENTIO-System is an array of chemical sensors with different sensitivities. Each sensor produces an unique characteristic response signal depending on a given contamination scheme.

The interaction between individual signals produces a signature, which shows an odour structure typical of the substance concerned, called the "olfactory fingerprint". By training the system with signal patterns of typical substance mixtures, the identification of defined substance mixtures becomes possible. The MGD-detector measures the actual composition of molecules in the air using a matrix of chemical gas sensors (MOS thick-film technology) where the elements of the matrix are sensitive to different odours. The sensors offer long term stability of sensitivity and response.

The detectors adapt continuously to long-term changes in the background values in the air due to e.g. seasonal variations. Rapid changes, such as occur in the initiation of a fire, are detected. Pattern recognition by the neural network using statistical analysis the detector identifies the molecular composition of the air. If a sudden change in the composition is detected, the pattern is analysed to determine if the change is due to a fire or another source and thereafter give an alarm. The detector is programmed with several levels. The sensitivity of the levels can be programmed individually.

2. SENTIO TUNNEL SAFETY

Temperature detection, smoke detectors (particle counting) and camera surveillance are examples of current commonly used tunnel protection solutions. These are however not efficient in detecting the early stage of a fire, which is the release of gases.
By using MGD detectors that can withstand the tough environment of a road tunnel, a unique solution arises where fire can be detected at an early stage while at the same time known, harmless disturbances can be suppressed.

2.1. Tunnel Application Technology

The Sentio® system is designed to operate in infrastructures environments as for example road and train tunnels. The system is designed to ensure that fires and related incidents can be detected at an early stage, and thereby give possibility for operators and first responders to initiate any further actions.
The Sentio® system for early fire detection uses a network of gas detectors that monitors the tunnel environment. The Sentio® system uses an existing Ethernet platform, and utilises MGD (Multiple Gas Detectors) sensor technology. The operator interface, SAC (Sentio® Alarm Client), can be customer adapted and data and information is also available from a SQL server or an OPC server solution.
By strategically positioning MGD’s in the area that shall be monitored the system can give alarm when deviation from the normal gas pattern occurs. The deviation can arise for example at the beginning or in the progress of a fire, overheating of cables or similar.

2.2. System set up

The Sentio® System consists of the following main system components:

- Multiple Gas Detector (MGD)
- System Monitor (SM)
- Database (DB)
- Sentio® Alarm Client (SAC)
- LAN/WAN
- Power over Ethernet switches (PoE)

2.3. System software

2.3.1. System Monitor (SM)

System Monitor is a software application for PC-server environment.
The main purposes of SM are:

- To display status of the total system
- To give the operator the possibility to access detailed information from the system.

The server shall run on operating system Microsoft Server 2008 – 64 bit..
SM communicates with:

- DataBase (DB)
- Multiple Gas Detector (MGD)

2.3.2. Data Base (DB)

The Data Base (DB) is placed on the network in one or multiple server/servers.
DB stores for example:

- Configuration parameters
- Gas patterns
- Statistics and system log file

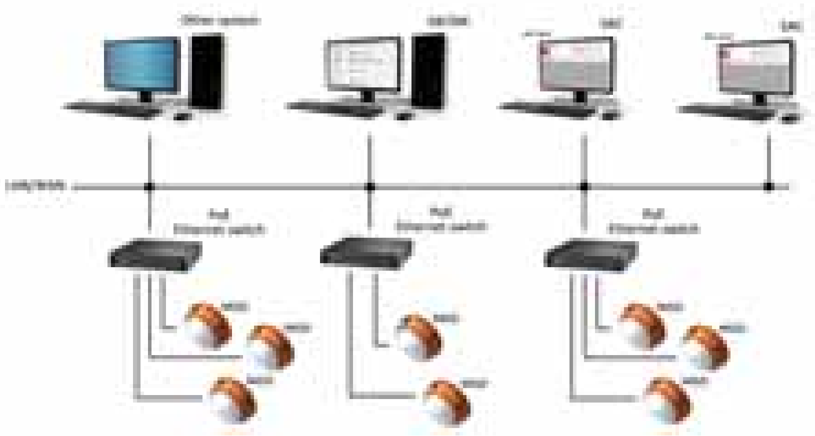
The DB can be run on one or more computers on the network. The computers which run DB will contain the same information in their database. The system is based on an SQL-database. The server shall run on operating system Microsoft Server 2008 – 64 bit. SM and DB can be installed on the same server.

The DB is accessed by:

- System Monitor (SM)
- Sentio® Alarm Client (SAC)

2.3.3. LAN/WAN

Local Area Network/Wide Area Network
Ethernet network based on TCP/IP.



2.3.4. Alarm Client (SAC)

Sentio® Alarm Client (SAC) is a software that provides information from events in the fire detection system to operators. SAC can be used, for example, at traffic management centres, operation monitoring centres and similar environments. SAC can also be used by system managers wishing to check the system status.

SAC can be configured at user level just to display selected information of the total quantity of available information. In this way users can only see information relating to - for example - operation-related alarms in a specific part of the system. There may also be a certain type of alarm or group of alarm types that shall be displayed.

SAC also includes an acknowledgement and logging function. All events are centrally logged. The logging contains when the incoming event is registered in the system, when the incoming event is acknowledged and by whom. By acknowledging an event, the user confirms that he has dealt with the incoming event for on-going action outside the system.

3. SYSTEM INSTALLATION

All components included within the Sentio® system is designed for easy assembly and installation.
The Multiple Gas Detector (MGD) is normally installed in the ceiling. The detector is upon delivery fitted with a mounting bracket for the position..
An industrial grade Cat 6 cable is installed from the MGD detector to the PoE switch. .
System Monitor (SM) and database (DB) can run on a standard server. Sentio® Alarm Client can run on a standard windows pc.

4. OPERATION

The Sentio® system is designed to be a simple and a reliable system to manage. All important functions are automatically monitored. At an alarm, information is given to the operator.
All the system components are listed in the database (DB), with detailed information on the location. The system also allows individual adjustment of the data; name, position information, etc.
Software update is done by downloading the new software to central server/database. The software is then downloaded to each unit

5. CONCLUSION

By using this technology that can withstand the tough environment of tunnel environments, a unique solution arises where fire can be detected at an early stage while at the same time known, harmless disturbances can be suppressed.

EARLY FIRE DETECTION IN SWISS ROAD TUNNELS WITH MORE THAN 1'500 FIREGUARD SENSORS

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ABSTRACT

Major fire incidents in road tunnels with a larger number of casualties led to a discussion and measures to increase the safety in road tunnels. Technical evaluation of the various incidents showed, that the monitors typically installed for visibility monitoring and ventilation control gave early and reliable signals, indicating the start of a fire. In most cases, fire start due to technical reasons on the vehicles, such as defective engines, turbocharger, brakes, tires, etc. Such defects typically lead first to the development of cold smoke before an actual fire starts (in many cases, there's even no fire, just smoke). Such incidents remain invisible to CCTV and linear fire cables.

In 2004, the Swiss Federal Roads Office (FEDRO) introduced the first draft of a standard for a suitable and reliable early fire warning detection system. Based on these recommendations, SIGRIST-PHOTOMETER was the first company developing and manufacturing a new smoke/fire detector fulfilling the requirements set by this draft, which eventually became the official standard in Switzerland in 2007.
The Gotthard road tunnel was the first tunnel which was equipped with more than 200 Fire-Guard sensors. In the meantime, several tunnels in Switzerland, Germany, Spain, Norway, Sweden and Czech Republic have been equipped with this monitor.

The presentation gives an overview about the major projects concluded in Switzerland and the practical experiences of early fire detection in road tunnels. At the end an impressive video demonstrates the reliable reaction of the smoke sensor in a real tunnel during the final inspection.

1. YES, IT HAPPENS!

Fire in a road tunnel - a nightmare for every driver! Fortunately, big accidents followed by an explosion or a big fire (like in the Montblanc or Gotthard tunnel) are rare. Smaller incidents however happen more often than generally recognized.
Below some incidents are listed which were important enough to be mentioned in the newspapers. In all these cases no casualties resulted, although in some cases people were just lucky. In any case, such incidents disrupt the heavy traffic flow and they can easily lead to costly structural damages.

June 19, 2011:
A coach with 59 passengers caught fire in a tunnel of the city ring west, Zurich. Damage on the infrastructure: € 400'000

January 27, 2012:
Due to a technical defect, a small truck
caught fire in the «Saas» tunnel

April 4, 2012:
A coach with 74 passengers caught fire just in front of the entrance of the «Gotthard» tunnel

July 13, 2012:
Due to a motor damage, a car caught fire in the «Gubrist» tunnel
Damage on infrastructure:
€ 160'000

August 15, 2013:
A passenger car caught fire in the «Donnersberg» tunnel in Austria.

December 20, 2013:
Two people were killed when a car crashed and caught fire in the "Lieferinger" tunnel near Salzburg.

2. FEDRO LEGISLATION FOR FIRE / SMOKE DETECTION

Investigations of the various fire incidents in road tunnels and their technical evaluation clearly showed, that the instruments installed for visibility monitoring, always gave the very first clear signal when smoke was involved. Based on these findings, the Swiss Federal Roads Office (FEDRO) came to the conclusion that smoke sensors, based on scattered light technology, are ideal tools to effectively detect and localize incidents of cold smoke/smouldering fires.

FEDRO is the first and still only country which has set clear standards and requirements [1)] for the installation of fire/smoke detectors in road tunnels. The most important requirements are formulated as follows:

1. The automatic system must be able to localize a fire within a maximum distance of 100 meters in less than 60 seconds
2. The automatic fire detection system shouldn't trigger more than one faulty alarm for every 2 kilometer per year
3. Fog must not be detected as smoke

Based on these requirements, SIGRIST was the first company which developed and introduced a suitable sensor, the "FireGuard", in the market in 2007.

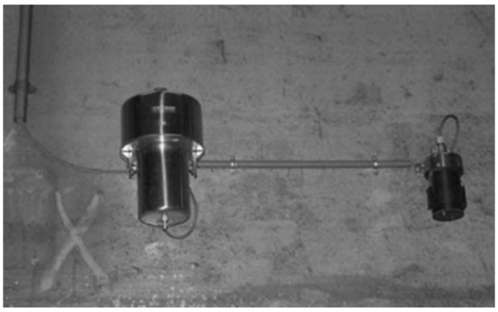
3. SIGRIST "FIREGUARD"

The "FireGuard" sensor uses the principle of light scattering. The unique design has no moving parts; the function is based on the natural air flow existing in the tunnel. The response time is less than 5 seconds. An integrated temperature sensor helps to localize the place of the incident in case of a fire. Fog is effectively eliminated by optional heating elements. Typically they are only needed at the tunnel entrance and exit. Communication is made either via simple programmable relays or by Profibus DP. Installation can be done on the wall or ceiling using a multi-purpose holder. As an alternative, a special model is available for installation in the intermediate ceiling of the fresh air channel or even directly into the frame of the dampers.

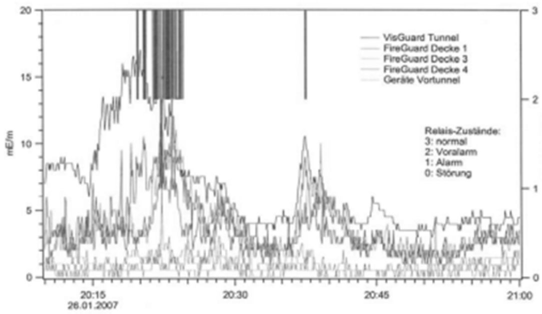
4. PROJECTS

4.1. “Gotthard” tunnel - 2007

In June 2006, SIGRIST presented the first prototype, followed by the first test installation in September in the “Gotthard” road tunnel. During this test period, data were collected during normal traffic conditions, as well as from incidents which happened during this time. All data were logged, and the results analysed. Parallel measurements with the already existing SIGRIST visibility monitor “VisGuard” confirmed the correct measurement of the sensors.



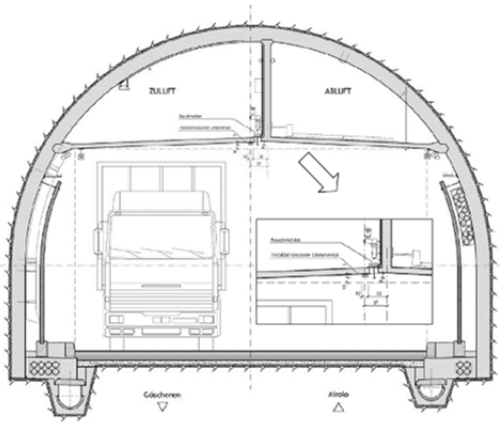
Test installation: VisGuard (left) & FireGuard (right)

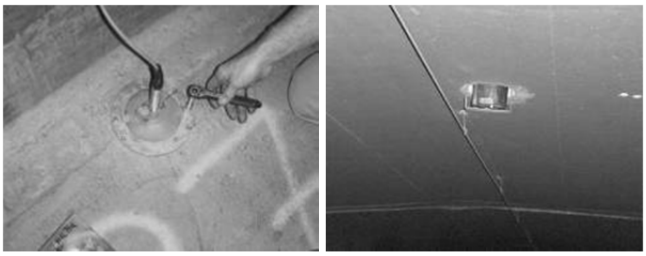


Collected data during the test received from various installations

After a successful trial period of 9 months SIGRIST received the order to supply 210 FireGuard sensors to be installed in September 2007.

Installation was made in the fresh air channel of the intermediate ceiling; the distance between the sensors was 96 meters.



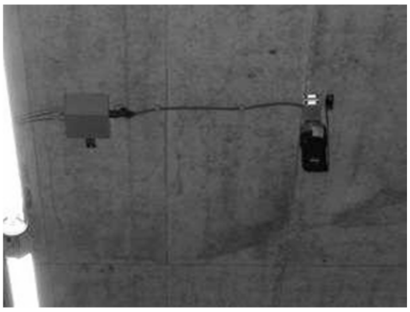


FireGuard installation: view from top of the intermediate ceiling (left) and under the intermediate ceiling (right). Also visible is the linear heat detector

The alarming concept is as follows:

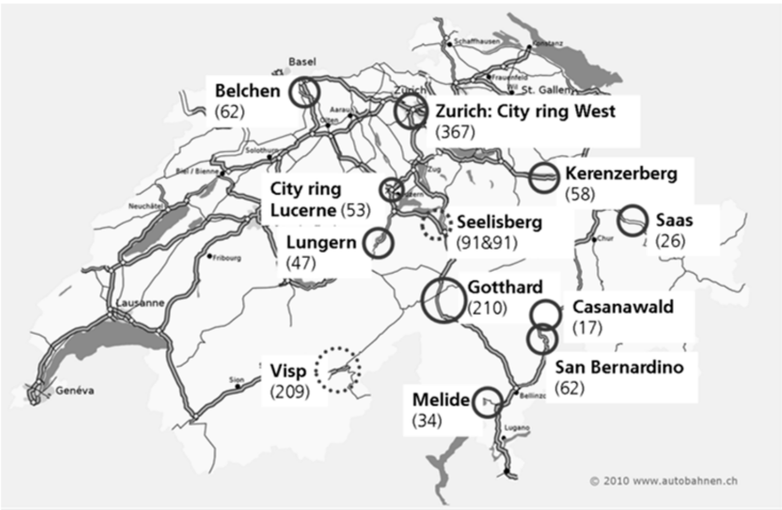
Detection of the smoke, differentiation between a moving and a stationary object based on time differences of the alarm sequences. Compared to linear heat detection systems, smoke detectors show a very rapid response time. The FireGuard sensors are used to automatically execute the first alarm and initiate the necessary actions, based on a complex algorithm defined in the software [2)].

4.2. City ring West, Zurich – 2009



After decades of discussion and a lot of opposition, the bypass for the city of Zurich was finally built and opened in May 2009.
This bypass connects the highways from Basel-Bern to Chur and also connects Zurich and Lucerne. The total length is 26.3 Km, 13.3 Km are tunnels. The total construction cost was approx. 3.2 Bn. Euros. The safety investment for the FireGuard sensors, including installation was only about 1‰ of the total cost. A total of 301 FireGuard sensors were installed every 100 meters in the newly constructed tunnels. Additional 66 FireGuard sensors were installed in the already existing "Gubrist" tunnel, which is part of the bypass system as well.
The FireGuard is used for early smoke detection, linear heat detectors are installed for fire detection.
For the visibility monitoring, a total of 77 VisGuard sensors were installed.

4.3. Projects concluded or planned



The following chart gives an overview about the major projects concluded (circle) in the past seven years and the projects currently executed (dotted circle). The number in brackets indicates the number of sensors installed in the tunnel.

Until now, a total of more than 1'500 FireGuard sensors have been installed in 60 tunnels in Switzerland.

5. PRACTICAL EXPERIENCES

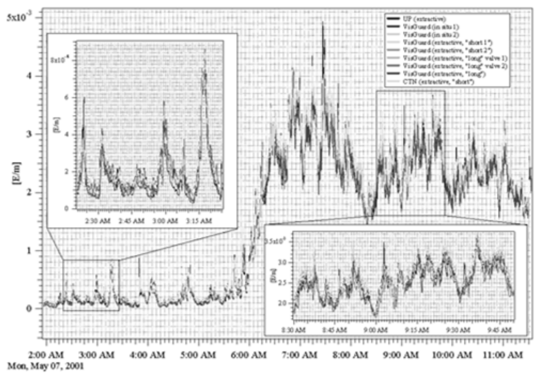
The following chapter informs about the practical experiences so far collected from the numerous installations.

5.1. Parameter settings

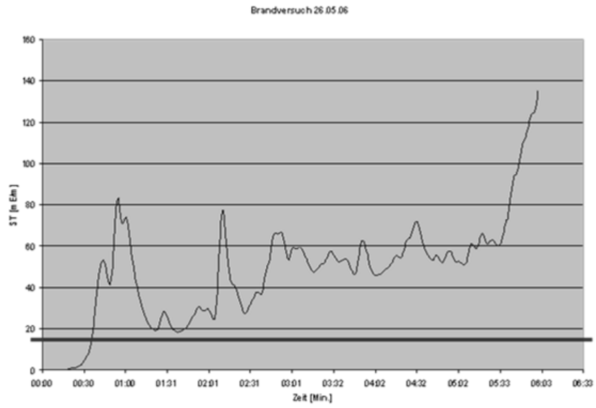
One of the critical questions is: where do we set the alarm level? This question is most important as this decision will have a direct impact on the rate of false alarm. The goal must be to set the limits low enough to detect an incident as early as possible, but to avoid false alarms because the limit has been set too low. The analysis of various incidents, as well as fire tests with calculated heat release, demonstrates that the visibility level quickly exceeds the limits typically used by the operators to close a tunnel (in Switzerland this would be at 12mE/m).

The diagram below on the left shows typical visibility values during the night and the beginning of a day until midday in the Gotthard tunnel. One can clearly see the very low values during the night with visibility values not exceeding 1mE/m. From approx. 6 am, traffic starts to increase, resulting in visibility peaks reaching up to 5mE/m.

The graph below on the right shows typical values measured for early fire/smoke detection. The thick line marks the maximum of the typical measuring range used for visibility monitoring, which is 15mE/m. As shown, visibility values quickly increase above the 15mE/m level. Reasonable limits therefore should be set at 10mE/m as a pre-alarm and 30mE/m for the main alarm.



Visibility values during the night and beginning of a day



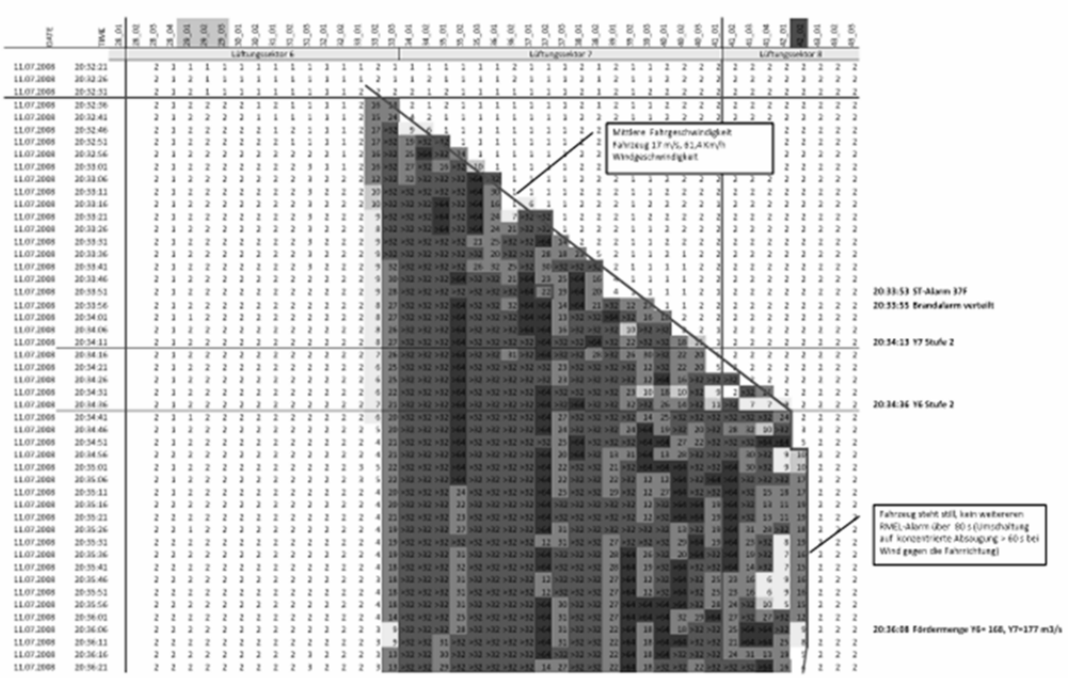
Increase of the visibility values in case of smoke

5.2. Example of the system reaction during a real incident

The following part describes the practical experience of the system reaction in the Gotthard tunnel from an incident which happened on July 11, 2008 [2)].

A truck with a defective turbocharger, developing strong smoke was moving south; about 2.1 Km into the tunnel before the driver realized that he had a problem with his truck and stopped. The air velocity in direction north was 2.2 m/sec. An area of 2.5 Km was covered with smoke.

The automatic reaction of the ventilation system was based on the alarm sequence triggered by the values of the FireGuard sensors. The algorithm determined that the truck was moving in the beginning and even allowed to calculate the average speed of the truck. As long as the truck was moving, an increased distributed suction was initiated by opening the corresponding dampers in the intermediate ceiling. Once the truck stopped (this again was determined by the algorithm applied), the ventilation system was changed to a concentrated suction, combined with a change of the flow direction towards the place where the truck stopped (S = 1.8 m/sec, N = 3.2 m/sec). The total time required to remove the smoke was 30 minutes.



Graphical display of the visibility values during the incident:
20:32:31 – Beginning of an increased distribution suction of the ventilation
20:35:51 – Change to a concentrated suction at the place where the truck stopped

6. PARAMETERISATION

Principle we learnt from the numerous installations: the optimum parameter settings must be established individually for each tunnel installation!

Parameterisation is complex and depends on:

- Kind of tunnel (profile, single or two-way traffic)
- Applied concept for the ventilation and fire
- Traffic volume and vehicle mix (passenger cars/trucks)
- Climatic conditions (e.g. salt spray in winter)
- Sensitivity (must be balanced between system reactions vs. risk for false alarms!)
- Way of data handling and philosophy of alerting. Basically, there are two possibilities:
    1. Transmission of the raw data to the control centre, evaluation and reaction based on safety concept (Example: Gotthard – fully automatic release, incl. definition whether the object is moving or stationary, all based on complex algorithms)
    2. Local evaluation and alerting by using the integrated parameter programmability in the control unit SIPORT

7. MAINTENANCE

Time for routine maintenance in road tunnels is limited. Typically, maintenance is done during scheduled closure times during the night. FEDRO regulations requests that sensors should be designed in such a way that a yearly scheduled maintenance must be sufficient to guarantee a proper and reliable function for the next 12 month, without any extra unplanned action. Therefore, the basic requirements for a sensor can be summarized as follows:

- One scheduled maintenance per year must be sufficient to guarantee a trouble-free function
- Maintenance must be simple and fast
- No parts subject to wear should be used

After 7 years of experience with the FireGuard we received the following feedback from operators:

- The only maintenance needed is to clean the measuring chamber. Sensors with heaters (tunnel entrance and exit) need to be cleaned once per year.
- Sensors without heaters: cleaning is only necessary every 2-3 years! The integrated soiling monitoring allows to immediately checking if cleaning is necessary or not.
- After the cleaning, an automated calibration is performed using a checking rod
- Time required per sensor for cleaning and recalibration: max. 15 minutes.

Operators training for maintenance

Recalibration with checking rod

8. VIDEO CLIP: SMOKE TEST OF A SWISS ROAD TUNNEL [3)]

Before a tunnel is opened for public it is thoroughly tested by the FEDRO authorities. Such a test includes the correct function of the complete electro-mechanical installation, including the ventilation control under normal traffic conditions and in case of an incident.

The video shows the simulation of an incident by creating artificial smoke generated on a small truck driving through the tunnel “Saas” and then stopping at a certain place. The graphic display shows the fast reaction of the FireGuard sensors installed and the corresponding ventilation control. It also demonstrates nicely that the linear heat detectors only reacted once the vehicle stopped and a slight temperature increase could be detected.

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2) Grässlin U., Lombardi Engineers, Switzerland: “Experiences from the Gotthard tunnel by using visibility, smoke and fire detection”, tunnel symposium SIGRIST, Brunnen/Switzerland, October 29, 2008

3) Smoke test tunnel “Saas”, September 9, 2011. Video by FEDRO and made available to SIGRIST by the courtesy of Mr Marcel Berner, specialist for operating and safety equipment

AIRFLOW MEASUREMENT IN ROAD TUNNELS

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ABSTRACT

Reliable and accurate monitoring and control of the longitudinal air speed is necessary in road tunnels equipped with exhaust dampers, used for concentrated smoke extraction, and in longitudinally ventilated tunnels where in the event of fire tunnel users can be located on both sides of the fire. The system's scope is to prevent an uncontrolled propagation of smoke and to improve the self-rescue conditions of the tunnel users.

In order to allow airflow control within narrow tolerances inside the tunnel, it is necessary to provide reliable and accurate measurements of the air speed, being used as input to a closed-loop control system of the ventilation equipment that regulates the air speed at the incident location.

The objective of the research project funded by the Federal Roads Office (FEDRO) was to compare different measurement techniques, consisting of a dynamic pressure head measuring system, two ultrasonic line measurement systems and three ultrasonic point measurement systems, a thorough field study has been conducted, which was funded by the Swiss Federal Roads Office (FEDRO).

Keywords: tunnel ventilation, air flow, air flow monitor, ultrasonic, pitot tube, tracer-gas

1. INTRODUCTION

The scope of the field study was to evaluate typical airflow measurement systems in representative tunnel configurations over a prolonged period (including the main seasons of a year). The available resources allowed installing up to 4 test sections each being equipped with all selected measurement systems. Two tunnels were thus selected, one with one-way traffic (RV-“Richtungsverkehr”) on two lanes and the other with two-way traffic (GV-“Gegenverkehr”) with one lane for each direction. Furthermore, only tunnels with a longitudinal ventilated horseshoe profile in the entrance area (“Hufeisenprofil” - HU) and a semitransversally ventilated rectangular false ceiling profile (“Zwischendecke” - ZD) in the inner area were picked out. Close attention was paid to the compliance of these tunnels to standard cross-section profiles according to the Swiss directives and guide lines. The chosen tunnels were the single-tube Flüelen tunnel and the twin-tube Bözberg highway tunnel.

Two test installations were build-up in each tunnel and the respective two cross-sectional profiles (**Figure 1**) to render the field study as representative as possible.

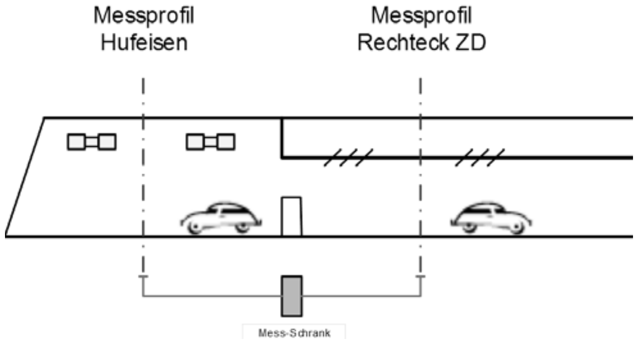

Figure 1: Schematic of measurement profiles

This comparative measurement campaign, with overall six different flow measurement devices in each test section, lasted approximately 10 months, from January to October 2012. The measurement readings were normally recorded and analyzed with a 10 seconds cycleFurthermore, to obtain independent reference values, tracer-gas measurements were performed at the beginning and end of the measurements campaign.

The data reduction and analysis focused on the consistency of the measurements, the response behavior of the airflow devices, and the performance of these instruments in various traffic conditions, including incident scenarios. A statistical analysis of the measurements was also performed.

The project faced some unexpected functional problems, which did not affect the final result but had to be solved in order to improve the reliability and stability of this long term study.

The measurement data of the airflow devices were documented and analyzed in detail. The recommendations which emerge from these investigations are aimed to improve and optimize the general concept of "airflow measurement inside tunnels" and thus address manufacturers, engineers and operators and shall contribute to the ventilation guidelines and the technical data sheets issued by FEDRO.

2. MEASURING AND ANALYSES

2.1. Airflow measuring systems

The following airflow measuring systems were tested in the study:

Dynamic pressure head measurement

- TMS 3000, Schiltknecht Messtechnik AG, Gossau ZH

Ultrasonic point measurement

- TK-300, ACP AG, 2563 Ipsach
- TunnelCraft3, Codel Ltd, by J.con-GmbH, 77815 Buehl, Germany
- Windcheck, Fives Pillard, 13272 Marseille Cedex 8, France

Ultrasonic line measurement

- D-FL 220T Durag Group GmbH, 22453 Hamburg, Germany
- Flowsic200, Sick AG, 6370 Stans

2.2. Calibration and operating conditions of the measurement systems

The 6 test system providers installed and calibrated their airflow devices in the two selected tunnels according to their company specific procedures. The measured values made available to the common acquisition system had to consist of 10 second averages. The requested measuring range was +10 / -10 m/s.

Since the measurements of the single point devices were performed close to the tunnel sidewalls, it was expected that wall distance and Reynolds number-dependant correction factors would have to be applied according to standard pipe flow theory (**Figure 2**).

However, according to the providers of these single point systems, such kind of corrections are usually not applied.

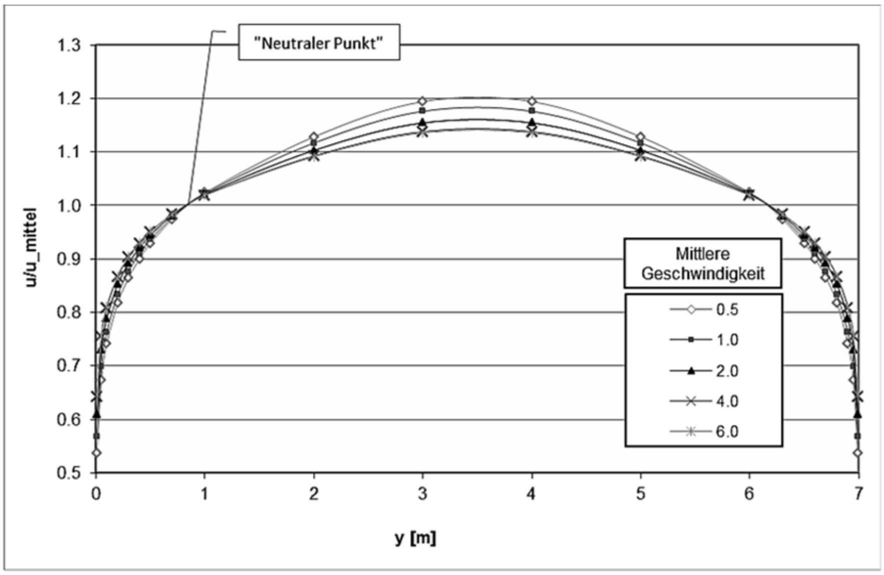

Figure 2: Pipe flow velocity profile

2.3. Data evaluation

Variations of ambient air pressure ranging from 950 to 980 mbar, of humidity from 20% to 95%, as well as strong temperature fluctuations (summer – winter) or traffic conditions didn't have any observable effect on the measurement quality during the whole campaign and this in both tunnels.

Typical data recorded in the one-way Bözberg tunnel is shown below (**Figure 3**). The figure displays the air speed in the two measurement sections installed in the tunnel as well as the influence of the traffic volume over a 24 hours period.

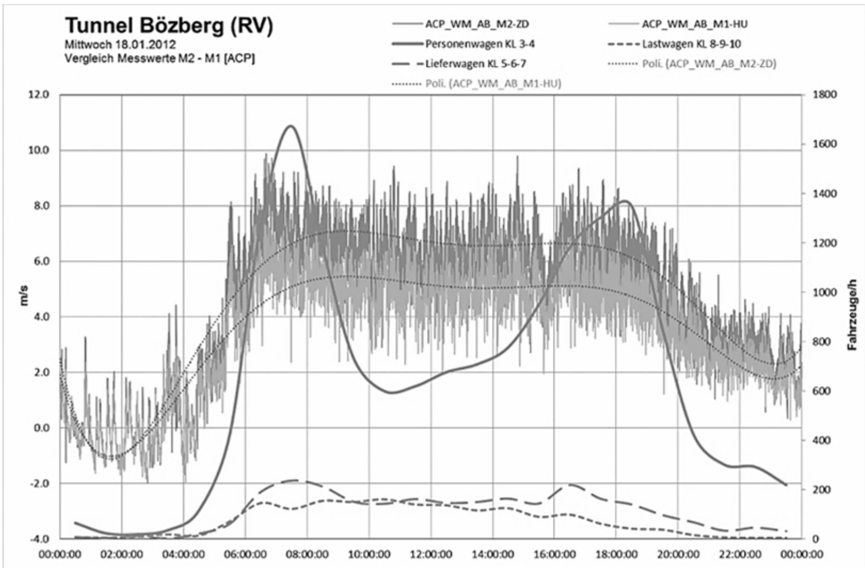

Figure 3: Tunnel Bözberg, air speed and traffic data.

As mentioned previously, the field study revealed a number of problems regarding some of the tested airflow devices:

- Measurement drifts due to unstable electronic components
- Failure of a measuring head and resulting in wrong averaged data
- Aberrant measurements caused by software failure
- Ultrasonic transducer salt corrosion (salt used during winter time)
- Reading errors caused by reflexions from the tunnel ceiling
- Improper virtual temperature values
- Defective soldering of a PT 100 temperature sensor
- Differences between positive and negative flow measurements
- Measurement sensors deformed during tunnel washing activities (brushes)

2.4. Tracer-gas

Tracer-gas measurements were performed at the beginning and end of the measurements campaign in order to obtain independent reference values; these measurements have been carried out under normal traffic conditions as the availability requirements of the traffic infrastructure overbalanced the needs of the field study.

Due to the traffic induced unsteadiness of the flowfield, the gas analysis was not fully able to capture the fast changes of the air speed. The resulting uncertainty didn't allow a precise real time comparison between the tracer-gas reference values and the air speed measured by the tested devices, although the tracer-gas measurements were corrected by an integral time-adjustment procedure. A comparison of the tracer-gas and device values is displayed in the following figure and shows generally a good agreement:

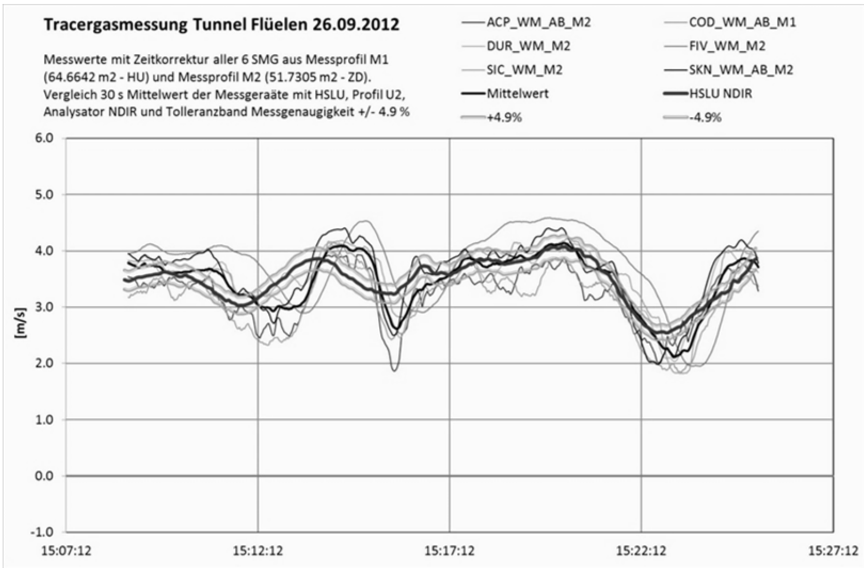

Figure 4: Tunnel Flüelen, measured data and tracer gas values

2.5. Statistical analysis

For a comparative, statistical analysis, the measurement data of two typical weekdays was closely evaluated for long-term comparison: a winter day (Wednesday, 8.2.2012) and a summer day (Wednesday, 05.09.2012). This was the longest possible time span with the same device configurations.

To smooth the measured values recorded every 10 s, a 60 s running average was applied to all data series. As basis for the consistency check of the data, the average value of well working devices was used at each time-step.

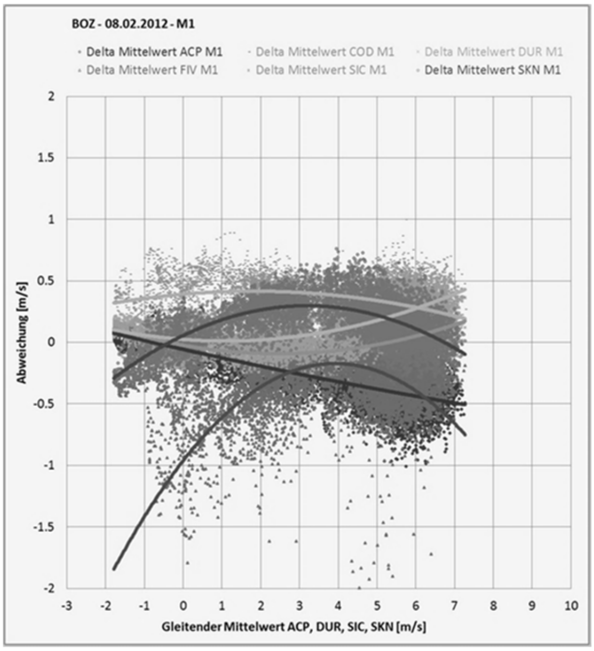

Figure 5: Tunnel Bözberg, measured data deviation from average value, February 2012

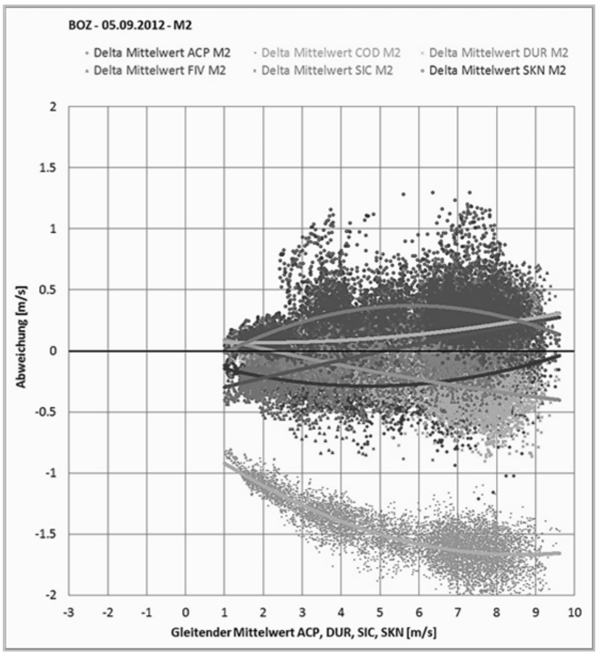

Figure 6: Tunnel Bözberg, measured data deviation from average value, September 2012

3. CONCLUSIONS

The results of the study reveal that there are still some discrepancies between the expectations and the actual performance regarding accuracy and reliability of tunnel air speed devices. The main conclusions are:

1. For reliability and confidence reasons, an automatic and autonomous detection and exclusion of wrong values within the measurement system is important. Information regarding possible system-inherent malfunctions must be transmitted to the control system.
2. Periodic, automated plausibility checks of the measured values are compulsory to permanently ensure the reliability of a flow measurement system; there i.e. the following three approaches:
   a. If a tunnel has a jet fan ventilation system, a longitudinal flow can be easily induced. Plausibility checks are thus carried out during low traffic time windows.
   b. If no longitudinal ventilation system is installed, longitudinal airflow may also be generated with semi-transversal or transversal ventilation systems (according to the push-pull principle).
   c. In tunnel with semi-transversal or transversal ventilation systems a volume flow rate balance can be calculated on the base of the supply and exhaust fan airflow rates; a "theoretical" distribution of the air speed along the tunnel can then be continuously compared to the actually measured values of the devices using the least squares method. Such a theoretical curve is shown below for the Gotthard road tunnel. Thus, if the actual measurements diverge too much from the theoretical curve the plausibility is questionable.

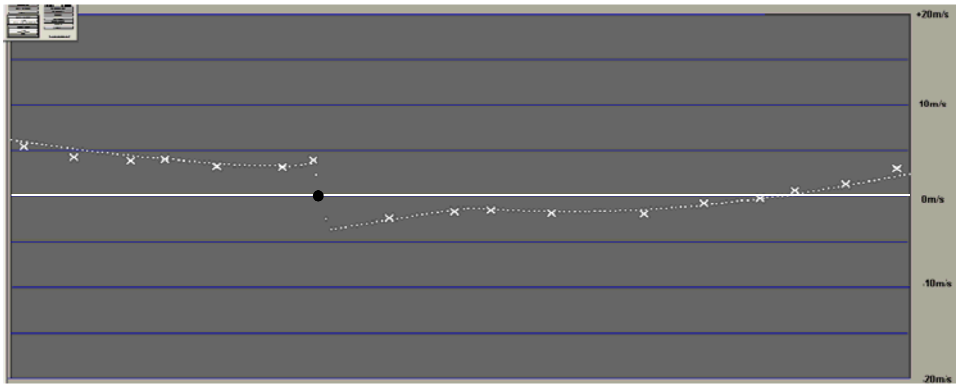

Figure 7: Gotthard road tunnel, theoretic calculated curve and measured values (x)

3. The various observed malfunctions of flow devices during the 10 months period have demonstrated that the requirement formulated in the FEDRO technical sheet 23001-11320 "Devices" – which states that the plausibility must be verified by at least three flow measurement devices, or by groups of devices – is indeed purposeful to ensure the reliability of the measurement system.
4. In general, the results of the study show that the tested technologies can meet the necessary requirements, when the recommendations of this field study are taken into account, in particular regarding periodic and automated plausibility checks of the measured data (see chapter 4).
5. As an outlook to the future, the development of standardized test procedures for plausibility checks is furthermore advised.

4. RECOMMENDATIONS

4.1. Recommendations to manufacturers

The practical experience collected during the 10 months period of this field study lead to the following recommendations:

- Stainless corrosion resistant instrument housing and mounting elements
- Mechanically robust design
- Stable electric and electronic components
- Automatic exclusion off faulty measurements caused by physical boundary conditions (e.g. tunnel ceiling) and tunnel operation conditions
- Improved device internal plausibility analysis and status return to control system
- Maintenance interval 1 year or longer
- Protection cover during tunnel washing, if required

4.2. Recommendations to engineers

While designing the system:

- Accurate definition of measurement sections, installation and operating conditions
- Accurate definition for the airflow devices
- Suppliers must specify all parameters (no black-box)
- Lowest average time of 10 seconds must be available in case of fire
- Galvanic separation modules and surge protection shall be provided
- Definition of commissioning test and calibration procedures

- Definition of periodic test procedures
- Clear separation between data reduction within the device and the control system (e.g. correction factor, running average value)

4.3. Recommendations to operators

While operating the system:

- Regular maintenance according the provider's instructions
- Record of operating statistics for every device (journal)
- Periodic functional tests
- After an event/fire the analysis of the airflow data is mandatory.

4.4. Recommendations for FEDRO guidelines

Ventilation guidelines

- If airflow devices are an active part of the ventilation control system, periodic and automatic plausibility checks are required.
- Plausibility check results must be stored (data warehouse archive).

Technical data sheets

- For point measurement devices, reference measurements are required during commissioning to obtain adequate correction factors for deriving the actual flow rate in the measurement cross section.
- Correction factors to compute the volume flow rate shall be stored in the control system
- Installation position: differentiation between linear and punctual devices
- Point measurement devices: minimal overhead from sidewalk ≥ 2.50 m
- Minimal distance from the wall ≥ 30 cm
- Linear devices: minimal distance to the tunnel ceiling to avoid deflecting and aberrant results

5. ACKNOWLEDGEMENT

The authors thank the Federal Road Office for funding the project and the members of the advisory board for the constructive and helpful assistance.

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ANALYSIS OF A 10 MW FIRE IN AN UNDERGROUND RAILWAY STATION USING FULL SCALE TESTS AND CFD

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ABSTRACT

The railway line operated by Zentralbahn Luzern (zb) was expanded to two tracks and re-routed underground on the section from Lucerne Station to Kriens Mattenhof Station. The new route section consists of a tunnel about 550 m long constructed by underground means, an underground railway station nearly 300 m long with three access points, a cut-and-cover tunnel about 470 m long and a ramp 140 m long, the total length thus being 1460 m.

The underground railway station is equipped with a smoke extraction system. The latter consists of a smoke extraction duct with openings along the platform, two axial fans in a ventilation building and an exhaust air flue. During project approval the Swiss Federal Office of Transport (FOT) stipulated that the performance of the smoke extraction system be verified by testing prior to commissioning and that the achievement of safety objectives be documented.

For this reason, a test concept was developed that not only comprises aerodynamic tests and hot smoke tests on a 1:1 scale with fire loads of 1 MW max. but also involves a mathematical proof based on three-dimensional flow simulations (3D computational fluid dynamics or 3D CFD).

As a result, it was possible to produce objective evidence that the safety objectives were achieved in a fire scenario with a heat release of 10 MW. In addition, the use of computational simulations for obtaining objective evidence meant it was possible to investigate certain influences more closely within the scope of a sensitivity analysis.

Keywords: underground railway station, smoke extraction system, hot smoke tests, computational simulation of hot smoke tests, smoke extraction

1. INTRODUCTION

Within the scope of the "Zentralbahn Upgrade" construction project, the railway line operated by the regional railway company Zentralbahn (zb) in Central Switzerland on the section from Lucerne Station to Kriens Mattenhof Station was upgraded to two tracks and re-routed underground. The new route section consists of a tunnel about 550 m long constructed by underground means (Hubelmat), an underground railway station nearly 300 m long with three access points, the Allmend cut-and-cover tunnel about 470 m long and the Mattenhof ramp 140 m long.

The underground railway station "Luzern Allmend/Messe" is equipped with a smoke extraction system for the safety of users. The latter consists of a smoke extraction duct along the platform, two axial fans in a ventilation unit and an exhaust air flue. During planning approval the Swiss Federal Office of Transport (FOT) stipulated that the performance of the smoke extraction system be verified by testing prior to commissioning and that the achievement of safety objectives defined in the safety concept [3] be documented.

Since at the scheduled time of testing the overhead line and other sensitive fittings had already been attached to the ceiling of the tunnel, the plan to simulate a 5 MW fire incident with hot smoke test apparatus had to be discarded.

Instead, in addition to aerodynamic tests and hot smoke tests with fire loads of 1 MW max., three-dimensional flow simulations (3D computational fluid dynamics or 3D CFD) were conducted. Apart from a check on aerodynamic design and the fire scenarios realised in the test, the aim was particularly to produce mathematical evidence that the safety objectives were achieved in a fire scenario with a heat release of 10 MW.

The use of computational simulations for obtaining objective evidence meant it was possible to investigate certain influences on the behaviour of the fire smoke extraction system more closely within the scope of a sensitivity analyses.

2. DESCRIPTION OF THE SMOKE EXTRACTION SYSTEM

At the "Luzern Allmend/Messe" station there is a ceiling duct made of fire-resisting material mounted above the platform, via which smoke can be mechanically removed from the station. The smoke extraction duct has a length of approximately 220 m and it follows the course of the platform. Due to the arrangement of several ceiling columns and 3 staircases the cross-section of the smoke extraction duct varies between 3 m² and 10 m². In addition, there are subsections with a united smoke extraction duct and subsections with two separate smoke extraction ducts. The ducts are routed past the stairs on the left and right (Figure 2).

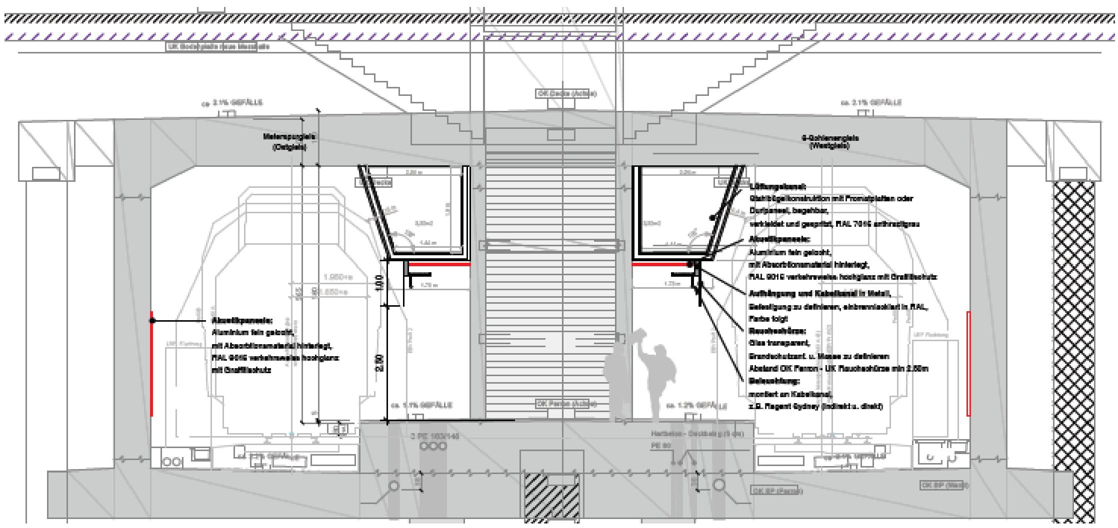

Figure 1: Cross-section of "Luzern Allmend/Messe" station with extraction duct

Smoke extraction takes place via extraction openings distributed at equal intervals along the length of the platform. Their size can be varied with the aid of slides and they are always adjusted so that the flow of air (approx. 6.5 m³/s) is the same at each opening. There are 11 x 2 extraction openings altogether, which means they are positioned at intervals of about 20 m. The openings are located on the side of the duct facing the track and do not have any flaps, i.e. they are always open.

The total volumetric flow is extracted by two parallel fans (partial redundancy) in the ventilation building. The system is designed for a rated volumetric flow of 140 m³/s but it has some reserve capacity so a maximum working point of 175 m³/s can be reached.

In addition, the duct is provided with a smoke apron along the station. The distance between the smoke apron and the top of the platform is 2.5 m.

3. PROTECTION OBJECTIVES

The aerodynamic tests, hot smoke tests and ensuing 3D flow simulations are designed to produce objective evidence that the safety objectives defined in the safety concept [3] are achieved:

- *Safety objective 1 - Accesses to the station:*
  The three accesses to the station remain low-smoke zones for at least 15 minutes.
- *Safety objective 2 - Height of the low-smoke layer within the station:*
  For the first 10 minutes the average height of the smoky layer in the platform area does not drop below 2.5 m. In this area of the station the height of the low-smoke layer does not drop below 2.0 m during the first 10 minutes, neither temporarily nor locally.

Compliance with the safety objectives is assessed by analysing the two parameters of temperature and extinction coefficient. The quantitative criteria indicated in Table 1 are examined in order to produce objective evidence.

Table 1: Criteria for producing objective evidence that protection objectives are achieved (quantitative analysis)

No.	Criteria	Limit	Explanation
1.	Height of the low-smoke layer	2 m	Applies to a period of 10 min
2.	Temperature of the low-smoke layer	50°C	Cf. **Fehler! Verweisquelle konnte nicht gefunden werden.**
4.	Extinction coefficient K of the low-smoke layer	≤ 0.15m-1	The recognisability of escape route pictograms is only severely restricted as of approx. K = 0.4m-1 (>> 0.15m-1) (cf. **Fehler! Verweisquelle konnte nicht gefunden werden.**).

4. HOT SMOKE TESTS

4.1. Test Setup

In order to minimise the temperatures at the ceiling of the station and at the conductor rail low rates of heat release (< 1 MW) were realised at the site of the fire. With several small gas burners positioned directly above the tracks it was possible to generate relatively large amounts of flue gas at relatively low temperatures (cf. Figure 2). The volumetric flow of flue gas from all the burners together corresponded approximately to that of a 5 MW fire. To protect the conductor rail a fire protection blanket was also suspended above the burners, directly under the conductor rail.

The flow situation in the station was recorded by simultaneous measurement of air flow velocity on the platform, in the staircases and in the two tunnel tubes. In addition, meteorological measurements were taken in the area of the tunnel approach in Mattenhof.

Temperature measurements were taken at the staircases in the two tunnel sections, at the Allmend portal and in the station, especially in the area of the fire directly below the conductor rail. The volumetric flow extracted by the two smoke extraction fans was measured and recorded in the control room.

Figure 2: Setup of equipment for the hot smoke test

4.2. Result of the hot smoke tests

On 25 and 26 September 2012 the I.F.I. ((Institut für Industrieaerodynamik GmbH) conducted a total of 6 hot smoke tests with various boundary conditions in collaboration with HBI AG.

The flow situation in the station prior to activation of the smoke extraction system depends not only on temperature differences between inside and outside but also on the wind forces acting on the tunnel portals and staircases. The temperature differences were not very substantial and the maximum was 4°C. During the first 4 tests, wind activity was also only moderate. Wind velocity fluctuated between 0 and 1.5 m/s. As of the 4th test the wind activity increased and in the 6th test it reached peaks of up to 9 m/s (1min means). As a result, flow velocities of up to 2.5 m/s were induced in the station.

At the beginning of the first 4 tests a basic flow of < 1 m/s was measured in the station. The air flowed out of the station via the staircases. When the ventilation system was activated the direction of flow was reversed. The same happened at the portal where the basic flow had previously excited. The total air flow entering the station is extracted by the two axial fans through the smoke extraction duct. When the ventilation system is activated, the flow velocity in the staircases temporarily rises excessively due to the smaller masses of air that have to be displaced.

At the beginning of fire development, the smoke within the track area rises to the ceiling and spreads out below the ceiling on either side of the fire site. Spread in one direction is slightly more intense due to the prevailing basic flow and the smoke ultimately reaches the end of the station.

Activation of the smoke extraction system draws the smoke back into the area of the fire source, from where it can be completely extracted. Temporarily, and only in the area of the fire source, there are also minimal smoke immissions into the low-smoke layer. After about 8 minutes a quasi steady state develops, in which the smoke layer remains stable and extends from the ceiling to the bottom of the smoke apron at most.

5. SIMULATION ANALYSES

5.1. Simulation Program

To obtain mathematical objective evidence (achievement of safety objectives) the flow simulation program STAR-CCM+ was used. The three-dimensional geometry of the station was modelled on the basis of CAD drawings. A train standing in the station was also modelled (cf. Figure 3).

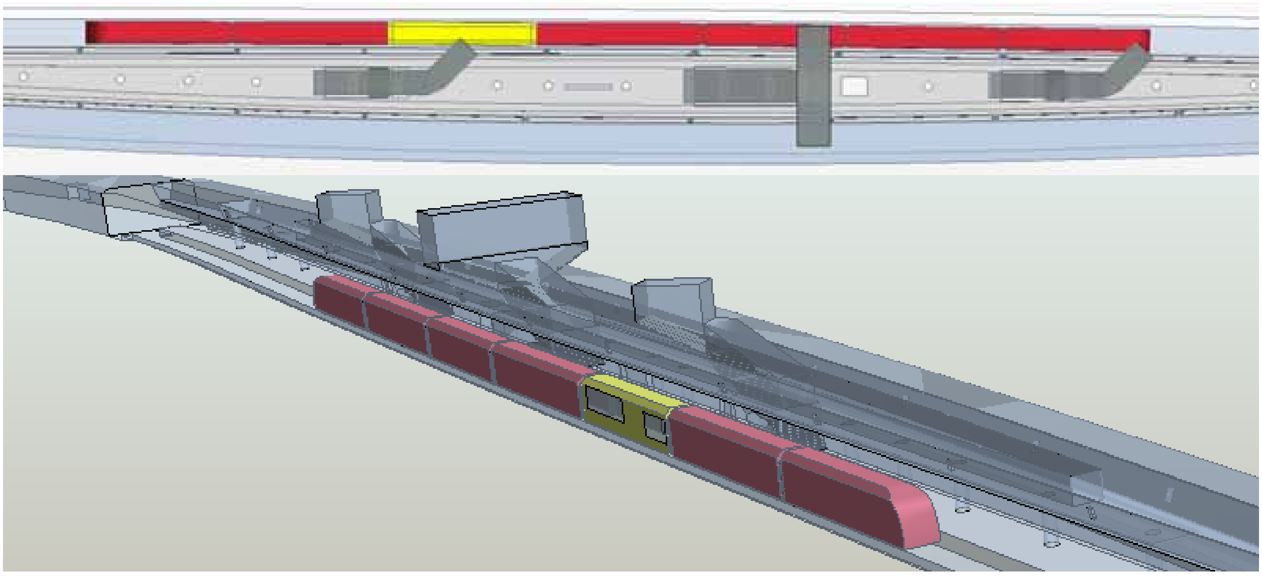

Figure 3: Geometric mathematical model with train

5.2. Result of the Simulations

Several simulations of the fire scenarios were performed using various boundary conditions. The check on the hot smoke tests was mainly used for calibration of the mathematical model and for validation.

The check on the 2nd hot smoke test was used for validation proper of the CFD simulation model and it consisted of several computation runs, of which some are accounted for by the modelling of energy release in the fire volume and for reproduction of temperature measurements in the area of the conductor rail above the fire location and some were used for a sensitivity analysis of the thermal boundary conditions. This involved the temperatures at the pressure boundaries (portals and exits) and temperature initialisation in the area of the fire. In addition, portal pressure difference was checked which generated a longitudinal flow through the structure corresponding to test conditions.

There was also an evaluation of the computation runs with regard to all the necessary state and flow parameters in the computational domain, such as visibility, smoke concentration (extinction), temperature, volumetric flows, flow velocities, turbulence parameters, etc. and an assessment of convergence characteristics.

The check on the second hot smoke test indicated that the simulation produces plausible results with regard to temperature distribution and smoke spread (cf. [9]). This can be very clearly seen in Figure 4. The latter shows photographic documentation of the smoke density situation in the station during test 2, alongside the same situation with a superimposed CFD simulation result. The level of smoke-free vision correlates well in both cases.

Figure 4: Actual and simulated smoke density during test 2 in the station

Several simulations were also performed with a constant heat release of 1 MW, which served to identify the influence of different longitudinal velocities in the structure. For this purpose the static pressure at one tunnel portal was successively increased from 0 Pa, as a result of which the longitudinal flow velocity induced in the station increases. At a longitudinal flow in the structure of about 2.5 m/s with the smoke extraction system activated the smoke layer of a 1 MW fire becomes unstable on the side facing away from the fire. This correlates well with the observations made in the 5th hot smoke test.

The mathematical proof of compliance with the safety objectives was obtained by means of flow simulation for a fire incident with a fire load of 10 MW. A total of 7 computation runs were performed with an energy release rate of 10 MW. Three were conducted without a rail vehicle in the station and four were conducted with. Within the scope of a sensitivity analysis, additional investigations were performed which produced findings concerning the following points:

- The stability of the smoke layer in relation to fire load and basic flow
- The influence of extraction flow on the quality of smoke extraction
- The influence of the rail vehicle in the station

A high basic flow in the station due to meteorological pressure differences has a detrimental effect on the smoke density situation because the spread of the stable smoke layer is disrupted. At high longitudinal flows (> 3 m/s) the smoke extraction system reaches the limits of its performance.

The investigations also showed that an increase in extraction flow to 175 m^3/s has a positive influence on the smoke density situation in the station because then meteorological influences can be kept under control more easily and the continuous inflow via the staircases is improved.

The rail vehicle in the station also has a positive influence on the smoke density situation because, on the one hand, a considerable volume of smoke can accumulate inside the vehicle, and on the other hand, the restricted inflow to the fire source leads to higher temperatures in the smoke layer, which therefore remains at the tunnel ceiling for a longer period.

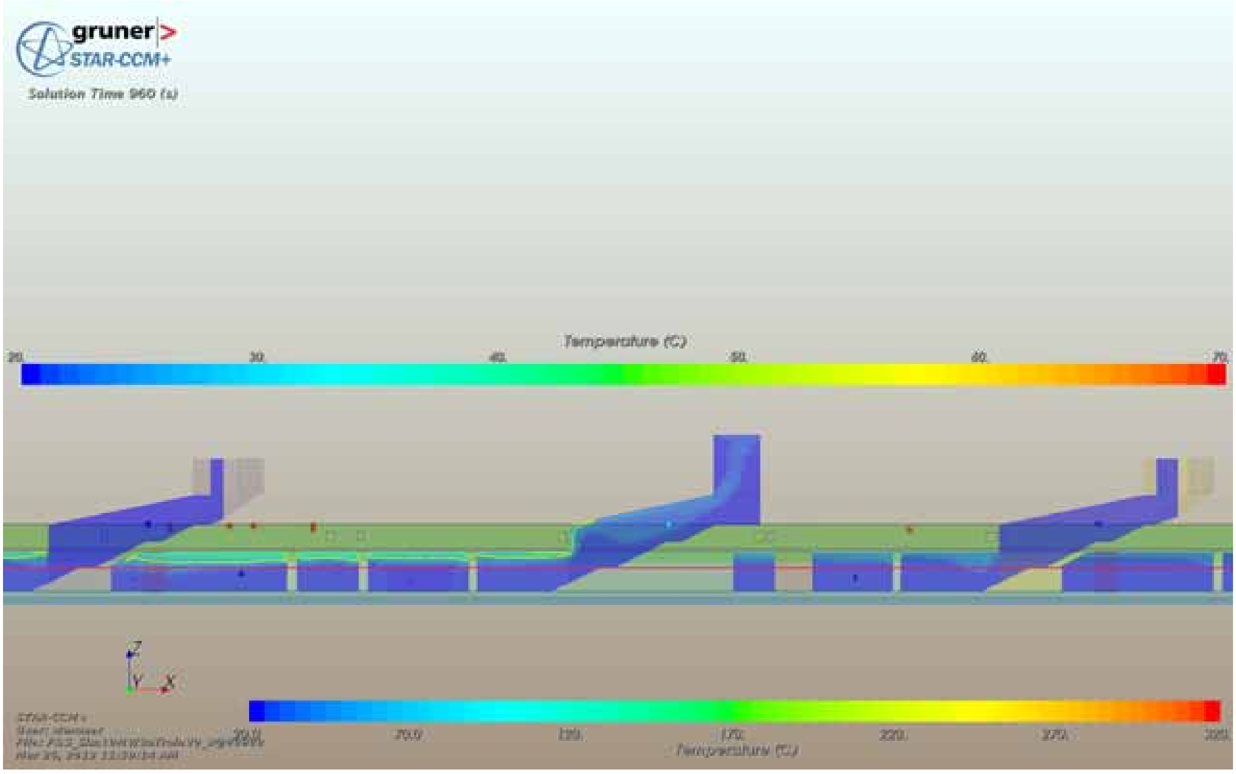

Figure 5: Example of compliance with the safety objective "temperature in the low-smoke layer" - longitudinal section of the station

6. SUMMARY

The newly built underground railway station of Zentralbahn, "Luzern Allmend/Messe", was equipped with a mechanical smoke extraction system. To produce evidence of the fact that it achieves the protection objectives specified by the safety documentation, the performance of the smoke extraction system was investigated by conducting hot smoke tests and three-dimensional flow simulations (3D CFD) prior to commissioning.

Several hot smoke tests in the station with fire loads of up to 1 MW were used to validate a 3D simulation model. For this purpose, simultaneous measurements of air flow velocity on the platform, in the staircases and in the two tunnel tubes were taken at the same time. In addition, air temperature was measured at numerous positions. Meteorological measurements in the portal area produced the initial boundary conditions.

Based on the validated simulation model, the mathematical proof of compliance with the protection objectives was obtained by means of flow simulation for a fire incident with a fire load of 10 MW. Several computation runs were performed with and without a rail vehicle in the station. Within the scope of a sensitivity analysis, additional findings were obtained with regard to the following points:

- The stability of the smoke layer in relation to fire load and basic flow
- The influence of extraction flow on the quality of smoke extraction
- The influence of the rail vehicle in the station

Evaluation of the state parameters obtained from the simulations, i.e. visibility, smoke concentration (extinction) and temperature in the computational domain, permitted a simple assessment of the criteria for producing evidence of safety objective achievement.

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AIR BARRIERS USED FOR SEPARATING SMOKE FREE ZONES IN CASE OF FIRE IN TUNNEL

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ABSTRACT

The aim of this paper is to take the advantage of CFD application in calculating, optimising, and designing air curtains used to separate smoke free zones in case of fire in tunnel. Air curtains can be a good solution in case when the usage of solid obstructions is not feasible (for example in a big tunnel).A properly designed air curtain produces a pressure drop which prevents transversal flow through the opening. An accurate CFD calculation of an air curtain is challenging because of the high air velocity and relatively thin nozzle. Most air curtains are tested on scaled down models which are difficult to extrapolate. Tests in a real scale model are performed and the tests results are used to verify the chosen turbulence model. The intention of this paper is to present the comparison between the CFD calculations and tests results.

Key words: air barrier, CFD calculations, fire, tunnels

1. INTRODUCTION

To avoid standstill and facilitate the flow of vehicles and people through doorways of buildings and other enclosures, solid doors are often replaced or supplemented by air curtains (air screens, air planes). Simultaneously, the air screen eliminates or reduces the transfer of heat and mass through the opening. Air curtains have become popular in the 60's of the 20th century; nevertheless, the principles of the air planes dates back to 1904. The concept of air screens was founded by Theophilus van Kennel [3][4][5] and his idea has become a fore-runner of modern air curtains. The flow of air across the doors is caused by the difference of pressure between two volumes of fluid, the dissimilar temperature values, and the presence of a ventilation system. Air curtain devices are often used in the entrances to public buildings, cooling rooms and refrigerators, as well as in chemical and electronic industry.

The knowledge that a direct exposure to fire is not the most immediate threat to people's lives, has been displayed by previous experience and research. A vast majority of fatalities connected with fire are triggered by the smoke-inhalation. Therefore, to decrease the number of fatalities air curtains can be used as virtual screens to stop smoke spreading in a building. Safe evacuation of people and secure intervention of fire fighters are of significant importance and need to be taken into consideration [11]. Air screens can be used to obstruct or reduce the movement of toxic smoke while enabling full access to emergency exits. Properly designed air curtains produce a pressure drop which preventstransversal flow through the opening (Fig.1).

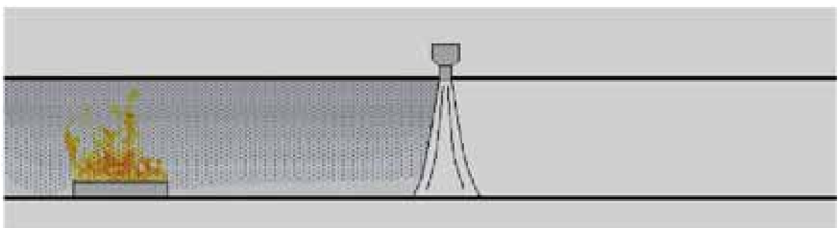

Figure 1: Illustration of zone separation

There are many applications of such kind of solution in example. tunnel junctions, elevators connected to the stations in underground tunnels, separation between tunnel and station.(Fig. 2)

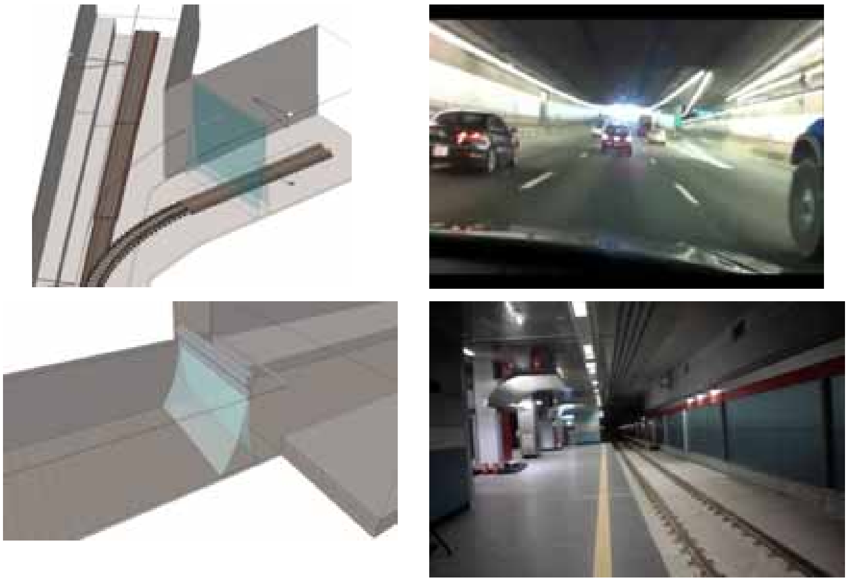

Figure 2: Application of air curtain

The main criterion for the air curtain is its efficiency which is the rate of mass and heat transfer crossing it, in comparison with the same opening without the curtain.

Air curtain design is considered relatively difficult. It is essential to know the conditions on both sides of the air curtain to choose its parameters correctly.

If the outlet velocity is too high and the blowing angle is not optimal, the air curtain can increase the heat and mass transfer through itself. On the other hand, if the jet velocity is too low, the air curtain will not be tight enough.

Currently, most of the installations are experimentally set up on scaled down or full scale physical models. Nonetheless, it is hard to extrapolate results from the scaled down model to the different geometrical dimensions because the Euler number similitude is unavailable. As it is written in literature that kind of extrapolation provides an wrong results by creating to high or to low speed [5].

To study the performance of air curtains the application of computational fluid dynamics (CFD) is useful. It is critical to properly define initial and boundary conditions and compare gained results from simulations with analytical equations.

2. AIR CURTAIN DESCRIPTION

2.1. Velocity distribution

There are numerous publications involving experimental data and mathematical analysis presenting the theory of a free stream jet as velocity profile and deflection of the centreline axis. Significantly in this subject, publications of Abramovich (1963) and Rajaratnam (1976) offer the most fundamental piece of information [1].

Particularly, depending on the height and the stream of air, a jet shows two, three or four regions. It is possible to distinguish between the potential core zone, the transition zone, and the developed zone or the impinging zone (Fig.3):

- Potential core zone: characteristic for this region is that the centreline velocity is almost constant and equal to the outlet velocity U_0.
- Transition zone; this region starts with the velocity decay and the amplification of the jet expansion. It generally starts after approximately 5 e from the nozzle. Analytical solution of the velocity can be described by:

$$\frac{U(x,y)}{U_0} = \frac{1}{2}\left[1 + erf\left(\sigma_1 \frac{y+\frac{e}{2}}{x}\right)\right] \qquad \text{Eqs. 1}$$

  e - characteristic dimmension of nozzle [m]
  U_o - outlet velocity on the nozzle [m/s]
- Developed zone – in this region velocity decay remains constant. Velocity decay expressed with non-dimensional quantities. It generally starts after approximately 20 e from the nozzle. Analytical solution of the velocity can be described by [10]:

$$\frac{U(x,y)}{U_0} = \frac{\sqrt{3}}{2}\sqrt{\frac{7.67e}{x}}\left[1 + \tanh^2\left(7.67\frac{y}{x}\right)\right] \qquad \text{Eqs. 2}$$

$$\frac{U_C(x)}{U_0} = C_1\left(\frac{x}{e} - C_2\right)^{-\frac{1}{2}} \qquad \text{Eqs. 3}$$

  C_1 and C_2 depends on the nozzle shape and on the boundary conditions. They are in the range $1.9 < C_1 < 3.0$ and $-8 < C_2 < 10$
- Impinging zone: this region is in the vicinity of the floor. The flow in that zone is very complex and still not well known. The thickness of that zone is approximately 15% of the total height.

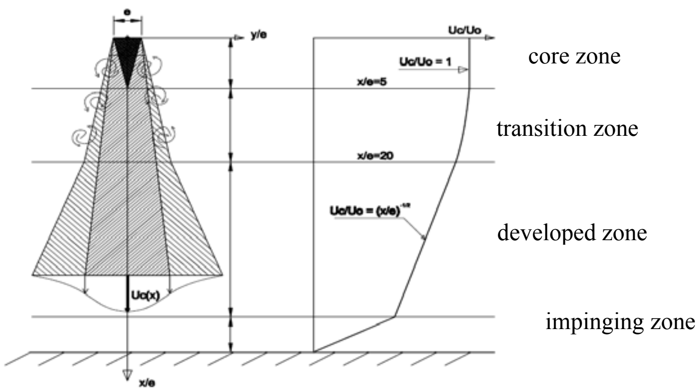

Figure 3: Zones of a free air jet

2.2. Deflection of jet axis

According to F. C. Hayes and W. F. Stoecker [7][8], the problem of a plane jet, subjected to a lateral side pressure and the blowing angle directed to the side of higher value of the pressure is treated in the literature with the conclusion that the axis of the jet represents a circular curvature

Looking at picture below (Fig. 4) there are 8 variables describing the problem. Air curtain can be set up 5 non-dimensional numbers which are representative of the phenomena. There are Euler number, geometric aspect ratio, the Reynolds number, turbulence intensity at exit and blowing angle.

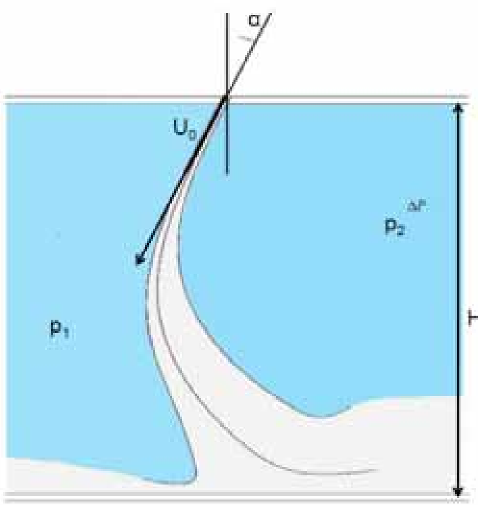

Figure 4: Air curtain

$$\frac{\Delta P}{\frac{1}{2}\rho U_0^2} = f\left[\frac{H}{e}, \frac{U_0 e}{\nu}, I_0, \alpha\right] \qquad \text{Eqs. 4}$$

g_c - gravity [m/s²]
ΔP - pressure difference [Pa]
ρ - density {kg/m³]
e - characteristic dimension of nozzle [m]
U_o - outlet velocity on the nozzle [m/s]
α - nozzle angel [°]
ν kinematic viscosity [m²/s]

3. EXPERIMENT

Before studying the air curtain used to prevent smoke movement, the numerical model isverified.The verification was done in a tunnel of 8 m length, 1 m width, and a 2 m height.

The test equipment enables to carry out tests with a blowing angle of the jet varying from 0 - 45° and velocities up to 30 m/s. The nozzle width is 20 mm (changeable). The pressure difference on both sides of the air curtain could be set in a range from 0 Pa to 200 Pa.

A schematic drawing of the test facility is presented below in Figure 4. The real scale model was build in Fire research Department in Building Research Institute (Fig. 5).

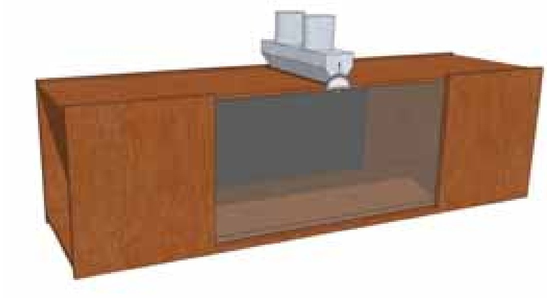

Figure 5: Illustration of test facility

3.1. The free air jet

The initial test, which was done to validate the numerical model, was a free jet test. Testes were carried out for three different air velocities at the nozzle outlet (10 m/s, 20 m/s and 30 m/s). Referring to free jet centreline velocity decay and transversal distribution of the jet velocity were compared with the CFD results.

The velocity measurements in the centreline were done using hot wire thermo anemometry with three wires to measure velocity in two directions (Fig.6) and viualisation..

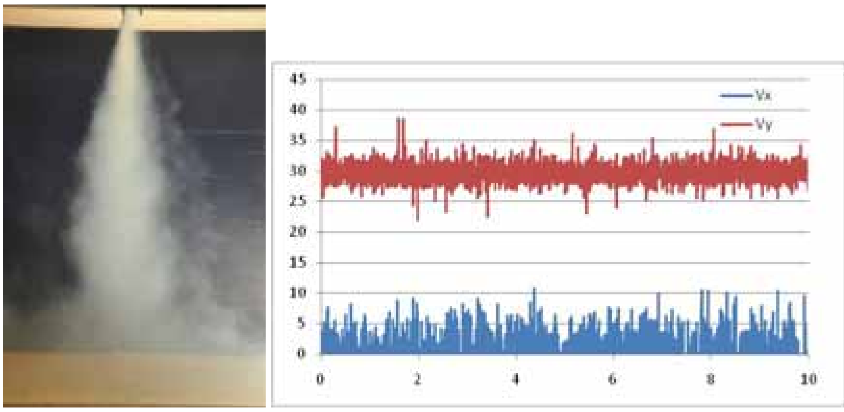

Figure 6: Velocity at the nozzle outlet

4. SIMULATION

In order to evaluate the parameters and the effectiveness of the air curtain, it is necessary to perform series of calculations using the CFD.

To confirm the correctness of the boundary conditions and CFD models, numerical calculations of free jet were performed. Defined initial conditions were the same as in the experiment. Blowing angle of the jet is equal to 0°, the outlet velocity from the nozzle is 10 m/s, 20 m/s and 30 m/s. Turbulence intensity is the same as in experiment (about 5%).

The three-dimensional model of the analyzed domain was build according to the experimental setup. In the middle of the ceiling an air curtain outlet was created. The domain has been divided into a finite number of control volumes using an unstructured hexahedral grid. The total quantity of control volumes was approximately 2 500 000 with dimensions ranging from 2 mm in the area of the air curtain outlet to 20 mm on the peripheries of the domain. The three-dimensional model is presented in Figure 7.

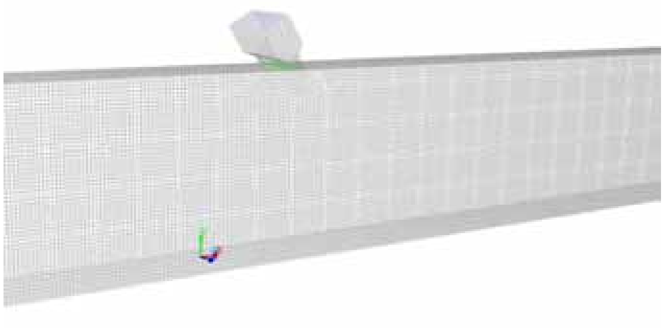

Figure 7: View of the CFD model

The numerical simulations were conducted using ANSYS Fluent 14.5. software. RANS k-ε Realizable turbulence model was applied in the calculations. Boundary conditions are defined as walls for the side, bottom and top of the analysed domain. Additionally, the air curtain slot is defined as velocity inlet; the upstream and downstream part of a model are pressure inlets. Various configurations to check the behaviour of the air stream have been investigated. For instance, diverse pressure differences and outlet velocities are simulated.The results from the CFD calculations were compared with those from the experiment.

5. RESULTS

The effects of the numerical calculations of the free jet are in good agreement with the examined results from the experiments with exception of the first part of the stream for almost all turbulence models (k-ε. k-ω, LES). As illustrated in Figure 8, the outcomes of the centreline velocity reveal a significant similarity to those obtained in the experiment. In order to visualize the velocity profile, the velocity counters in cross-section of analytical domain are presented in figure 9. Comparing detailed analyzes of measurements it seems that time averaged RANS k-ε model describes air curtain phenomenon very well.

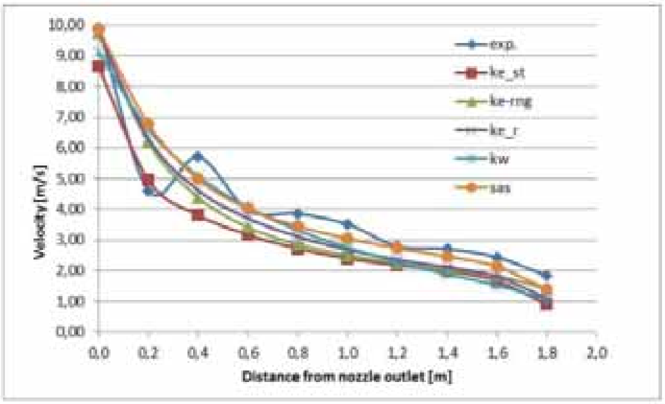

Figure 8: Centreline Velocity (α=0°, U=10 m/s)

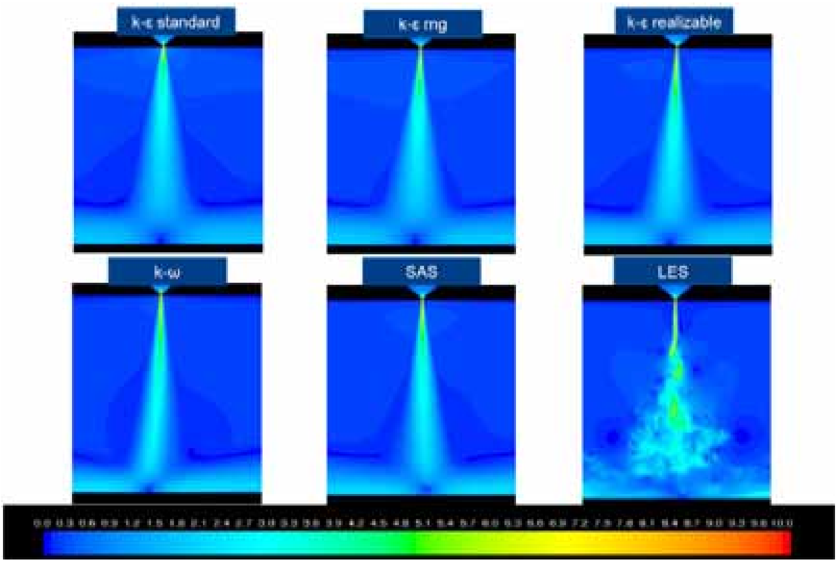

Figure 9: Velocity counters in cross-section of numerical domain

The experimental result of using the air curtain as a separation of two zones (one full of smoke and one free of smoke) is shown in Figure 10.

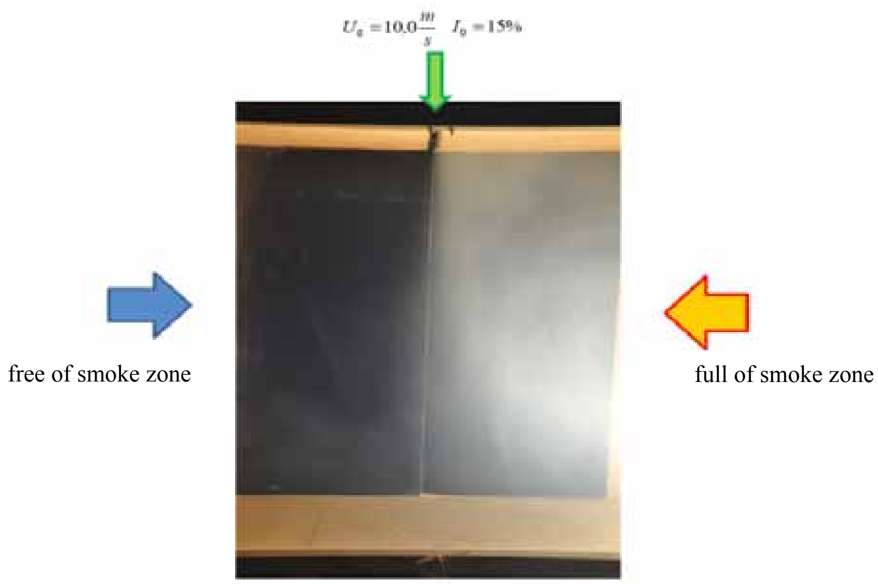

Figure 10: Division of two zones using air curtain

Visualisations of the air curtain shapeunder the influence of lateral pressure are given in Figures 11 and 13.

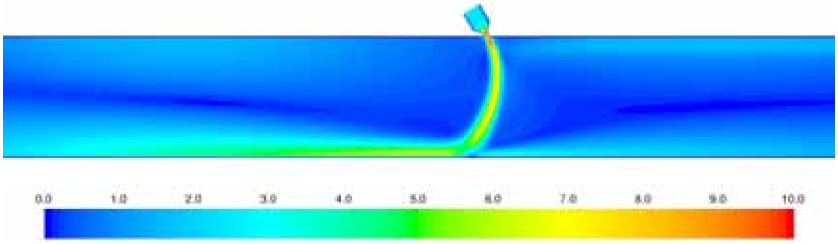

Figure 11: Velocity profile in cross section e=5 cm, U= 10 m/s

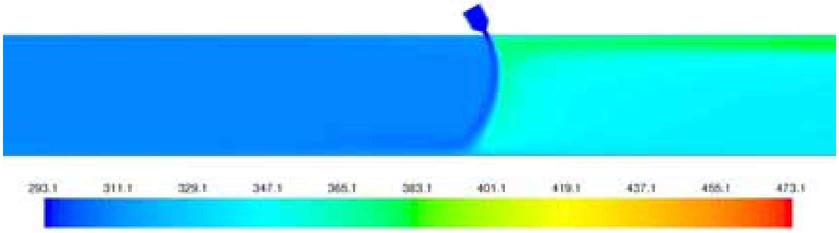

Figure 12: Temperature range in cross section e=5 cm, U=10 m/s (K)

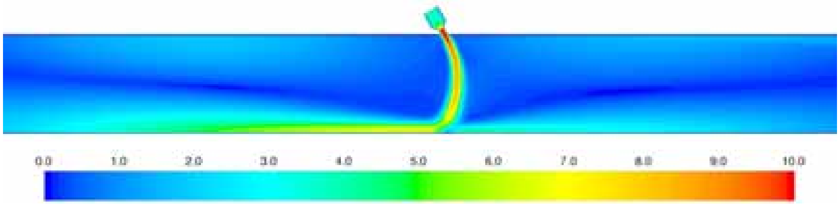

Figure 13: Velocity profile in cross section e=10, U=10 m/s

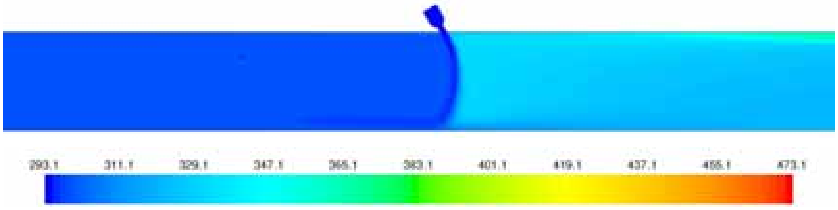

Figure 14: Temperature range in cross section e=10 cm, U=10 m/s (K)

In Figure 12 and 14 the simulation results of a division of two separate zones of fluid is presented. One of them has higher temperature then second one, on the opposite side of the air curtain, is not higher then 5 K that it was in the initialisation moment. On the left side of air curtain (normal temperature) an underpressure was defined, that why the jet has an arc shape.

The amount of heat (smoke) which is transferred through the air curtain is significantly low. More detailed analysis of air curtain leakages will be done in further research using CFD calculations [12] and scale model tests.

6. CONCLUSION

This paper demonstrates the possibility of using CFD methods to properly design and analyse air barrier. According to conducted simulations, it is crucial to declare that air curtains can be used as a division of smoke free zones in case of fire.

In addition, properly defined boundary conditions and chosen turbulent model have fundamental influence on received effects.

Research has been done in the framework of the project "Innovative measures and effective methods to improve the safety and durability of buildings and transport infrastructure in the strategy of sustainable development" co-financed by the European Union from the European Regional Development Fund under the Innovative Economy Operational Programme.

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EVALUATING SMOKE RECIRCULATION POTENTIAL AT THE PORTAL OF A SWISS ROAD TUNNEL IN CASE OF A FIRE

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ABSTRACT

The self-rescue phase in the case of a road tunnel fire requires the evacuees to be able to escape either into the adjacent tunnel or, when available, into a dedicated exit passage leading to the open air. The adjacent tunnel and/or the dedicated exit passage serve as the first safe haven for the evacuees and therefore a high visibility level should be guaranteed by keeping it smoke free. In the first instance, the smoke could enter the safe haven (non-incident tunnel and/or escape passage) either via the escape routes themselves (e.g. doors of cross passages, exit tunnels etc.) or via the portals of the tunnel.

This paper concentrates on the transmission phenomena of smoke from the incident tube to the non-incident tube using 3-D numerical simulations. The object considered for this study is a real road tunnel in Switzerland. The exact geodetic, meteorological and tunnel geometry data is taken into account for the numerical simulations. Constructional measures such as the length of the anti-recirculation wall and the effect of meteorological conditions such as the wind speed and direction are investigated. The results of the simulation studies - the smoke recirculation level for different scenarios - are plotted on a "harm potential" graph. The harm potential graph defines the critical recirculation level that can pose a threat to the evacuees in terms of loss of visibility. This type of graph was developed as part of a research project financed by the Swiss Federal Roads Office (ASTRA) and has been applied in this case to evaluate and quantify the preventive measures needed to minimize the smoke recirculation issue at the tunnel portals in the case of a road tunnel fire.

Keywords: Smoke recirculation, numerical simulations, anti-recirculation wall

1. INTRODUCTION

The phenomena of smoke recirculation at the tunnel portals is defined as the amount of smoke or air from one portal entering into the adjacent portal and is usually expressed as a percentage level "%" ranging between 0 % (no recirculation) to 100 % (full recirculation). Recirculation itself can be subdivided into three sub-phenomenon namely Emission, Transmission and Immission. "Emission" deals with the production of smoke in the incident tube and its transport to the portal, "Transmission" is the transport of this smoke from the portal of the incident tube to the portal of the non-incident tube whereas "Immission" describes the mechanism of smoke spread in the non-incident tube.

The present work focuses on the transmission phase of the recirculation phenomena which mainly depends upon the local topographical, constructive and atmospheric conditions together with air speed in the tunnel due to the flow of traffic. These local conditions can either amplify or nullify the transmission of smoke from one portal to the adjacent one. Recirculation at tunnel portals has been addressed by a number of researchers in the past such as Maarsingh and Swart (1991), Haerter & Baumann (1978), Haerter (1979) and Baumann (1979). There is also some work on recirculation issues which involved laboratory and full scale testing such as by Wendeler (1967), Chock (1982), Zumsteg (1993) and Koopmans (2005) but the results were very much case specific. The most notable work among the above mentioned references that can be generalized to a greater extent is that done by Baumann (1979). Based on the experimental work, he concluded that a recirculation of about 46 % (maximum values in his experiments) occur with cross winds blowing at about 60° to the tunnel axis.

In the present work, the Transmission phenomena is investigated using 3-dimensional numerical simulations for the north portal of the Habsburg Tunnel located on the A3 motorway in Switzerland.

2. GOALS & OBJECTIVES

Even though the Swiss Federal Road Office (ASTRA) guideline 13001 (2008) requires a 30 m long anti-recirculation wall between tunnel portals in order to minimize the smoke recirculation effects, some existing tunnels do not meet this requirement. These tunnels are being investigated to see if they are prone to a recirculation threat due to the prevailing topographical, operational and wind conditions. One such example is the Habsburg Tunnel.

The major goal of the presented work is to numerically investigate the effectiveness of an anti-recirculation wall on the smoke recirculation at the tunnel portals in the given local topographical, operational and atmospheric conditions. This goal is realized by achieving the following objectives:

a. Quantifying the amount of recirculation in the current state of the tunnel.
b. Quantifying the amount of recirculation for different constructional scenarios (anti-recirculation wall length and height).
c. Estimating the harm potential due to smoke recirculation.

3. BACKGROUND

The Habsburg Tunnel is a twin bore tunnel approximately 1.5 km long. There is a bridge structure about 40 m from the north portal which places financial and constructional constraints on the construction of an anti-recirculation wall. The traffic volume is about 36’000 vehicles per day at present which is expected to increase to about 43’000 vehicles per day in the year 2030 FEDRO (2014).

The two tubes of the tunnel are equipped with cross connections every 300 m. Both tubes have a longitudinal ventilation system by means of jet fans. The tunnel portals are shown in **Figure 1**. The north portals are staggered by about 5 m from one another in an aerodynamically unfavourable condition (the entry portal is staggered ahead of exit portal).

Figure 1: North portal (left) and south portal (right) of the Habsburg tunnel (source: Google and www.structurae.de)

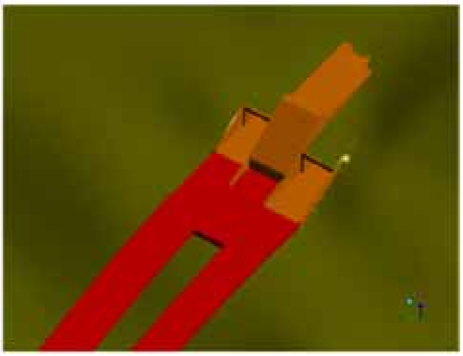
The tunnel control centre building in the north provides an inclined wall about 15 m long starting from the tunnel ridge to the road level. In the south, the portals are staggered by about 15 m in an aerodynamically favourable condition (exit portal is staggered ahead of entry portal). The wall in the south is also constructed in an inclined fashion by the second tunnel control building.

4. SCENARIOS

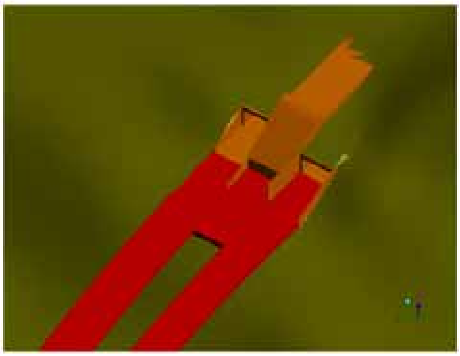
Four geometrical scenarios were simulated to investigate the effect of recirculation from the exit portal to the entry portal of the Habsburg Tunnel. These scenarios are as follows:

a. The actual situation of the north portal.
b. North portal with a 15 m long anti-recirculation wall. The height of the wall was kept constant over the entire length starting from the tunnel ridge.
c. As b. but with the wall 2 m higher.
d. As b. but with the wall 30 m long.

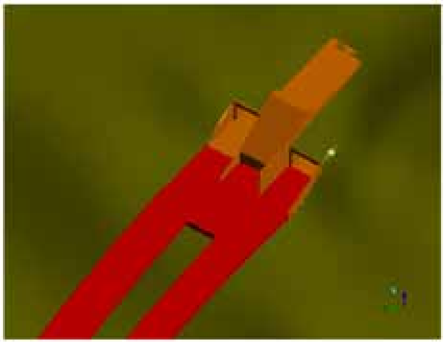
For all the above mentioned scenarios, the wind speed, wind direction and the tunnel in- and outflows were kept constant. The numerical simulations were carried out with isothermal conditions representing an atmospherically neutral environment. The 3-D models for the above geometrical configurations are shown in **Figure 2**.



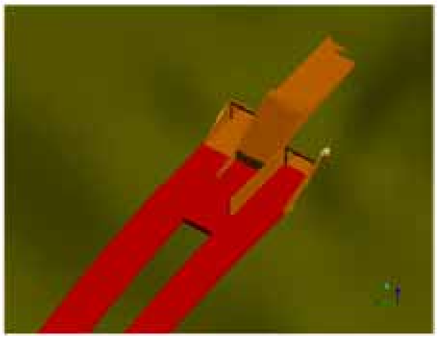
(a) 3D-Model of the actual geometrical configuration



(b) 3D-Model with 15 m long smoke separation wall (level: tunnel ridge)



(c) 3D-Model with 15 m long smoke separation wall (level: 2 m above the tunnel ridge)



(d) 3D-Model with 30 m long smoke separation wall (level: tunnel ridge)

Figure 2: Geometrical variations used in 3-D numerical simulations

In addition to the above mentioned geometrical variations, two further simulations were carried out with different wind and temperature conditions i.e.;

e. Actual situation of north portal with a wind velocity of 2 m s^{-1} with isothermal conditions.
f. Actual situation of north portal with a wind velocity of 4 m s^{-1} with non-isothermal conditions – a temperature difference of 25 K between tunnel and ambient air.

5. NUMERICAL SIMULATIONS

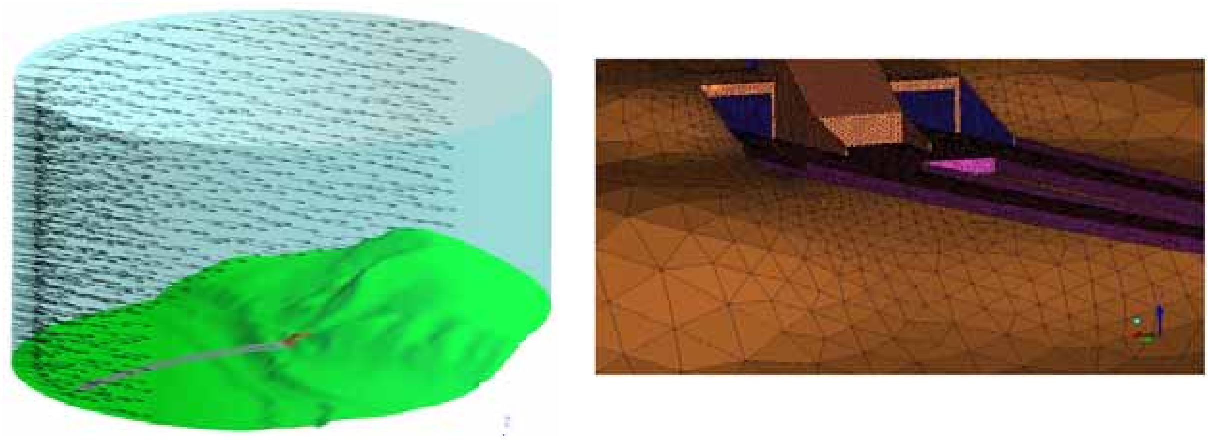
Numerical simulations were performed for the scenarios using a commercial 3 dimensional computational fluid dynamics (CFD) tool. The different modelling aspects, boundary conditions, along with the governing numerical details are described in sections 5.1 to 5.4.

5.1. Topography

The topography used for the portals and their surroundings was based on data with a maximum resolution of 2 m obtained from the Swiss Federal Office for Topography (Bundesamt für Landestopographie).

5.2. Geometry and Meshing

Based on the topographical data, the tunnel geometry and the surroundings were modelled using the surface modelling tool Rhino 3D (Robert McNeel & Associates). The complete CFD domain was modelled in the form of a cylinder with both the height and radius of 500 m as shown in **Figure 3**.



(a) (b)

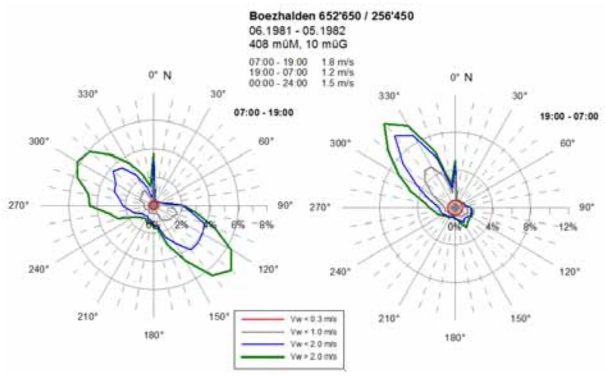
Figure 3: (a) Representation of the complete CFD model along with the topographic and surrounding details.
(b) Meshed model near to portals

The cross sectional area of the tunnel portals (63 m^2) was taken from the provided CAD plans with a corresponding hydraulic diameter of 7.7 m. The flow boundary conditions for the entry and exit tubes of the tunnel were set 42 m into the tunnel (about 5.5 times the hydraulic diameter) in order to avoid any numerical influence of boundary conditions directly in the vicinity of the portals. The surroundings were modelled as rough walls representing land with vegetation and trees as given by Aynsley et al (1977). The dimensions of the domain and tunnel were selected in light of the guidelines issued by COST (2007).

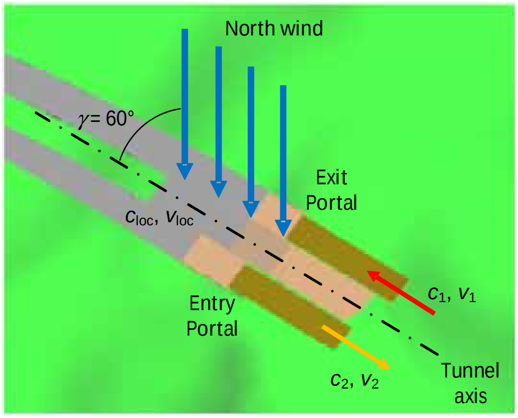
In order to solve the transport equations governing the flow, the geometrical model was meshed (i.e. subdivided into finite number of calculation cells). The complete model required about 3.2 million volume cells. The selection of meshing parameters to ensure a mesh independent result was based on the experience gained during the ASTRA research project (ASTRA FGU 2008/007_OBF) which involved simulation domains of similar extents. An example of the surface mesh used in the presented work is shown in **Figure 3**.

5.3. Boundary Conditions

The meteorological data for the nearest meteorological station ("Bözhalden") was used for investigating the possible wind conditions (wind direction and speed). The wind rose data (Figure 4) indicates that cross winds at an angle of about 60° to the tunnel axis (incident angle) are possible at the tunnel's north portals. This angle is reported to cause maximum recirculation in both the ASTRA research project (ASTRA FGU 2008/007_OBF) and the work done by Baumann (Baumann 1979). A general representation of the physical boundary conditions is shown in **Figure 4**.



a) Wind rose data used in simulations



b) General representation of the used boundary conditions

Figure 4: Boundary conditions used in numerical simulations

In order to see the effect of wind speed, the actual geometrical configuration was investigated with a wind speed (v_w) of 4 m s^{-1} and 2 m s^{-1}. The flow velocities in the exit tube (v_1) and entry tube (v_2) depends upon a number of factors such as the traffic flow, traffic density, meteorological conditions, tunnel geometry etc. In the present investigation, both the exit and entry tubes of the tunnel are given an air velocity of 4 m s^{-1} as boundary conditions. This tunnel in- and outflow velocity lies in the observed velocity range of 2 - 8 m s^{-1} typical for unidirectional tunnels. One of the main reasons for choosing this value was the experimental work done by Bauman (Baumann 1979). This showed that the maximum recirculation for a wind incident angle of 60° to the tunnel axis occurs when both the ratio between the in- and outflow velocities (v_2 and v_1 respectively) and the ratio between the wind velocity (v_w) and tunnel outflow velocity (v_1) are one. To simulate the smoke a non-reacting scalar species with concentration (c_1) was released at the exit tube boundary. The variations in its concentration in the surroundings (c_{loc}) and in the entry tube (c_2) are the results of the simulation.

5.4. Numerical Parameters

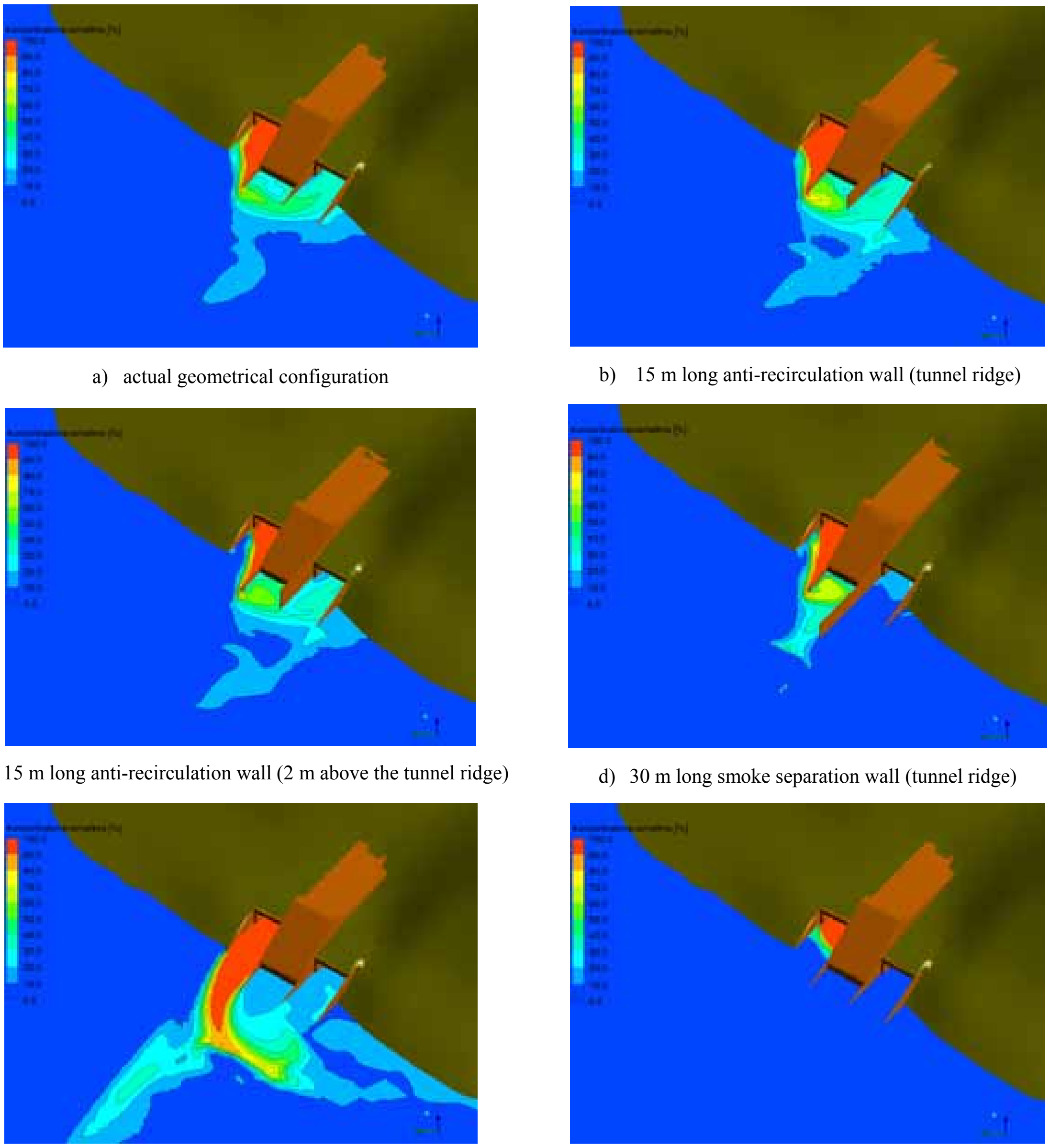
Reynold's Averaged Navier Stokes (RANS) equations (Versteeg, Malalasekera 2007) are used to model the flow. The turbulence is modelled using the Shear Stress Turbulence (SST) model (Versteeg, Malalasekera 2007), (Ansys 2009) was employed to resolve the turbulence effect. The kinematic diffusivity of the scalar species was set to 1e^{-5} m^2 s^{-1} (Ansys 2009) to represent smoke dispersal in air.

The process of converting the partial differential RANS equation to computer solvable algebraic equations is called discretization. For this investigation a second order discretization scheme with a coupled solver (Versteeg, Malalasekera 2007), (Ansys 2009) has been used.

6. RESULTS

Results are shown as CFD contours representing the recirculation level, where recirculation level is defined as the ratio of the different concentrations i.e. c_2/c_1 and c_{loc}/c_1 in percentages in the entry tube and in the surroundings respectively.

Four geometrical configurations were investigated. A comparison of recirculation levels at 1 m above the tunnel floor level for the different configurations are shown in **Figure 5**.



a) actual geometrical configuration

b) 15 m long anti-recirculation wall (tunnel ridge)

c) 15 m long anti-recirculation wall (2 m above the tunnel ridge)

d) 30 m long smoke separation wall (tunnel ridge)

e) actual geometrical configuration with wind 2 m s^{-1}

f) actual geometrical configuration wind 4 m s^{-1}, ΔT = 25 K

Figure 5: Recirculation level at 1 m above the tunnel floor level

The evaluation of concentration levels in the entry tube for the different configurations shows the following outcomes:

a) The current tunnel geometric configuration with unfavourable wind conditions allows a recirculation of about 35 % from the exit to the entry tube.

b) A 15 m long anti-recirculation wall starting from the ridge level of the tunnel reduces this recirculation level to about 30 %.

c) A 2 m increase in the height of the 15 m separation above the tunnel ridge level reduces this recirculation rate further down to 24 %.

d) An increase in the wall length (ridge level height) to 30 m reduces the recirculation to about 16 %.

e) A reduction in wind speed from 4 to 2 m s^{-1} for the tunnel current geometric configuration reduces the recirculation from 35 % to about 13 %.

f) A temperature difference of 25 K between the exit tube of the tunnel and the ambient air with unfavourable wind conditions (60° incident angle and 4 m s^{-1}) reduces the recirculation to 1.4 %.

All the above mentioned values are plotted on the log-log harm potential graph developed during the course of the ASTRA research project shown in **Figure 6** (see ASTRA FGU 2008/007_OBF and Gehrig S., 2013 for detailed background information). The abscissa represents the fire power (n-Heptane fire) whereas the ordinate of the graph represent the critical recirculation. The critical recirculation is defined as the amount of recirculation at which the average visibility reduces below 10 m. It should be noted that the critical recirculation limit is to be read for the air velocity in the exit tube (incident tube) which in the present case is $4\ m\ s^{-1}$ for a fire power of 30 MW (design fire power according to ASTRA). The critical recirculation level for the case under consideration is 18 %.

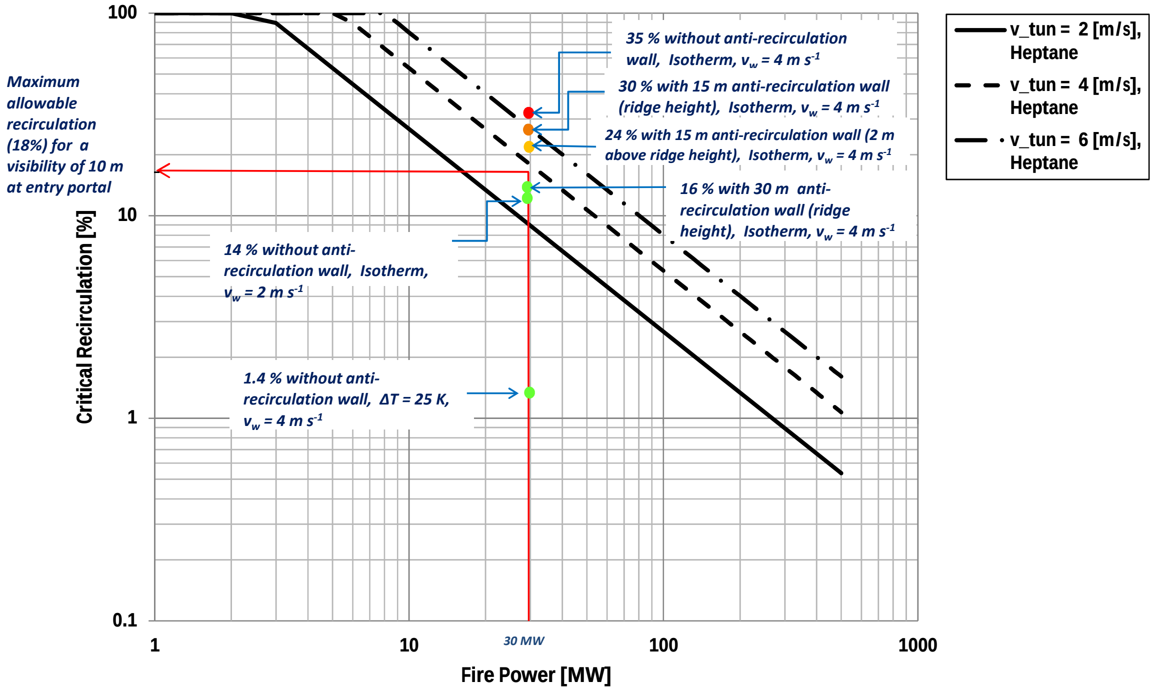


Figure 6: Recirculation values plotted on the harm potential graph

7. DISCUSSION

The results of variations in the geometric configuration of the tunnel portals show that only the construction of a 30 m long anti-recirculation wall can reduce the recirculation level to below the critical recirculation level. This means that if the two portals of the tunnel are kept aerodynamically separate (starting from the ridge level) for a distance of 30 m in an unfavourable wind condition, the turbulent dispersion dilutes the smoke level sufficiently to attain favourable escape conditions (visibility above 10 m) via the entry portal.

It is seen from the results that a reduction in wind speed from 4 to $2\ m\ s^{-1}$ reduces the recirculation level by one third with the tunnel's current geometric configuration (no anti-recirculation wall). This is because the exit velocity in the incident tube is higher than the surrounding wind velocity, resulting in less deviation in the flow path of the air coming out of the exit tube. This fact can be seen in the **Figure 5** (e).

Simulation results for a non-isothermal condition are based on a temperature difference of 25 K between the air coming out of the incident tube and the surrounding ambient air. This value is based on the analytical calculations according to Carlotti and Voeltzel (2004) and is found to be typical for a 30 MW fire located at 800-1000 m upstream of the portal in the incident tube. In such situations the thermal buoyancy overrides the impulsive behaviour of the air stream from the exit portal thereby reducing the recirculation for the current tunnel geometry with unfavourable wind conditions to just 1.4 %.

Based on the harm potential graph it can be seen that the tunnel portal of the non-incident tube in its current configuration (without anti-recirculation wall) can be considered as safe for fire powers below 12 MW as the value of critical recirculation is then higher than 35 %.

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THE EFFECT OF FIXED SMOKE BARRIERS ON EVACUATION ENVIRONMENT IN ROAD TUNNEL FIRES WITH NATURAL VENTILATION

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ABSTRACT

This paper investigates the effect of fixed smoke barriers on the ceiling of a tunnel on improving the evacuation environment in the case of a tunnel fire. First, the behavior of thermal fumes around the smoke barriers was investigated by CFD simulation [1], and it was clarified that the thermal fume layer along the ceiling hit the smoke barrier and formed a refluxing thermal layer, thus reducing the smoke velocity. Additionally, the influence of longitudinal slope (*s*) and natural ventilation were investigated by the above-mentioned method [2]. The Number of People Requiring Help (*NPRH*) (surrounded by thick smoke) in the case without smoke barriers was approximately 7 people for s = 1.5%. Meanwhile, it was clarified that when 2 m high smoke barriers were installed, *NPRH* for s = 1.5% was reduced to only one person, that is, *NPRH* may be zero by installing smoke barriers higher than 2 m. Moreover, natural ventilation was also improved by smoke barriers. Smoke barriers do not require control and maintenance and are very cheap, yet effectively block smoke and improve safety in tunnel fires.

Keywords: tunnel fire, natural ventilation, smoke barrier, evacuation environment

1. INTRODUCTION

The tunnels longer than 500 m on expressways in the EU must be assessed for fire risk and managed adequately. Meanwhile, the grade of road tunnels in Japan is determined by the traffic volume and tunnel length: tunnels with light traffic of less than 4,000 vehicles per day and shorter than 1000 m in length are rarely fitted with emergency facilities and ventilation systems. There are approximately 1200 tunnels (200 expressway tunnels, 1000 ordinary tunnels) which are 500 - 1000 m long in Japan, so it is impractical to install new facilities economically. The present paper examines the smoke control effect of smoke barriers fixed on the ceiling (see Figure 1), and the smoke behavior by CFD analysis [1] and one-way coupling evacuation simulation [2]. If the barriers are effective of the propagation of smoke along the ceiling, they would be a cheap solution. There are past studies [3], [4] related to the present study.

2. METHODOLOGY

Highly quantitative 3-D CFD analysis using an LES turbulence model developed by Fireles in 1998 is used for studies on tunnel disaster prevention, therefore the behavior of smoke in the present study was investigated by Fireles [1]. Additionally, an evacuation simulation (original code [1]) was used to evaluate the evacuation environment. Figure 2 shows the geometry of the tunnel considered in the present study: it was horseshoe-shaped, bi-directional, 700 m long, 10 m wide, and 7 m high. The height of the smoke barriers (*h*) was varied from 1, 2, and 2.5 m from the ceiling and the barriers were installed at every 100 m from the left portal. The fire source was assumed to be a large vehicle fire (maximum convective heat release rate 20 MW, maximum smoke generation rate 90 g/s) located at 100 m from the left portal, which was considered as the origin in the present study. The *x*, *y*, and *z* directions corresponded to the longitudinal, transverse, and horizontal coordinates, respectively. The congestion length was 300 m (100 m from the left portal to the fire source, plus 200 m from the fire source in the right direction), and evacuees were assumed to exist in the same length. The mix rate of large vehicles was 25%. The longitudinal slope varied from 0 to 4%. The exterior domains are shown in Fig. 2. The case of no pressure (*P00*) in the domains and the case of a 10 Pa difference between the domains (*P10*, longitudinal natural ventilation velocity approx. 1.8 m/s in the case of h = 0 m) were investigated for the influence of natural ventilation.

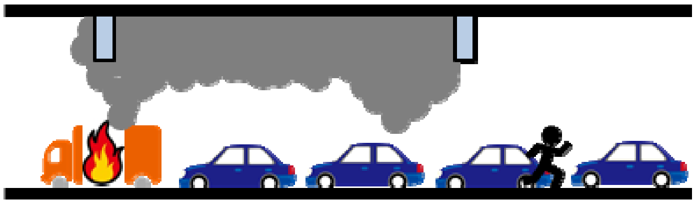


Figure 1: Schematic diagram of the effect of a smoke barrier in the case of fire.

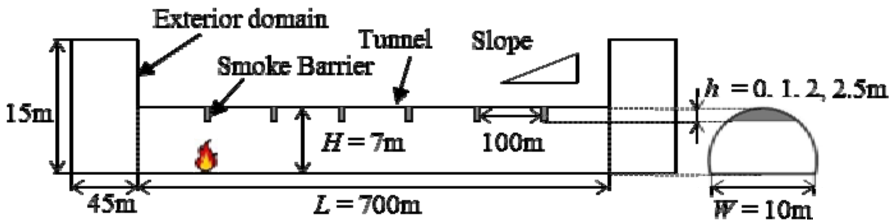


Figure 2: Dimensions of the model tunnel and computational domains.

3. SMOKE BEHAVIOR CLOSE TO SMOKE BARRIERS

To investigate the smoke behavior close to the smoke barriers, the smoke distribution (*Cs*, optical smoke density) in the case of h = 2 m and s = 0%, from t = 150 s to 165 s after ignition, is shown in Fig. 3 (y = 0 m). The lines in Fig. 3 are the *Cs* value every 0.2 m^{-1}. Smoke arrived at a smoke barrier at x = 100 m in t = 150 s, descended to approximately z = 1 m upon colliding with the smoke barrier at t = 155 s, but then formed two smoke layers at t = 160 s; one layer rose by buoyancy over the smoke barrier and the other layer could not surmount the barrier and refluxed. Then at t = 165 s the refluxed smoke became thick from x = 93 m to 98 m, while the other layer of smoke rose to z = 2 m from x = 100 m to 103 m.

The smoke tip was defined as *Cs* = 0.4 m^{-1} at z = 6 m, and the location of the smoke tip plotted as a x–t distribution is shown in Fig. 4, with the value averaged in the width direction (y). In the case of *P00*, there was little difference in the location of the smoke tip from the fire source to the left portal, while the location of the smoke tip from the fire source to the right portal differed since x = 100 m, where the smoke barrier was installed, at x = 200 m the smoke arrival time in the case of h = 0 m was 247 s, but in the case of h = 2 m the smoke arrival time was 267 s, that is, a time lag of 20 s existed. At x = 300 m the smoke arrival time in the case of h = 0 m was 339 s, but in the case of h = 2 m it was 378 s, that is, a time lag of 39 s existed and was longer than that at x = 200 m. At x = 400 m the smoke arrival time in the case of h = 0 m was 425 s, but in the case of h = 2 m it was 493 s, that is, a time lag of 68 s existed and was longer than that at x = 300 m. In the case with natural ventilation (*P10*), at x = -50 m, the smoke tip arrival time was 329 s in the case of h = 0 m, and was 345 s in the case of *h* = 2 m. At *x* = -100 m (the left portal), the smoke tip arrival time was 402 s in the case of *h* = 0 m, and was 433 s in the case of *h* = 2 m, with a lag between the two cases of 30 s. The location of the smoke tip from the fire source to the right portal was different since *x* = 100 m the same as *P00*, where the smoke barrier was installed, however, the smoke went up easily and rapidly due to natural ventilation, and so the time became earlier than *P00*. At *x* = 200 m, the smoke arrival time in the case of *h* = 0 m was 122 s, but in the case of *h* = 2 m it was 148 s, that is, a time lag of 26 s existed and was longer than that in the case of *P00*. At *x* = 300 m, the smoke arrival time in the case of *h* = 0 m was 173 s, but in the case of *h* = 2 m it was 216 s, that is, a time lag of 43 s existed and was longer than that at *x* = 200 m. At *x* = 400 m, the smoke arrival time in the case of *h* = 0 m was 224 s, but in the case of *h* = 2 m it was 286 s, that is, a time lag of 62 s existed and was longer than that at *x* = 300 m, hence smoke propagation was delayed by the smoke barriers.

The horizontal distribution of smoke and *x*-direction velocity at *x* = 92.8 m and *y* = 0 m in the case of *h* = 2 m, which is 7.2 m ahead of the smoke barrier, is shown in Fig. 5. The values are averaged from *t* = 175 s to 185 s. In the smoke distribution, an extremely thick layer with *Cs* of more than 1 m^{-1} along the ceiling decreased as *z* decreased, however, *Cs* was constant at 0.7 m^{-1} once at approximately *z* = 4 m, then decreased drastically and became 0 at *z* = 2.5 m. Because the direction of *x*-direction velocity turned from positive to negative at *z* = 4.5 m, the part of *Cs* = 0.7 m^{-1} at *z* = 4 m may have been because thick smoke collided with the smoke barrier and refluxed, therefore the smoke barrier caused smoke to accumulate.

The average smoke tip velocity in the transverse direction, which was defined as *Cs* = 0.4 m^{-1} at *z* = 6 m from x = 200 to 400 m, was influenced by the smoke barrier height (*h*) in the case of *s* = 0%, as shown in Fig. 6. As h increased, the smoke tip velocity decreased linearly, and the velocity in the case of *h* = 2.5 m decreased by 0.3 - 0.5 m/s compared with the case of *h* = 0 m.

Consequently, the smoke tip velocity was decreased by the smoke barriers, and the velocity became smaller as h became greater, even in the case with natural ventilation.

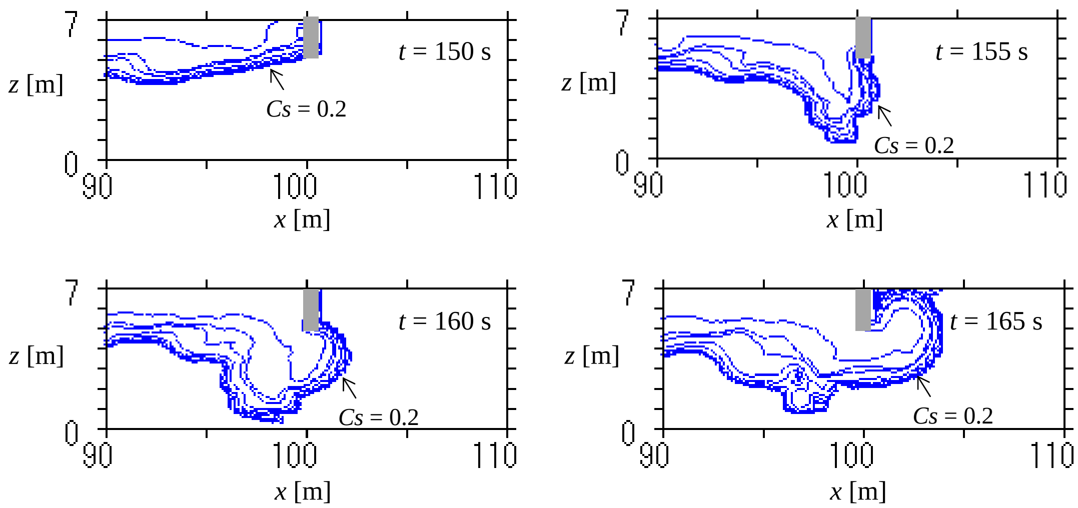
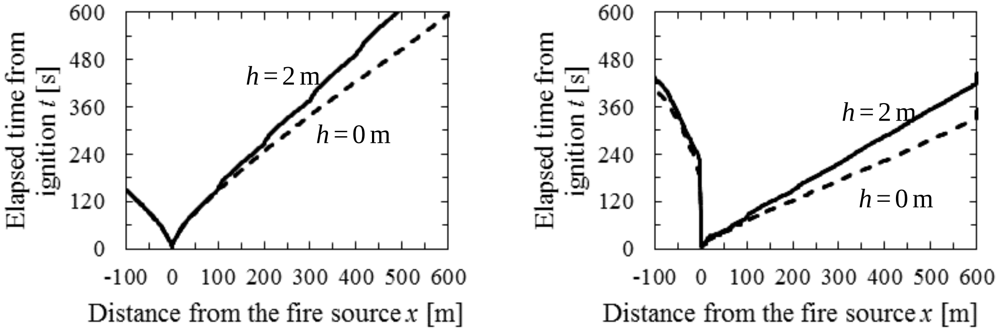


Figure 3: Smoke behavior close to the smoke barrier (*h* = 2 m, *s* = 0% and *y* = 0 m).



(i) *P00* (ii) *P10*

Figure 4: Comparison of cases without smoke barriers (h = 0 m) and with smoke barriers (h = 2 m) for difference in location of smoke tip (x - t distribution, s = 0% and averaged width direction, the dotted line is h = 0 m and the solid lines are the effect of smoke barrier height h)

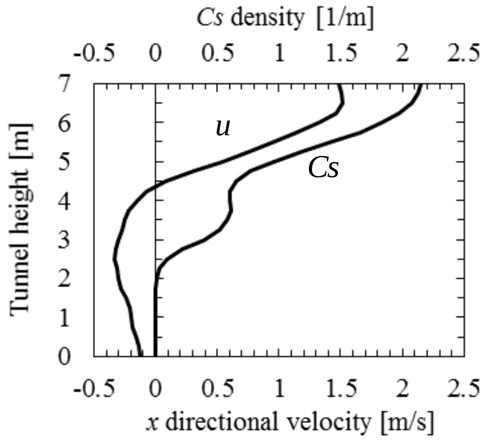


Figure 5: Horizontal distribution of smoke and x-direction velocity in the case of h = 2 m

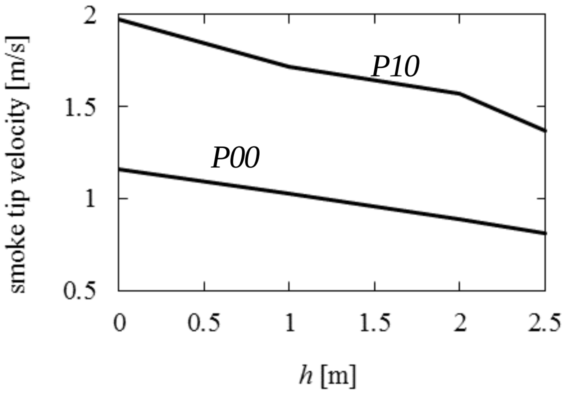


Figure 6: Influence of smoke tip velocity by smoke barrier in the case of s = 0%

4. EVACUATION ENVIRONMENT AND TUNNEL FIRE SAFETY

To evaluate the influence of smoke on evacuees, Smoke Environment Level (*R*) has been defined as a function of time and longitudinal location, by simplifying the smoke distribution derived from 3-D CFD analysis and then weighting it with visibility. By mapping *R* on the time–distance plane, the smoke behavior in a tunnel fire can be concisely expressed. In the developed 1-D evacuation simulation method using *R*, each evacuee recognized the necessity of evacuation through the behavior of smoke or other evacuees. The number of people who were surrounded by thick smoke (Cs = 0.4 m^{-1} at z = 1.5 m) in 10 minutes was used as an index for evaluating tunnel fire safety and the index *NPRH* (Number of People Requiring Help) was calculated by performing the evacuation simulation 1000 times [2]. Hence, *NPRH* is the injured. The evacuees' walking speed was distributed from 0.9 to 2.1 m/s, and the average speed was 1.5 m/s. The total of number of evacuees in the tunnel was 53, 16 on the left and 37 on the right, due to the traffic conditions, and the average passenger rate was 1.4 people/vehicle in Chapter 2.

The change in *NPRH* with smoke barrier height is shown in Fig. 7. In the case of no natural ventilation (*P00*), *NPRH* for *h* = 0 m was 15 people, but reduced with increasing smoke barrier height, becoming 14 people for *h* = 1 m, 8 people for *h* = 2 m and 6 people for *h* = 2.5 m, that is, an additional 10 people could evacuate safely compared with the case of *h* = 0 m. In the case of with natural ventilation (*P10*), *NPRH* for *h* = 0 m was 35 people, hence almost everyone on the right side was injured. However, *NPRH* reduced as the smoke barrier height increased, and was 34 people for *h* = 1 m, 24 people for *h* = 2 m and 17 people for *h* = 2.5 m, that is, an additional 10 people could evacuate safely compared with the case of *h* = 0 m.

The change in *NPRH* with slope (*s* = 0 to 4%) in the case of *P00* and *h* = 0 to 2.5 m is shown in Fig. 8. In the case of *h* = 0 m, *NPRH* increased linearly from 0 as the slope increased; 15 people were injured for *s* = 4%. As the barrier height increased, the range of no *NPRH* increased, i.e. no one was injured even for *s* = 2% in the case of *h* = 2.5 m. Even with the steep slope *s* = 4%, smoke barriers of *h* = 2 m reduced *NPRH* by at least half compared with the case of *h* = 0 m. The change in *NPRH* with slope (s = 0 to 4%) in the case of *P10* and *h* = 0 to 2.5 m is shown in Fig. 9. *NPRH* was reduced by 10 people when the barrier height exceeded 2 m compared with the case of *h* = 0 m. Even with the steep slope *s* = 4%, smoke barriers of *h* = 2.5 m reduced the smoke velocity, and *NPRH* was approximately two-thirds of the case with *h* = 0 m. Also in the case of natural ventilation, smoke barriers of *h* = 2 m reduced *NPRH* by at least half compared with the case of *h* = 0 m.

Consequently, smoke barriers effectively improve tunnel fire safety regardless of slope and natural ventilation, and their height should be more than 2 m.

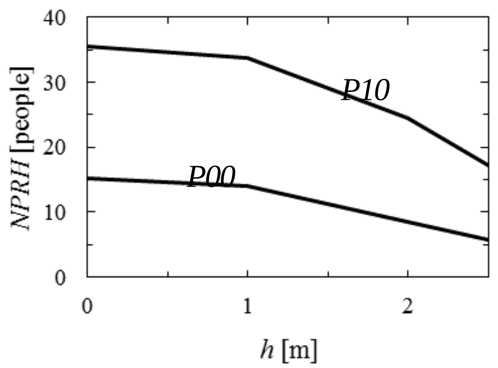


Figure 7: Change in *NPRH* with smoke barrier height in the case of *s* = 4%

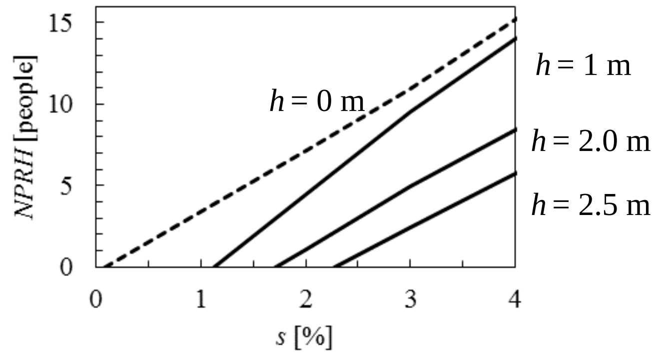


Figure 8: Change in *NPRH* with smoke barrier height in the case of *P00* (the dotted line is h = 0 m and the solid lines are the effect of smoke barrier height)

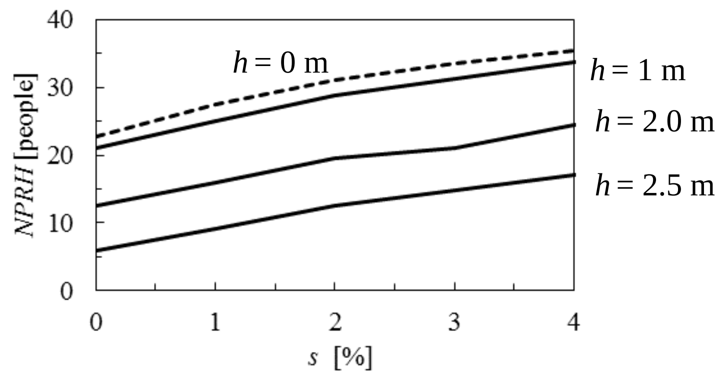


Figure 9: Change in *NPRH* with smoke barrier height in the case of *P10* (the dotted line is h = 0 m and the solid lines are the effect of smoke barrier height)

5. CONCLUSIONS

The effect of fixed smoke barriers on the ceiling of a tunnel on improving the evacuation environment in the case of a tunnel fire was studied by applying 3-D CFD analysis and evacuation simulation to a model tunnel. The following results were obtained.

- In the case of no natural ventilation, thick smoke collided with the smoke barriers and refluxed, causing smoke to accumulate.
- The smoke tip velocity was decreased by the smoke barriers as the smoke barrier height was increased, even in the presence of natural ventilation.
- Smoke barriers should be at least 2 m high, and should result in no injuries when the slope is less than 2%.
- *NPRH* is greatly increased by natural ventilation, but smoke barriers reduce such increase.

Consequently, smoke barriers help stop the propagation of smoke and greatly reduce injuries. Smoke barriers are a cheap and effective measure.

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STUDY FOR SAFETY AT A RELATIVELY SHORT TUNNEL WHEN A TUNNEL FIRE OCCURRED

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ABSTRACT

Progress in vehicle exhaust control has greatly improved environments in road tunnels in recent years. Consequently, we discuss the downsizing or removal of tunnel ventilation systems formerly installed to secure the environments in road tunnels. On the other hand, tunnel ventilation systems are also used as smoke control systems in case of fires. So it is also important to discuss safety from tunnel fires. We studied factors that affect the safety of tunnel users in a relatively short road tunnel (around 500m, without a ventilation system) when a tunnel fire has occurred. The examination was analysed by a three-dimensional simulation (Large-Eddy Simulation model) to reproduce the smoke spread and by a one-dimensional evacuation simulation. We evaluated the number of people requiring help (NPRH) who cannot evacuate from a tunnel fire. Among the results of the study without a ventilation system, we found some conditions related to safety when a tunnel fire has occurred. The conditions were the fire source point, road longitudinal gradient, presence or absence of wind velocity and a bus. Especially when evacuating from a bus, people need more time to evacuate. This case has an increased risk of someone being left behind in the bus. And we confirmed that many passengers cannot evacuate from a bus because of the smoke from the fire when the bus is close to the fire source point. The second factor influencing safety is the natural wind in the tunnels. Even in a small natural wind of about 1.0 m/s case, smoke catches up to tunnel users when the direction of the natural wind matches the evacuation direction. In this case, we have confirmed that many evacuees cannot evacuate, even there is no bus.

Keywords: tunnel fire, short tunnels, natural ventilation, bus, evacuation simulation

1. INTRODUCTION

In Japan, the scale of tunnel ventilation systems has been determined by the amount of vehicles exhausting gases, and this system is used when a tunnel fire has occurred. Tunnel ventilation systems have been installed not only in long distance tunnels, but also in short distance tunnels with heavy traffic in urban areas. The Tokyo metropolitan expressways carry heavy traffic, so its operators put tunnel ventilation systems in tunnels about 300m long. Lately, the improvement of vehicle exhaust control has greatly improved the environments of road tunnels. For this reason, this system does not ventilate vehicle exhausts, but operates when a tunnel fire has occurred. Long tunnels about 10km are designed to prepare for a tunnel fire [1], this is a dangerous condition. In contrast, in relatively short tunnels of about 500m, the safety of tunnel users has almost never been studied. For tunnel ventilation systems, the central issue is downsizing and removal. This study determined factors affecting the safety of tunnel users when removing a tunnel ventilation system from a relatively short road tunnel.

2. EXAMINATION CONDITIONS

2.1. Simulation model

The spread of smoke from a tunnel fire was simulated using an original three-dimensional simulation (Fireles) [2]. This simulation is developed partly by the authors, and the turbulence model is a Large-Eddy-Simulation. Comparing this with full size tunnel experiment results confirmed the accuracy of this simulation [3]. In Japan, it is generally used to study road tunnel safety when a tunnel fire has occurred. To grasp the simulation of the evacuation of tunnel users, this study used an evacuation simulation [4]. This simulation calculated the number of people requiring help (NPRH), those who cannot evacuate for 10 minutes after the occurrence of the tunnel fire.

2.2. Specification of the model tunnel

• Tunnel length	450m
• Cross section of the tunnel	rectangular (around 8.5 m W x 4.5m H)
• Longitudinal gradient	-4% - 4%
• The computational grid sizes	0.33 m in the x direction, 0.31 m in the y direction, 0.23m in the z direction
• Number of divisions	1429 in the x direction, 43 in the y direction, 29 in the z direction (Include area outside the tunnel)

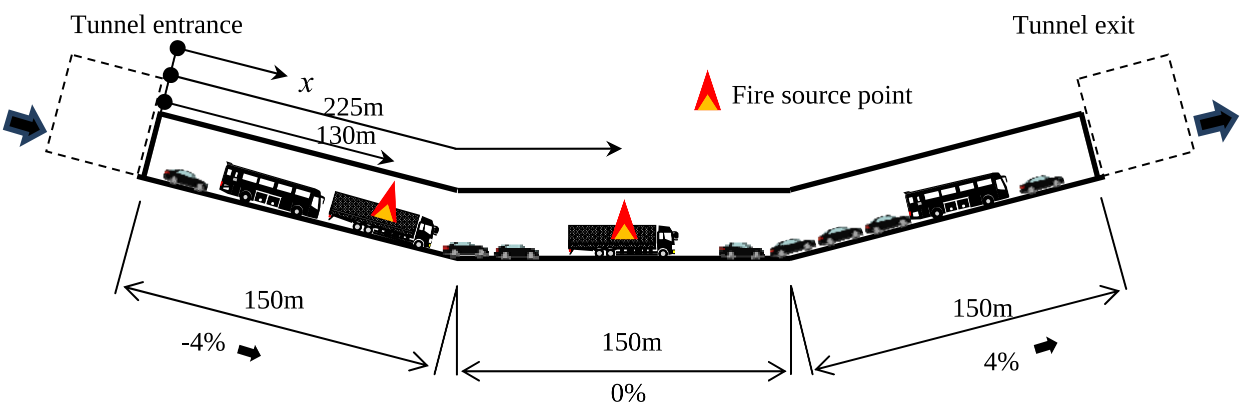

Figure 1: Outline of the tunnel that was studied

2.3. Tunnel fire conditions

When a tunnel fire has occurred, factors affecting the safety of tunnel users are fire source points, natural wind, and arrangements and configuration of vehicles. The fire source points have an impact on smoke spread by the longitudinal gradient. The natural wind, which is the pressure difference between the tunnel entrance and exit for natural ventilation (*Δ*), causes the smoke to spread in the tunnel. The arrangement and configuration of vehicles is related to the number of NPRH. Table 1 shows fire source points and pressure difference *Δ* conditions. Vehicles were arranged from the tunnel entrance to the fire source point and from the fire source point to the tunnel exit. The configuration of vehicles assumed only passenger vehicles, large size vehicles comprised 10% of total traffic and a bus was included. In this paper, it was assumed that a single large size vehicle caught fire in the tunnel. Heat release rate adopted was 30MW, and it changes over time to become constant after 480 seconds.

Table 1: Tunnel fire conditions

Category	Conditions
Fire source points	x=225m (Sections of longitudinal gradient 0%) x=130m (Sections of longitudinal gradient -4%)
Δ (Pressure difference between the tunnel entrance and exit for natural ventilation)	0Pa [0 m/s], 5Pa [0.85 m/s], 10Pa [1.2 m/s]

Table 2: Number of passengers (per vehicle)

	Number of passengers
Passenger vehicles	Average of 1.4 people
Large size vehicles	Average of 1.3 people
Bus	50 people

Conditions under which it is difficult for tunnel users to evacuate were defined as smoke density greater than Cs 0.4 [1/m] and smoke height less than 1.5 m from road surface. Smoke density of Cs 0.4 [1/m] reaching the ceiling triggered the start of evacuation of tunnel users; they evacuate when they see other tunnel users evacuating. The evacuation velocity distribution linearly increased from 0.9 m/s to 1.2 m/s, was constant from 1.2 m/s to 1.8 m/s, and linearly decreased from 1.8 m/s to 2.1 m/s. The direction of evacuation of tunnel users was assumed to be evacuation towards the tunnel portals.

3. TRENDS IN CONFIGURATION AND PLACEMENT OF VEHICLES

3.1. Simulation conditions

Table 3 shows simulation cases, excluding cases including emergency exits. These cases are mentioned later. A bus is located 100 m from the tunnel entrance and exit.

Table 3: Simulation cases

Case		Vehicle positions	Number of Vehicles		
			Passenger vehicles	Large-size vehicles	Bus
F225	F225-L	Left of fire source point	59	7	0
	F225-R	Right of fire source point	59	7	0
F225-B	F225-B-L	Left of fire source point	57	6	1
	F225-B-R	Right of fire source point	57	6	1
F130	F130-L	Left of fire source point	33	4	0
	F130-R	Right of fire source point	85	9	0
F130-B	F130-B-L	Left of fire source point	31	3	1
	F130-B-R	Right of fire source point	83	9	1

3.2. Simulation results

Table 4 and Figure 2 shows the simulation results for case F225 and case F225-B. For case F225-L and case F225-B-L, the fire source point is 225m and the vehicles are arranged from the tunnel entrance to the fire source point, and the results show no NPRH being affected by the pressure difference *Δ* and configuration of vehicles. In case F225-R and case F225-B-R, vehicles are located on the right side of the fire source point, NPRH break out in these cases according to the increase of the pressure difference *Δ*. This result shows that tunnel users are exposed to smoke by a tunnel fire which has occurred and it flows from the fire in the direction tunnel users evacuate, so as a result, tunnel users cannot evacuate. In the case of an arrangement including a bus (case F225-B-R), NPRH are drastically increased.

Table 4: NPRH of fire source point 225m

Case		Vehicle positions	NPRH [people] ⊿ 0 Pa [0 m/s]	NPRH [people] ⊿ 5 Pa [0.85 m/s]	NPRH [people] ⊿ 10 Pa [1.2 m/s]	Average numbers of people in a tunnel
F225	F225-L	Left of fire source point	0	0	0	89
	F225-R	Right of fire source point	0	0.54	12.89	89
	Total		0	0.54	12.89	178
F225-B	F225-B-L	Left of fire source point	0	0	0	135
	F225-B-R	Right of fire source point	0	26.38	53.39	135
	Total		0	26.38	53.39	270

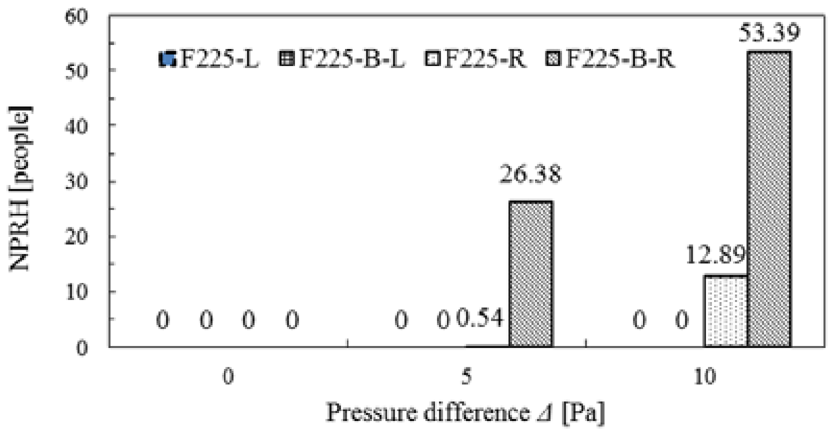

Figure 2: The results of fire source point 225m

Figure 3 shows the simulation results at ⊿ 5 Pa and Figure 4 shows results at ⊿10 Pa.

The x-axis represents the distance from the tunnel entrance and the y-axis represents the elapsed time after the start of the simulation. In the figure, the green part indicates where smoke density is Cs 0.4 [1/m] at 1.5m from the road surface and the black-line shows the state of tunnel users' evacuation.

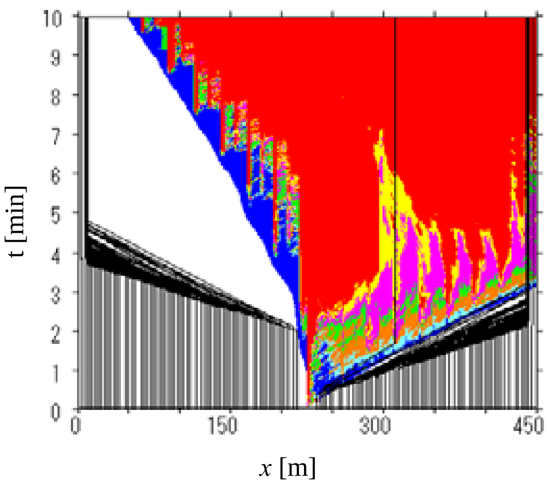

Figure 3: The results of case F225 ⊿5 Pa

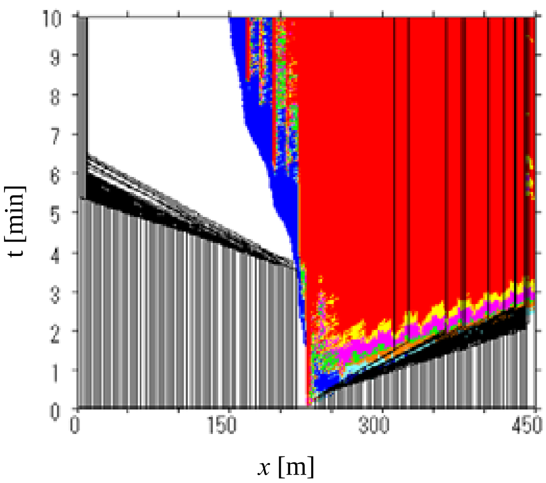

Figure 4: The results of case F225 ⊿10 Pa

Table 5, Figure 6 and Figure 7 shows the simulation from the tunnel entrance to the fire source point 130m from the tunnel entrance. NPRH trends differ between cases of fire source points 225m and 130m. For case F130-B-L, vehicles are arranged from the tunnel entrance to the fire source point and include a bus, and the results show there are NPRH in all cases. The factors probably are the exposure of tunnel users to smoke backlayering and the presence of a bus near the fire source point. However, owing to the smoke backlayering moving to the tunnel exit, NPRH decreased as the pressure difference ⊿ increased. With case F130-L and case F130-R, a trend similar to the source point 225m is indicated.

Table 5: NPRH of fire source point 130m

Case		Vehicle positions	NPRH [people]			Average number of people in a tunnel
			⊿ 0 Pa [0 m/s]	⊿ 5 Pa [0.85 m/s]	⊿ 10 Pa [1.2 m/s]	
F130	F130-L	Left of fire source point	0	0	0	49
	F130-R	Right of fire source point	0	0.04	10.24	128
	Total		0	0.04	10.24	177
F130-B	F130-B-L	Left of fire source point	27.65	23.98	9.19	95
	F130-B-R	Right of fire source point	0	0.04	37.76	175
	Total		27.65	24.02	46.95	270

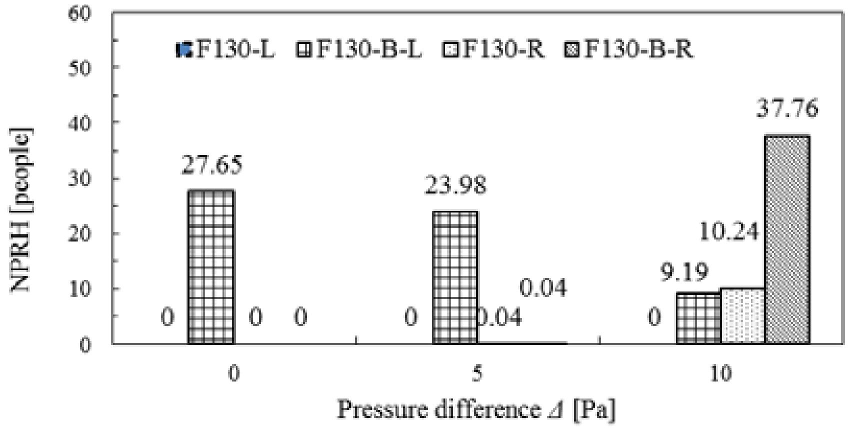

Figure 5: The results of fire source point 130m

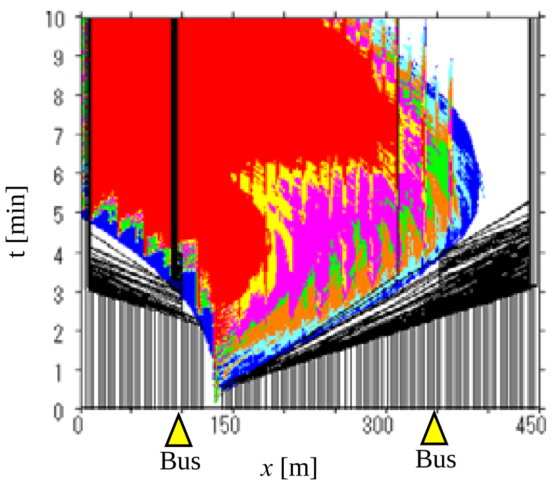

Figure 6: The results of case F130-B, ⊿5 Pa

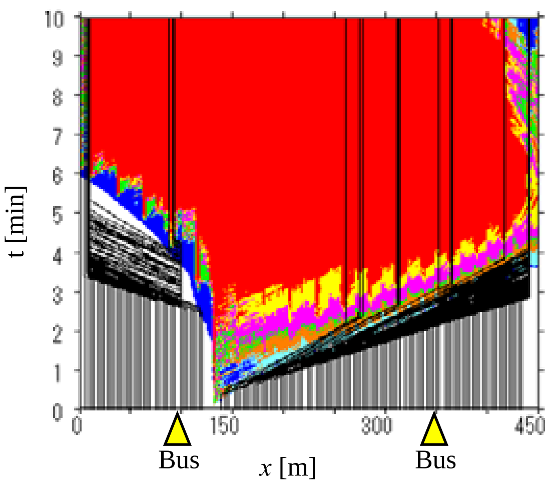

Figure 7: The results of case F130-B, ⊿10 Pa

4. VALIDITY OF TUNNEL DISASTER PREVENTION SYSTEM

As mentioned above, if there is a bus in the tunnel, NPRH tend to increase. Therefore, this section determined the effect of an emergency exit. In the tunnel, a bus is leeward of the fire source point 225m; and the interval between the fire source point and the bus is 10m. The distances from the bus to an emergency exit are 50m, 75m, 100m, 125m, 150m and 175m. Figure 8 is a schematic view of these conditions. The pressure difference Δ is 0 Pa.

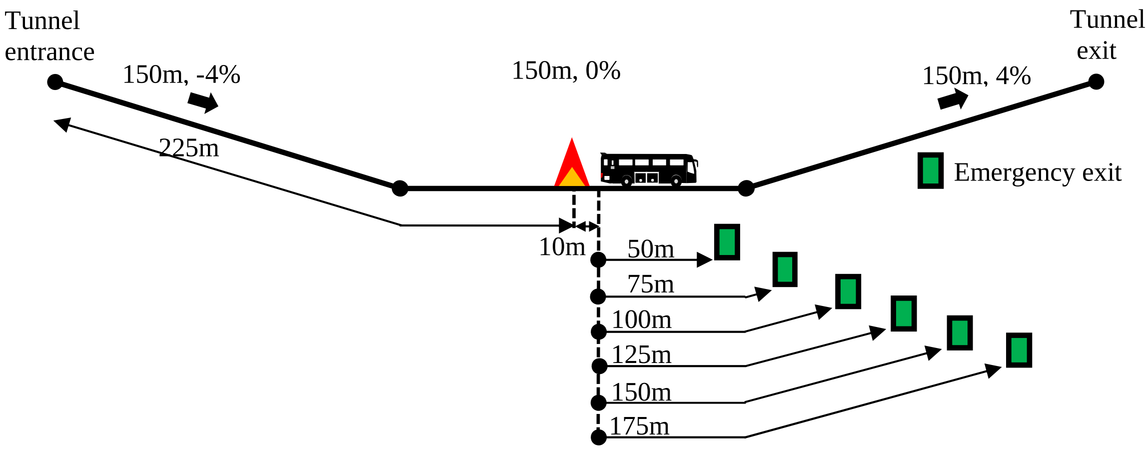

Figure 8: Arrangement of emergency exits [225m]

Figure 9 shows the simulation results for smoke density distribution in the x-z plane across the tunnel model.

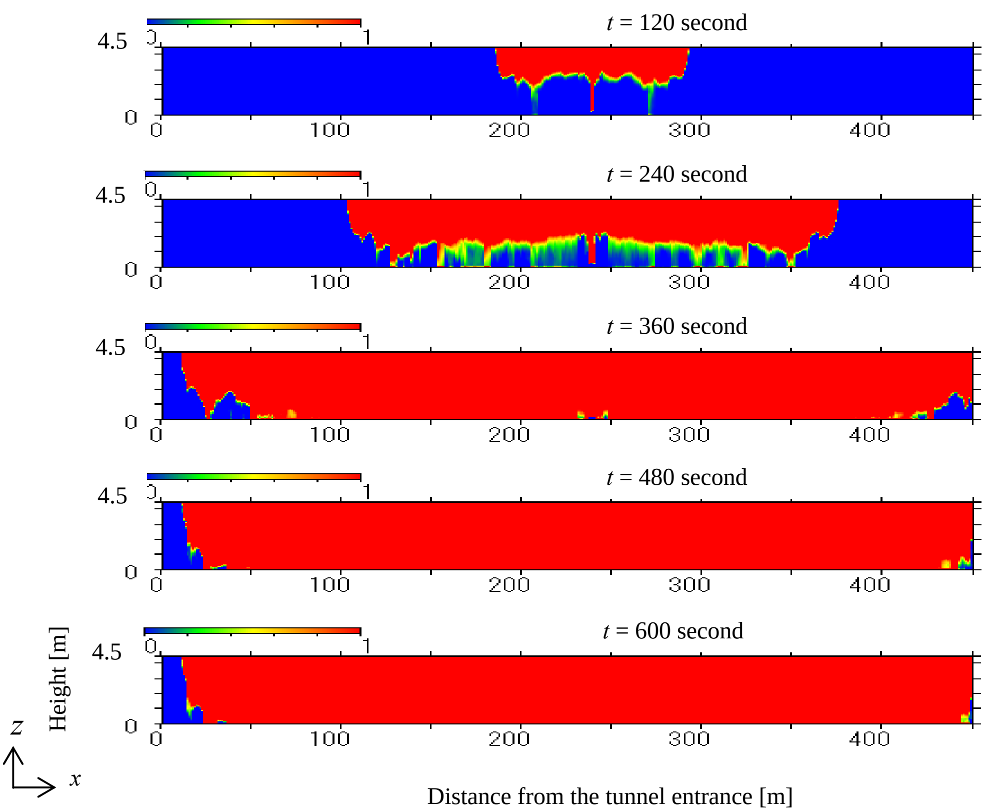

Figure 9: Smoke density distribution in the x-z plane across the tunnel model

Figure 10 indicates the simulation results for the effect of the emergency exit. For the distance of 50m and 75m, the emergency exit reduces NPRH.

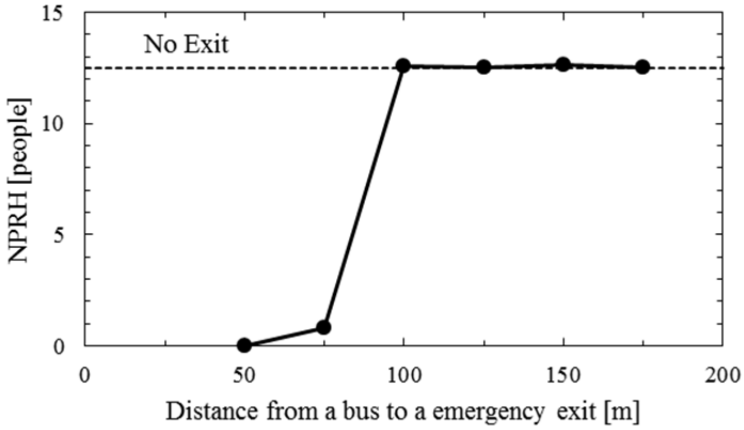

Figure 10: Effectiveness of the emergency exit, ⊿ 0Pa

5. CONCLUSIONS

This study quantitatively revealed factors affecting safety for tunnel users when a tunnel fire has occurred in a relatively short road tunnel. The factors affecting safety of tunnel users are as follows.

- A natural wind flows in the direction the tunnel users evacuate: tunnel users are on the leeward of the fire source point, and smoke catches up to tunnel users.
- The tunnel users are exposed to the smoke spread by backlayering.
- When a bus is in the tunnel, especially if the bus is close to a fire source point.
- Under the study conditions, with the distance of 50m and 75m, the emergency exits effectively reduce NPRH.

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EFFECTIVENESS OF IMPLEMENTATION DRAUGHT RELIEF SHAFT IN SUBWAY RAILWAY TUNNELS

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ABSTRACT

Use of draught relief shaft has often been proposed as a means of reducing air velocity and improving passenger comfort on platform, concourse level and stations' portals. Air velocity due to piston effect in railway tunnel depends on tunnel structural specifications, speed, acceleration, location and headway of train and draught relief shaft characteristics. This piston effect of train causes subways air to flow out of a draught relief shaft when as train approaches it and fresh air to flow into a draught relief shaft after the train passes. Blast air velocity to station and stairway has negative effect and to overcome these negative effects, ventilation shafts are usually placed at locations closer to the station beginning and end of tunnel. The high cost of these ventilation structures and acquisition require an optimum design for performance. Internal resistances due to bends and offsets, cross-section and length of draught relief shaft are important design parameters. When draught relief shaft combines with ventilation shaft, it must be balanced with requirements in different modes of operation and limitations of construction. This study gives methods about draught relief shaft configurations and techniques about reduction the costs of draught relief shafts construction up to 32% in compared with other configurations. Saving in draught relief shaft construction and high costs of land acquisition, preventing deterioration of fan's equipment, minimizing the air velocity in stations and comfort feeling of passengers and staff are the important conclusions of this study.

Keywords: draught relief shaft, piston effect, ventilation, tunnel, station

1. INTRODUCTION

Train piston effect phenomena usually supposed negligible during design by subway tunnel designers, by not having draught relief shafts at tunnel entrances to stations, the train piston effect driven air rushing into the station. Train piston effect causes air movement and air pressure changes in a subway tunnel system. By ventilation viewpoint, air movement is functional, but if too much piston effect occurs, uncomfortable high velocities may be occurring on platform, corridors and in station's portals.

A draught relief shaft is a ventilation shaft conventionally constructed immediately upstream and downstream of the station. The purpose of the draught relief shaft is to divert as much air as possible from the tunnel to the atmosphere, by means of that minimizing the blast in stations. Stairways, escalator passages and entrance corridors also act as ventilation shafts, and the piston effect may cause excessive air velocities in these sections. A simplified schematic of the blast air flows is shown on Figure 1 that should be reduced air velocity on station platforms, up the stairways and ticket hall levels.

Natural ventilation in subway systems is primarily result of train movement in the tunnel. The air flows created by movement of the trains through tunnels and stations are similar to the types of flows caused by the movement of a piston within a cylinder. Then, the ventilation of a subway which is created by the movements of the train is also called "piston effect" ventilation. As the train moves beside the relief shaft or station, fresh air is drawn into the system behind it and moving train pushes air ahead of it through the subway system and some of the air escapes to the outside atmosphere via draught relief shafts. Therefore, some cooling is accomplished by exchanging hotter inside air with cooler outside air.

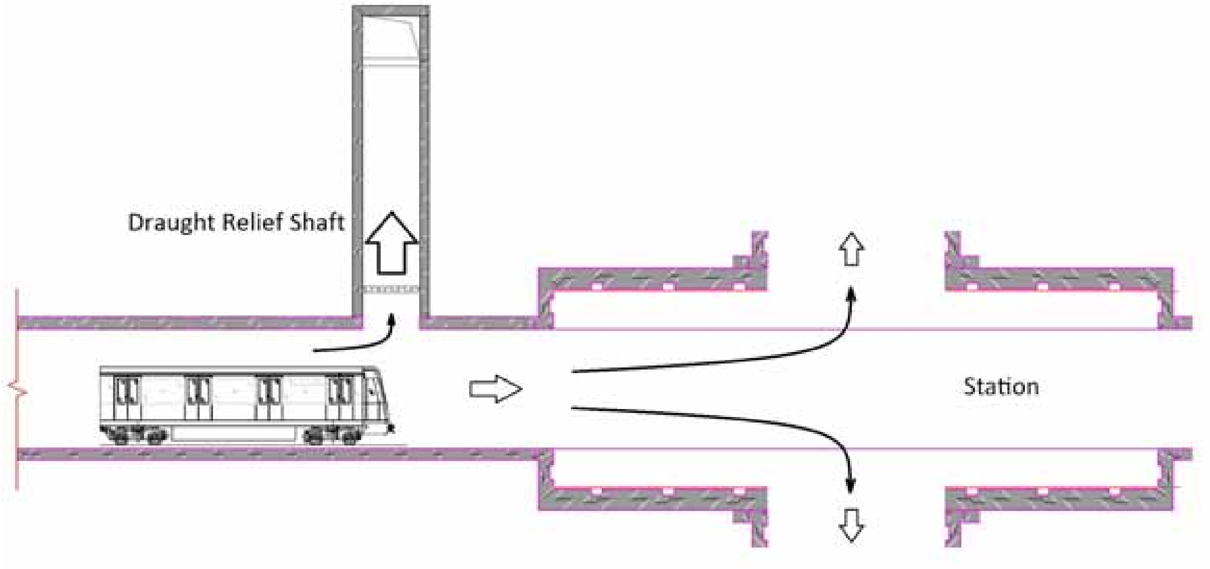

Figure 1: Air blast flows in a station

2. FUNCTION AND EFFECTS OF DRAUGHT RELIEF SHAFT

The underground subway network of Karaj line 2 has 23 stations and 24 tunnel sections and they have been modelled under SES (Subway Environmental Simulation) program. Knowledge of the characteristics of air flow in subway stations and tunnels resulting from train piston effect is necessary to determine the methods for controlling air velocities in the subway stations.

Air flows in a subway are generated by two primary sources: the piston effect of trains moving through tunnels and in certain cases, mechanical ventilation by fans. The computation of aerodynamic drag is an essential component of the subway simulation because this factor determines both the air resistance trains must overcome to accelerate and the amount of energy imparted by the moving trains to the surrounding air. The aerodynamic equations used by the SES program to describe the air flow in subway tunnels resulting from train piston effect and from mechanical ventilation are based on the fundamental relationships which govern conservation of energy, mass, and linear momentum. Subway air flow is influenced by system geometrical parameters, such as the location, shape, length, cross-section, perimeter, wall roughness, etc. of the stations, tunnels, and ventilation shafts. Air flow is also affected by dynamic parameters, such as train speed, acceleration, location, and headway, as well as ventilation fan operating characteristics [5].

Air temperature, air velocity and air pressure changes within a subway depend on design of tunnel ventilation system. Much of the ventilation airflow is induced by the motion of the trains through the tunnel. This piston effect of the train causes subway air to flow out of a draught relief shaft as the train approaches it and fresh air to flow into the draught relief shaft after the train passes. Hot and warm air that produce due to braking action and air conditioning system mixes with the tunnel air behind the train, which then is carried either into the station by its remaining momentum or is pulled by the piston effect of the train when it subsequently departs. The piston effect of train causes a blast of air to enter the station portal from the tunnel and expand to the cross-sectional area of the station inside 15 to 45 meters approximately. Peak velocities on the platform will occur near the station portal before fully expanded. The air blast from an arriving train is usually greater than the velocity induced in the station by a departing train and is, therefore, the critical condition on the platform.

Some shafts may serve a dual purpose. During normal operation, they may handle piston effect air flow without the aid of fans, unless fans would be required for congested and emergency ventilation modes. Such dual purpose shafts are fitted with dampers and air bypasses around the fan by siding duct during normal operation and through the fan for congested and emergency operation. Other shafts, which are not equipped with fans, would require dampers to preclude bypass of air during emergency operation. Blast air velocity to station and stairway has negative effect and to overcome these negative effects, ventilation shafts are usually placed at locations closer to the station beginning and end at the tunnels. Through which part of the air pushed in front of the train is forced out from the tunnel. Additional ventilation shafts may be provided between stations depending on the tunnel lengths. The high costs of these ventilation structures and acquisition requires an optimum design for performance. Internal resistances due to bends and offsets, cross-section and length of draught relief shaft are important in design parameters [1].

In multi track tunnels, induced piston effect ventilation may not be adequate. The air in the tunnel between two draught relief shafts is pushed one way and forward through the tunnels, and thus there is little net flow of air through the tunnel or relief shafts. Fans in ventilation shafts help produce a net flow through the tunnel. Also, it sometimes becomes necessary to locate a ventilation shaft in an area where a suitable grade level site is at a considerable distance from a deep tunnel, and the airflow resistance may be too high to provide adequate ventilation without a fan.

In single track tunnels, trains movement through tunnels with small clearances will produce considerable draughts at stations unless some measures are taken to reduce them to acceptable levels. Draught relief shafts can be constructed over or alongside the tunnel which allows air to escape to atmosphere while the train approaches and then to rush down the shaft when the train passes the shaft. Draught relief shafts are often located at stations where they have a good effect on reducing high air velocities on platforms.

Relief shafts, fan shafts, and station entrances all contribute to subway ventilation to at least some degree. The piston effect of moving trains is often sufficient in itself to maintain adequate ventilation. Suppose train is running with fans off and dampers open. Then, all draught relief shafts are open to the atmosphere effectively as ventilation shafts. The piston effect of trains passing below a ventilation shaft generates a periodic, alternating velocity within the shaft. The concentration near the opening varies periodically with the follow reversal. The cycle is as follows:

- As the nose of a train approaches the relief shaft, the increasing pressure pushes air up the shaft, expelling it into the atmosphere
- The train passes the shaft, and the pressure equalizes,
- After the rear of the train passes the vent shaft, the decreasing pressure pulls air down the shaft, drawing air from the atmosphere into the shaft.

The actual volume of fresh air exchanged depends upon the extent of the thrust within the relief shaft. If the relief shaft is very long, the net effect of the oscillation is just to shift air between the tunnel and relief shaft. On the other hand, if the shaft is relatively short the displacement likely exceeds the length of the relief shaft, so the oscillation completely flushes the relief shaft on both the upward and downward cycles. In that case, any concentration initially inside the shaft before the train arrives will be expelled, and then fresh air will be drawn down through the relief shaft into the tunnel [4].

One of the more obvious ways of increasing the resistance in the tunnel between the draught relief shaft and the station portal is to increase the length of that particular tunnel section. When that tunnel section becomes too long, however, the blast in the station caused by the decelerating train after it passes the draught relief shaft may exceed the blast in the station caused by the train before it reaches the draught relief shaft. The locations of the draught relief shaft and deceleration profile of the train are used to determine the maximum air velocity experienced in the station. This maximum velocity occurs when the train either is upstream or downstream of the draught relief shaft. The airflow velocity distributions induced by moving train on tunnel ventilation system are dependent on the traffic conditions as train specification, train speed, train length, tunnel and station configurations, and so on [2].

In general, smaller cross-section and shorter length of draught relief shaft lead to reduced construction costs, especially when combine with ventilation shafts. The relief shaft acts as a mechanical ventilation shaft and larger cross section will reduce the pressure loss, noise and fan power. These advantages must be balanced with requirements in different modes of operation and limitations of construction.

3. CONFIGURATION OF DRAUGHT RELIEF SHAFT

All subway tunnels require ventilation to remove the contaminants and superfluous heat produced by train and passengers during normal operation. Ventilation may be provided by natural means, by the train piston effect or by mechanical equipment. Natural ventilation and traffic induced ventilation are suitable for relatively short tunnels or tunnels with low traffic density. Generally, if the tunnel is long relatively and the piston effect of air velocity is less than half of the train speed, the subway tunnels should be adopted mechanical ventilation. The selected method should be the most economical in terms of construction and operating costs [3].

There may be many possibilities to implement the draught relief shafts. Figures 2 to 5 are shown the different possibilities with one synoptic sketch and one physical layout implementation of the principle.

Table 1 shows modes of operation and tunnel temperature criteria for acting dampers of draught relief shaft and divert airflow to ventilation shaft and vice versa.

Table 1: Modes of operation and tunnel temperature criteria for acting shafts damper

Modes of Operation / Types of Shaft	Normal	Congested	Emergency
Tunnel Temperature Criteria	T<40°C	40°C<T<46°C	T>46°C
Draught Relief Shaft	OPEN	CLOSE	CLOSE
Ventilation Shaft	CLOSE	OPEN	OPEN

3.1. Configuration one

A complete independent draught relief shaft fitted with a separated motorized damper and has no structural interface with ventilation shaft. In normal mode operation, damper of draught relief shaft is opened and ventilation shaft damper is closed and allows free flow of air escape to the atmosphere as the train approaches tunnel and allows free flow of air pull down from the atmosphere as the train departures tunnel. In congested and emergency mode, damper of draught relief shaft is closed and ventilation shaft damper is opened and allows force ventilation occurred. Figure 2 shows this configuration schematically.

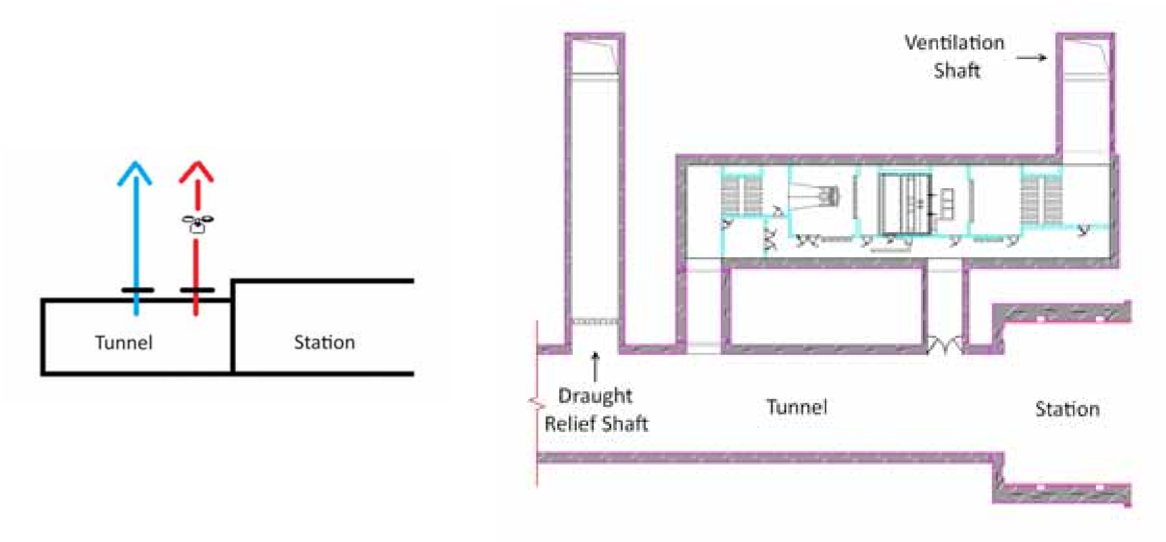

Figure 2: Independent draught relief and ventilation shaft

3.2. Configuration two

A common intake shaft used with tunnel ventilation shaft, but has a different exhaust kiosk shaft. In normal mode operation, damper of draught relief shaft that located at the end of the common shaft is opened and ventilation shaft damper is closed and has a same previous configuration ventilation manner. In congested and emergency mode, damper of draught relief shaft closed and ventilation shaft damper opened and allows force ventilation occurred. Configuration two reduces costs of construction in compared with configuration one 15% approximately. Figure 3 shows common intake shaft configuration schematically.

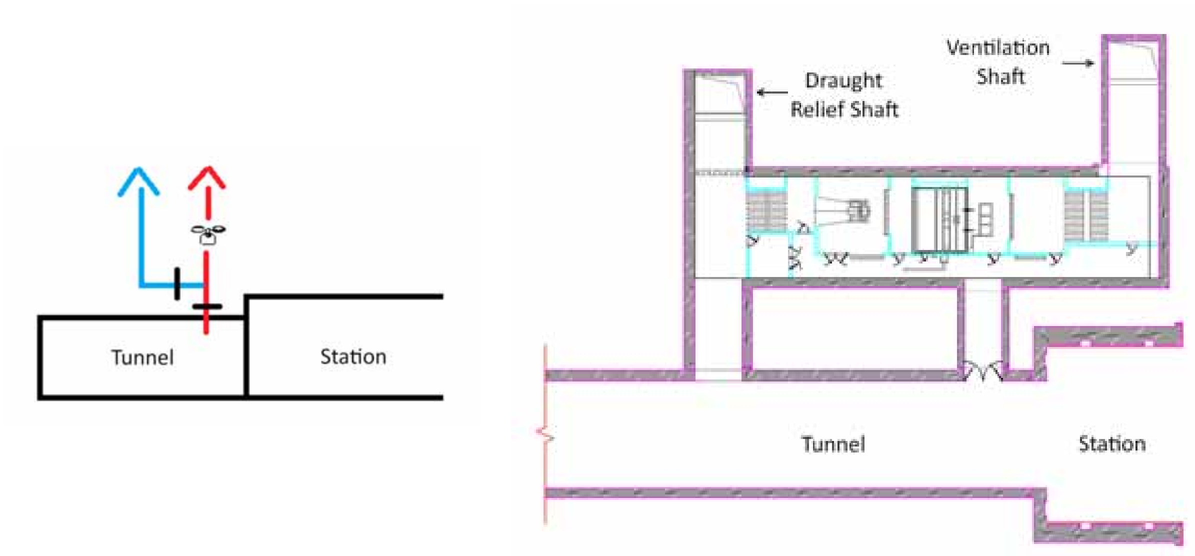

Figure 3: Common intake shaft for draught relief and different in exhaust shaft

3.3. Configuration three

In this configuration used different intake draught relief and ventilation shaft, but with common structural exhaust kiosk shaft. In normal mode operation, damper of draught relief shaft is opened and ventilation shaft damper is closed and in congested and emergency mode, damper of draught relief shaft is closed and ventilation shaft damper is opened and allows force ventilation occurred. Configuration three reduces cost of construction in compared with configuration one 24% approximately. Figure 4 shows a common structural exhaust shaft with the tunnel ventilation, but a different intake shafts configuration schematically.

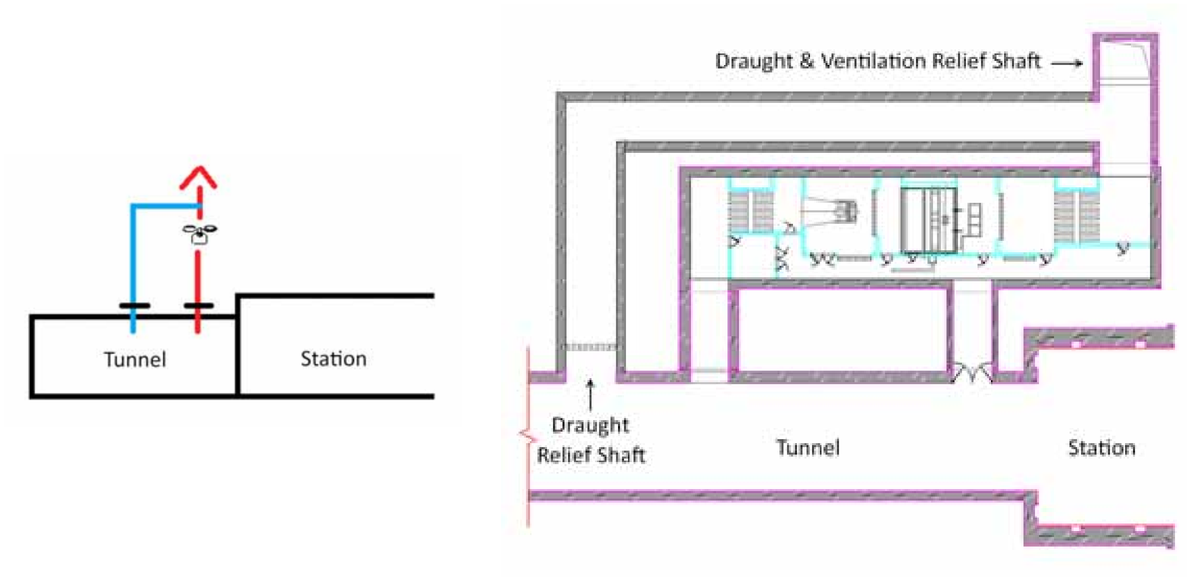

Figure 4: Common structural exhaust and ventilation shaft with different intake shaft

3.4. Configuration four

A common structural intake and exhaust kiosk shaft used for combination draught relief and ventilation shaft like a by-pass shaft. In normal mode operation, separate damper of draught relief shaft that located at the entrance of by-pass shaft is opened and ventilation shaft damper is closed and in congested and emergency mode, damper of draught relief shaft closed and ventilation shaft damper opened and allows force ventilation occurred. Configuration four reduces cost of construction in compared with configuration one 32% approximately. Figure 5 shows common structural intake and exhaust shaft configuration schematically.

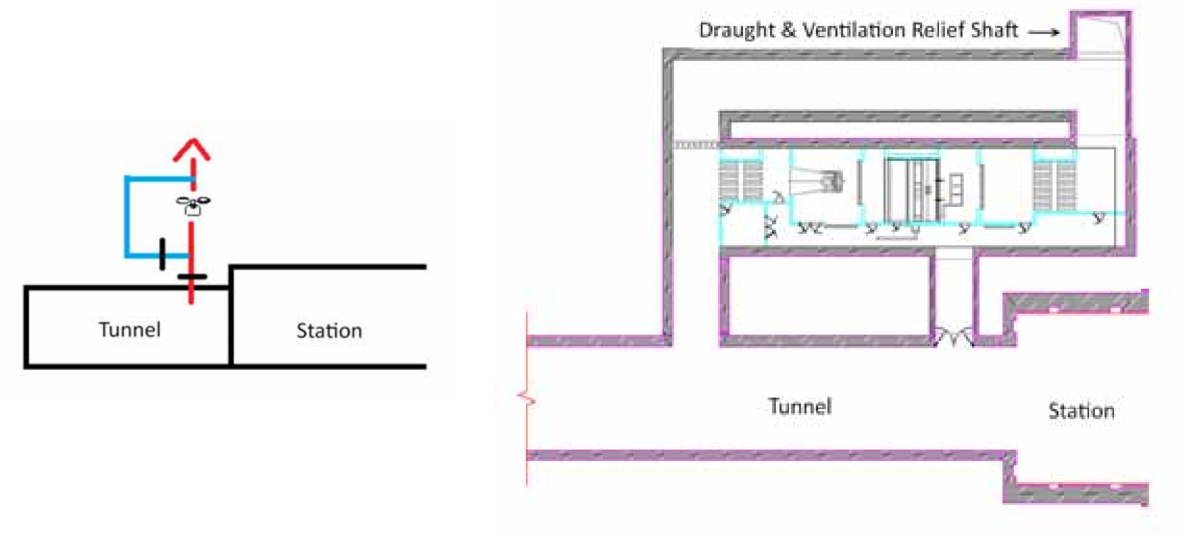

Figure 5: Common structural intake and exhaust shaft

4. COMPARISON OF CONSTRUCTION COSTS

According to mentioned configurations and due to length of shafts, their dimensions (4m x 5m), 2.5 minutes headway and other parameters obtained from 1D simulation with SES software results and also taking account the limitations of land acquisition in major cities, table 2 shows the comparison of construction costs in different configurations.

Combined kiosks of ventilation and draught relief shaft in the street level and combined opening duct in the tunnel level and also combination of two shafts reduce the construction costs up to 32% in compared with configuration one.

Table 2: Comparison of construction costs in different configurations

Configuration	Total Length of Shafts	Opening Duct at Tunnel Level	Kiosk at Street Level	Total Cost of Construction and Land Acquisition	Cost Reduction in Compared with Configuration One
Unit	m	QTY	QTY	$	%
1	70	2	2	450.000	-
2	60	1	2	382.500	15
3	60	2	1	342.000	24
4	50	1	1	306.000	32

5. ADVERSE INFLUENCE OF PISTON EFFECT ON FANS

Studies influence of the piston effect and mutual influence of piston effect and exhaust mechanical fans have received attention for many years. The piston wind velocity and its effect on fan’s flow should be calculated before subway tunnel ventilation design.

Draught relief shaft is an important parameter when piston effects used for tunnel ventilation. Head of the train has positive pressure while the rear part for the negative pressure. As for the pressure difference, part of air exports from the front part of the tunnel and other part go through the space between train and tunnel to form a piston wind.

When taking account the construction of a fan with its housing and connecting airways, it is crucial to make certain that all components can endure the fluctuating surge caused by the passage of trains. Non-return dampers are used with positive effect to stop the piston effect of a passing train from reversing the fan. Without such basic precautions, the train's air volume would stall the fan, with probable adverse effect on the fan motors and drives. Hence, use of draught relief shaft techniques would prevent deterioration and freewheeling of fans, damage to the motor engine and blades. In addition, prevent accumulation of more debris in fan rooms in normal ventilation mode.

6. CONCLUSION

Structures and ductworks are the major cost elements of the ventilation systems. Even with an extensive utilization of fans, dampers, electrical and mechanical equipment, the structure cost will be most of the capital expenditure. Then, civil and structural design considerations and applicable construction techniques will dictate the cost of the structures. So, the high costs of these ventilation structures require a design for optimum performance accordingly. Draught relief shafts allow reducing the quantity of air velocity fluctuations, generated by train’s movement. When draught relief shaft combines with ventilation shaft, it must be balanced with requirements in different modes of operation and limitations of construction. Due to the high costs of land acquisition in major cities and saving in underground constructions and also reducing cost of draught relief shaft, configurations four, three and two in terms of land acquisition and construction costs savings 32%, 24% and 15% in compare with configuration one, respectively and configuration four is recommended as the preferred configuration in terms of performance and construction costs.

The advantages of draught relief shafts and combination with ventilation shafts are as follows:

- Divert as much air as possible from the tunnel to the atmosphere, by means of minimizing the blast in stations and comfort feeling of passengers and staff.
- Preventing the entering high volume of polluted and warm air that produce due to braking action and air conditioning in train system to the station and keeps up platform's air quality.
- Preventing the deterioration and freewheeling of fans and reduction maintenance and repair costs.
- Preventing the damage of motor engine and blades by passing tunnel air through draught relief shaft.
- Preventing the accumulation of more debris in fan rooms in normal ventilation mode.
- Saving in draught relief shaft construction and high costs of land acquisition in major cities.
- Combines ventilation shaft with draught relief shaft and reduces construction costs up to 32%.
- Configuration four is recommended as the preferred configuration in terms of performance and construction costs.

ACKNOWLEDGMENT

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STANDARDIZING THE TECHNICAL AND STRUCTURAL SPECIFICATION OF DOORS IN TUNNELS

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ABSTRACT

In the past few years the technical and safety needs for railway tunnel systems designed for a cross travel speed of more than 160 km/h caused a steady increase of tunnel facilities. In addition to the structural engineering experience required, a more sophisticated approach of planning the highly complex tunnel equipment is needed. This also to comply with the permanent on-going change in the legal framework.

Experience in the operation has shown that due to the high complexity the tunnel facilities not always work in the way expected (e.g. failure indication) and that facilities in tunnels are often not designed in consideration with other interacting facilities (e.g. tunnel doors and tunnel ventilation). It becomes apparent, that in the future an integrated design of the tunnel facilities is mandatory. This to take part already in the design phase of a tunnel. Various issues with doors in recently opened tunnel-systems forced an evaluation, that subsequently led to a review of the specifications of tunnel facilities, especially doors.

1. INTRODUCTION

To understand related to tunnel facilities, in this case with doors, following questions have to be discussed:

- Why are these facilities in tunnels?
- How did the current requirement of each specific facility come up?

The answer to the first question can be found in the increased inquiry of safety in tunnels on one hand, and in the increased number of various facilities that are believed to be essential in a tunnel on the other hand (e.g. telecom equipment).

The object of this paper is to give an insight in the complex correlations between the different parts of tunnel facilities on the example emergency exit doors.

There are no precise technical regulations, which define uniform specifications of doors in tunnels. Hence the technical solutions are based on project-related individual solutions.

A future goal is to develop a guideline for the design of emergency exit doors to unify their design and simplify maintenance.

Therein it also has to be taken into account, which system of ventilation for operational, maintenance and emergency situations, is or will be installed, because the issues “doors in tunnels” and “tunnel ventilation” interact very closely. The newly obtained findings and experiences show that to reduce the costs of maintenance and the times of interruption of operation, it is necessary to establish a uniform standard for all the different facilities and equipment in tunnels.

It appears that due to the high aerodynamic impact of passing trains, resulting in suction and compression, complications with the fastening devices for the doors in the cross passages and emergency exits already occurred after a short time of operation.

A study was commissioned, which should investigate and record the impacts in means of strain on the doors with measurement devices.

2. REQUIREMENTS ON DOORS IN TUNNELS ACCORDING TO INTERNATIONAL AND NATIONAL REGULATIONS

In international and national regulations set out requirements to ensure the safety of the passengers and staff in case of emergency depend on the design of the tunnel (length of the tunnel, number of tubes, number of tracks) .

To satisfy these measures, additional rooms have to be created, which imply doors with various requirements. In a first step the requirements on doors based on the international and national regulations have to be assessed to understand how the current problems in existing tunnels have arisen.

2.1. Technical Specifications for Interoperability, Safety in railway tunnels (TSI-SRT)

[1] The TSI SRT 2008 represents a European standard of how to deal with safety issues in railway tunnels. The regulations in the TSI are binding and apply to new, renewed and upgraded tunnels. The purpose is to define a coherent set of tunnel specific measures for the infrastructure, energy, rolling stock, control-command and signalling and operation subsystems, thus delivering an optimal level of safety in tunnels in the most cost-efficient way.

One of the measures required by the TSIis the installation of evacuation facilities. So called *safety areas* shall guarantee the evacuation, maintain survivable conditions, allow people to move to the surface without having to re-enter the affected tunnel tube. For this reason it is necessary to separate the affected tunnel tube from the safe area, which can be accomplished either as a cross passage or an emergency exit. The most efficient way of creating a space, where survivable conditions can be maintained is to shield it with a door, which can withhold the exposure of fire (smoke, heat) from entering.

Chapter *4.2.1.1. Prevent unauthorised access to emergency exits and technical rooms* regulates, that doors of technical rooms have to be locked to keep unauthorised person off from entering. Furthermore it regulates, that emergency exits should be locked for security purposes, but shall always be possible to open frominside.

Chapter *4.2.1.2. Fire reaction of building materials* request, that non-structural panels and other equipment (including doors in tunnels) shall fulfil the requirements of classification B of Commission Decision 2000/147/EC. According to TSI SRT 2008, the structural fire protection of the HC curve (Eureka curve) has to match. This curve was applied to the calculations of tunnel doors. In the TSI SRT 2014 this requirement is eliminated and doors can be calculated specifically.
Paragraph *4.2.1.5.2 Access to the safe area* regulates the minimum clear opening of doors giving access from escape walkways to the *safe area,* which shall be at least 1,4 m wide and 2,0 m high. Also multiple doors next to each other which are less wide are allowed, as long as the flow capacity of people is demonstrated to be equivalent or higher.

2.2. Guideline of Austrian Federal Fire Service Association for protection requirements for the construction and operation of railway tunnels

[2] The Austrian Federal Fire Service Association published a guideline for protection requirements in railway tunnels. This national guideline is much more specific regarding means of structural demands for safety in railway tunnels. It describes the structural and operational safety measures to preserve the self-rescue possibility of passengers and railway personnel, but also to enable the rescue forces to operate in case of emergency.

The following chapters of the ÖBFV-RL A-12 address doors in tunnels.

Chapter *2.1 principles* in the paragraph *preservation of the functionality* requests the escape route illumination, emergency communication devices, energy supplies and the opening mechanism of emergency exits in the affected tube to preserve their functionality for a minimum duration of 90 minutes (E90 due to ÖNORM DIN 4102).

Chapter *2.3 emergency exits, emergency stair cases, rescue tunnels* in the paragraph *locks* requests that between track tubes and between emergency exits respectively rescue tunnels locks of a minimum length of 12,0 m have to be installed. Moreover it is demanded that the doors have to be sealed against fire according to T90 (now EI2 90-C). Doors of emergency exits must open in the direction of escape and the wings of the door must have a minimum width of 1,0 m.

Chapter *2.3 emergency exits, emergency stair cases, rescue tunnels* in the paragraph *object protection* requests that doors of emergency exits have to be equipped with panic locks (horizontal bar). These doors have to open from the inside of the affected tube with just moderate effort.

3. DYNAMIC MEASUREMENTS OF EMERGENCY ESCAPE DOORS

The first issues with emergency escape doors in tunnels occurred in recently opened tunnel-systems for the expanded railway lines between Vienna and St.Pölten as well as between Kundl-Radfeld and Baumkirchen , where the trains travel up to 230 km/h. Both lines include a number of tunnels with different tunnel lengths and tunnel constructions.

It was decided to run further investigations to assess the exposures and the critical parts of the doors in tunnels in the course of the *Innovationsmessfahrten 2012* on above named railway lines. Summaries of the result of these measurements will be presented in this chapter.

3.1. Measurements during the *Innovationsmessfahrten* 2012

In 2012 measurements on two selected emergency exit doors in the newly built railway lines have been performed in the course of the *Innovationsmessfahrten*. The focus was to measure the pressures and deformations in the doors, the forces in bolts and the strain in the door hinges.This was done in the *Wienerwaldtunnel* and *Stierschweiffeldtunnel* accomplished by special trains equipped with several measurement devices. .

The emergency escape doors were constructed as double wing door constructions, where one wing is “standing” and one wing is denoted as “moving door”. Both wings are capable of being opened in escape direction with a maximum width of the door (both the wings) of about 2 m.

The **Figure 1** details, the way the door is fixed to the building.

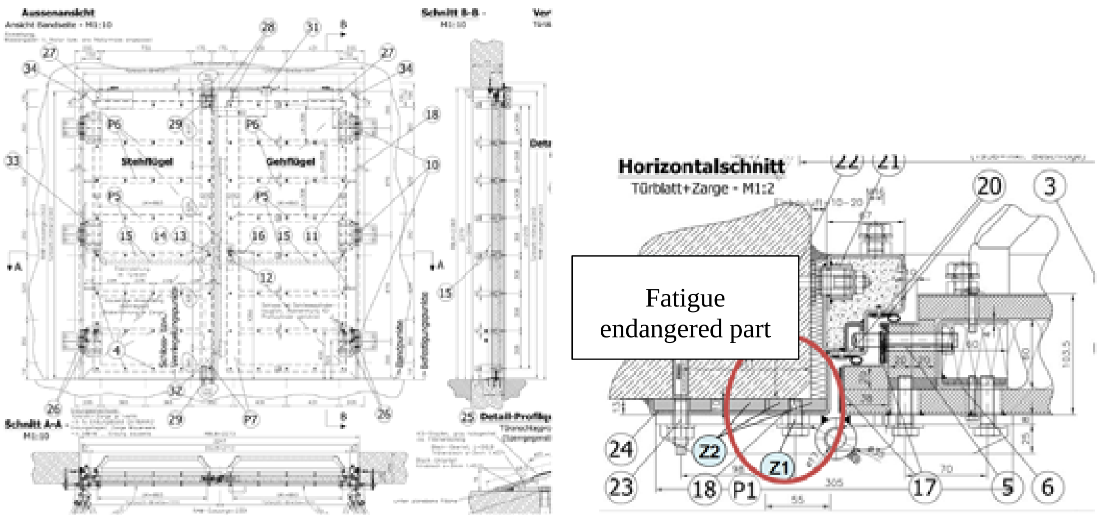

Figure 1: Blue prints of the emergency exit door, Detail of the attachment of the hinges to the door frames. [3]

The measurements during the *Innovationsmessfahrten 2012* were done with twelve measurement sensors (air pressure sensor, displacement sensor, force sensor, strain gauge and photo sensor) to measure the impacts of a variation of passing trains on specified parts of the investigated doors. **Figure 2** shows the alignment of the measurement.

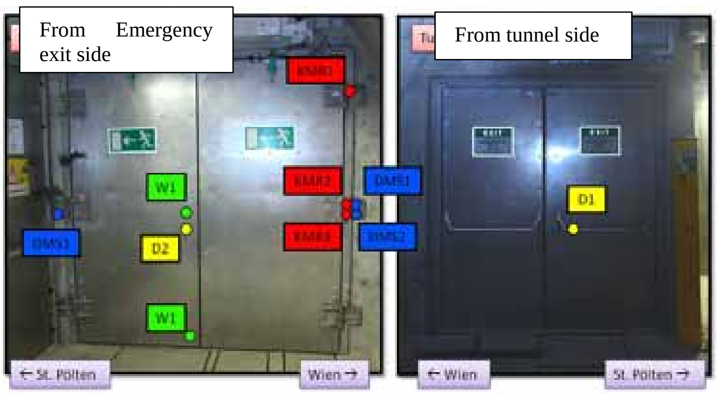

Figure 2: Arrangement of the sensors in the Wienerwaldtunnel [3]

The difference in the air pressure in the tunnel and inside the escaping room due to passing trains was measured by air pressure sensors. Pressure sensor D1 measured the barometric pressure in the tunnel perpendicular to the door, while Pressure sensor D2 observed the air pressure inside the escape room.

The deformation of the doorblade was gauged by a laser displacement sensor. In the 1st phase solely the deformation in the middle of the door W1 was measured. The sensor was placed in middle height in the middle of the doorblade of the “standing door”. In the 2nd phase the displacement measurements were enhanced and another laser displacement sensor was added to measure the movement of the door close to the floor. The forces in the fatigue relevant bolts were measured with three ring force sensors (KMR 1, KMR 2, and KMR 3). For triggering the start of the measurement record, there were mounted tow light barriers (LS1, LS 2).

3.1.1. Summary of the results of the Innovationsmessfahrten in the Wienerwaldtunnel

[3] The Wienerwaldtunnel is a double tube, single-track tunnel with a length of 13 km and a cross-section area of 51 m². The two tubes are connected every 500 m with cross passages and separated by escape doors cross passages.

The results of the measurements show, that the maximum compression and suction impacts on the doors are greatly depending on the direction of the train passing the tunnel. Trains travelling with 235 km/h cause a maximum air compression of 3,7 kN/m² and a maximum intake pressure of -3,1 kN/m². The greatest difference between the measured maximum compression and measured intake pressure caused by a passing train was 5,3 kN/m².

Figure 3 shows the maximum compression and intake pressure impacts of passing *Railjet* trains. The 2 purple lines in the graph represent the design value of the maximum compression/suction values (±4 kN/m²) without considering a dynamic factor $\varphi_{dyn} = 2{,}0$.

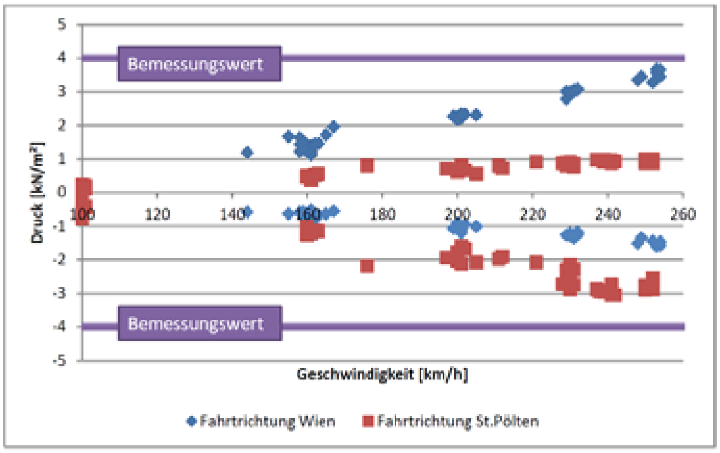

Figure 3: Maximum compression/suction impacts compared to the design values, Wienerwaldtunnel. [3]

The maximum movement was measured at the lower edge of the door blade of the emergency exit doors with around ±3 mm. The distortion (the difference of the movement in the middle and at the edges of the doorblade) was around ±1,5 mm.

Additionally the influence of the tightening torque of the screws in the door hinges on the stresses of the screws was investigated. According to the manufacturers the tightening torque should be around 30 Nm. By means of force sensors it could be assessed, that by reducing the tightening torque the dynamic forces in the screws are doubling.

Figure 4 shows the maximum values of compression in the tunnel due to passing *Railjet* trains. It obvious, that the compression respectively the suction impact on the door is highly depending on the direction of travel.

The impact of this suction is superposed with the impact of the compression resulting from the portal entry wave. That's the reason why the maximum value of suction of a train heading to Vienna is lower than one heading to St. Pölten.

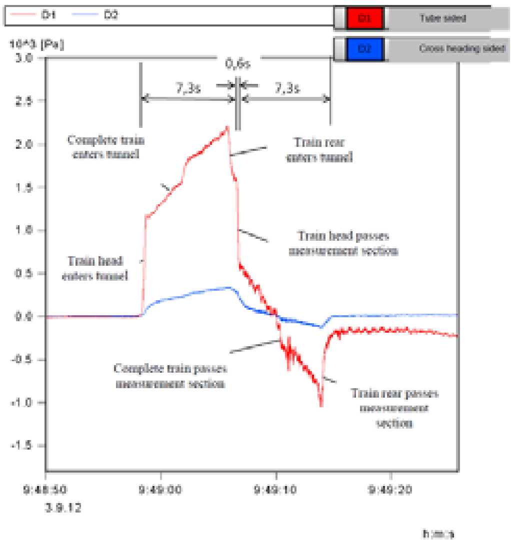

Figure 4: Maximum values of Compression in the tunnel (sensor D1and D2) [3]

3.1.2. Summary of the results of the Innovationsmessfahrten in the Stierschweiffeldtunnel

[4] The *Stierschweiffeldtunnel* is a single tube, double track tunnel with a length of 3 km and a cross-section area of 76 m². The investigated emergency escape doors separate the tunnel tube from the emergency exit.

The analysis of the measurements shows, that the maximum measured compression/suction values cluster around 2,1 kN/m² respectively -3,2 kN/m². It turned out, that no matter on which track the train is travelling, the compression/suction impact on the doors is more or less the same.

Figure 5 shows the maximum compression and intake pressure impacts due to passing *Railjet* trains. The design value of ±4 kN/m² was not exceeded.

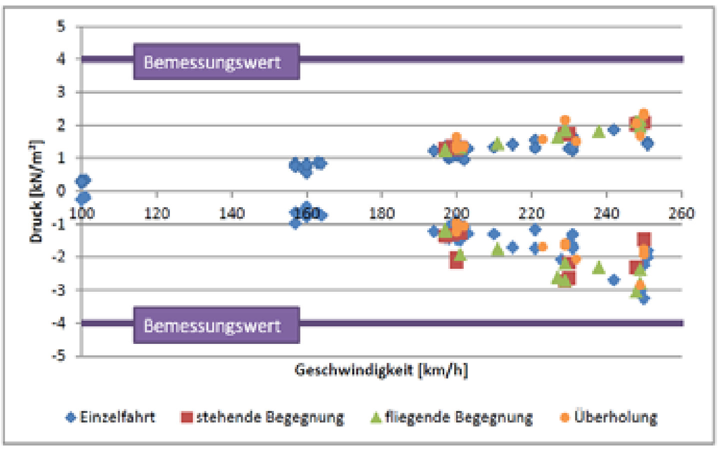

Figure 5: Maximum compression/suction impacts compared to the design values, Stierschweiffeldtunnel. [4]

4. EXAMPLES OF ISSUES WITH DOORS IN TUNNELS

An evaluation of the maintenance records of the emergency exit doors in the first year of operation showed, that doors were occasionally opened by passing trains. An examination of the affected doors showed that the fastening systems are suffering from fatigue damage, because of the load changes caused by passing trains.

The malfunction of a subsystem like the emergency exit doors subsequently causes a reduction of possible train operations of the line.

4.1. Contamination of the closing mechanism of emergency exit doors with magnetic dust caused by abrasion.

In the first year of operation a malfunction of the closing mechanism of emergency exit doors was observed. As already mentioned before, some of the emergency exit doors opened by passing trains. This unwanted opening immediately starts the emergency ventilation program, and also sends a message to the facility service center.

Investigation showed, that the closing mechanism of the doors couldn’t lock the doors properly. The emergency exit doors have three locking pins, which are connected with a locking bar and can be moved by operating panic bar. This bar was contaminated with magnetic brake dust of the trains and caused an adherence of the locking mechanism (**Figure 6**).

Figure 6: From left to right: contaminated locking pin, brake dust behind the coverage, magnet placed on coverage [5]

4.2. Interactions between tunnel doors and tunnel ventilation systems

It has become apparent, that not only the choice of the type of door (Swing door, double swing door, sliding door, etc.) is of importance, but also the verification of requirements really necessary and if they areaccomplishable.

Therefore it also has to be taken into account, which system of ventilation for operational, maintenance and emergency situations, is or will be installed, because the issues “doors in tunnels” and “tunnel ventilation” interact very closely.

5. PROSPECT AND GOALS FOR FUTURE TUNNEL PROJECTS

Given the various interactions of the individual tunnel facilities a working group was established to evaluate the specifications of tunnel facilities, especially doors, in already operating tunnel-systems. This working group is composed of representatives of the departments project management, construction management, maintenance of tunnel constructions and emergency management to exchange experiences and expertise.

The group's objective is to develop a technical regulation, which defines the uniform specifications of tunnel facilities e.g. of the doors in tunnels. Furthermore a specification sheet will be created, describing the essential operational procedures and service intervals for the maintenance.

It is expected that these will make a valuable contribution to reduce the costs of maintenance and the times of interruption of operation.

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[5] Klaus Liebwald, Ludwig Rossbacher

FOLGOSO TUNNEL REFURBISHMENT WORKS: FEATURES AND CHALLENGES

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ABSTRACT

The tunnel of Folgoso is located in A-52 Highway, in Pontevedra, in the northwest of Spain. It enhances the road communication between the central plateau and the region of Galicia.

It is a 2,551-metre-long unidirectional twin-tube tunnel. It was open in 1998, With a traffic intensity of 3,750 veh day^{-1}, being 17,2% heavy vehicles. Traffic of heavy good vehicles through the tunnel is permitted, as well.

In 2006, a project design for tunnel refurbishment was undertaken in accordance with the Spanish standard for safety in road tunnels (Royal Decree 635/2006). The refurbishment works began in 2008, keeping the tunnel within operation.

The tunnel of Folgoso is the longest highway tunnel in Spain that has been revamped to meet RD 635/2006 requirements. There has been a wide renovation of equipment concerning electrical systems, lighting, ventilation, firefighting and communications, mainly.

The tunnel is a pioneer in deploying some features. For instance, it is the Spanish longest highway tunnel with fluorescent lighting, and the first to be endowed with an anti-glaring system. This device avoids the risk of the drivers to be glared by the sunlight, due to the tunnel's east-west orientation.

Besides, a new Tunnel Control Centre of great architectural value has been built, perfectly merged with the environment. The building hosts the whole equipment that is needed for the tunnel's control and monitoring, as well as the offices for the personnel in charge of the maintenance and exploitation.

Several challenges were undertaken during the works, since the tunnel remained in operation. Risk analyses were done taking into account different ways to divert traffic through one tube and a county road, in order to assess whether or not the safety conditions of the tunnel were high enough to ensure a reasonable safety level.

Another hindrance for the works raised when the electrical supplier stated that the whole electrical power demand couldn't be provided. Thus, an electrical optimization study was developed in order to suit electrical demand and protocols to the actual power supply.

All these circumstances altogether bring out the tunnel of Folgoso as a notorious and referential tunnel in Spain.

Keywords: tunnel refurbishment, anti-glare system, risk analysis, fluorescent lighting

1. INTRODUCTION

The tunnel of Folgoso is located in A-52 Highway, in Pontevedra in the northwest of Spain. It enhances the road communication between the central plateau and the region of Galicia (see Figure 1 below).

It is a 2,551-metre-long unidirectional twin-tube tunnel. It was opened in 1998, and it has a traffic intensity of 3,750 veh/day, with a 17.2% of heavy vehicles. Traffic of heavy good vehicles through the tunnel is permitted, as well.

Figure 1: Tunnel's location in Northwest of Spain and East Portal of the tunnel

In 2006, a project design for tunnel refurbishment was undertaken in accordance with the Spanish standard for safety in road tunnels (Royal Decree 635/2006). The refurbishment works began in 2008, keeping the tunnel within operation.

2. WORKS DESCRIPTION

The aim of the Project was to refurbish and upgrade the tunnel's safety conditions to meet the safety requirements stated in Spanish RD 635/2006. This standard is the national transposition of European Directive 2004/54/CE on minimum safety requirements for tunnels in the Trans-European Road Network.

2.1. Civil Works

Though the main activities concerned electromechanical systems, some civil works needed to be done according to RD 635/2006. The main civil works undertaken are listed below.

- Asphalt paving: Due to its bad condition, a complete rehabilitation of the road surface was required. According to RD 635/2006, it is mandatory for road tunnels' surface to maintain the Skid Number over 60.
- Sidewalks: In order to avoid collisions inside the tunnel, the sidewalks had been beveled to allow a vehicle to climb the curb. This measure also allows disabled people to climb the curb in case of emergency, with little effort.
- Drainage: The works consisted in repairing water filtrations inside the tunnel, conducting this water to the rainwater gutter, along with a canalization of a natural fountain located outside of the tunnel. Both these repairs improved tunnel safety, clearing the water from the road surface.
- Besides, it was built a separated sewage system for collecting dangerous and flammable liquids.
- Aesthetic coating: This system has a double aim, on the one hand improving wall's reflection properties to make a better lighting of the tunnel, and on the other hand conveying a comfort sensation and better aesthetic impression on the drivers.

So, a mixed solution consisting in 3.5 m high vitrified steel panel in both tunnel walls was deployed. The remaining surface was painted with a special sprayed ceramic coat.

- Landscape integration of both tunnel portals: Since Galicia is a region with lots of vegetation, it was paramount to enhance a smooth integration of the tunnel structure along with the landscape. Local tree species were planted along the portals' sides.

  Both portals were hydroseeded at the beginning and at the end of the works.

- Road signs: There was a complete renovation of the road signs, complemented with new requirements from RD 635/2006 and Spanish standard for road signing.

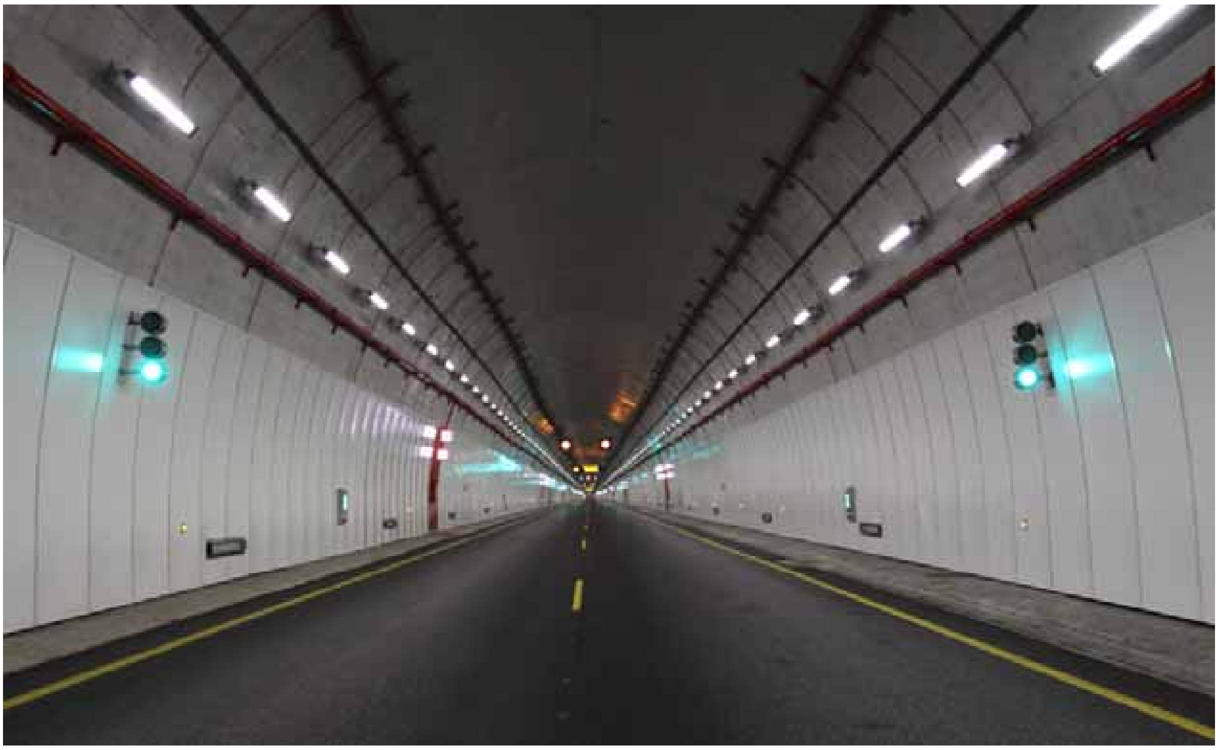

Figure 2: Tunnel of Folgoso after the revamping works

2.2. Safety systems' works

The tunnel of Folgoso was opened in 1998, so safety criteria were quite different to current ones. Thus, the scope of the project laid mainly in upgrading electromechanical systems.

- Ventilation: a whole new design of the ventilation system was developed, taking into account modern standards and the increase of the traffic flow.

  A risk analyses-based new algorithm was developed to ensure the system's capacity to manage tunnel ventilation in case of a 100 MW fire. It is envisaged to carry out smoke tests as a final stage for commissioning of the tunnel.

  Moreover, a new ventilation monitoring system has been deployed. CO and NO are monitored every 300 m, along with air speed and direction and opacity. The SCADA analyses the inputs from the measuring devices and, in case an incident is recorded, it triggers the start of a ventilation protocol, always under tunnel operator supervision.

- Emergency exits: The tunnel has 8 galleries connecting both tubes. They serve as emergency galleries, free of fire and smoke. Overpressure inside the emergency exits is granted by maintaining its doors closed and a fire resistant ventilation system with fans, dampers and ducts.

- CCTV: The tunnel already had an analogical-based surveillance system with Automatic Incident Detection (AID). This system merges with the new extension consisting in technical rooms monitoring and new dome cameras located outside the tunnel providing direct vision of the portals and Variable Message Signs (VMS).

  Along with CCTV, a new Automatic Number Plate Recognition (ANPR) system was deployed in both tubes. Its aim is to deter drivers to exceed speed limits by recording their plate numbers and their average speed. The system raises an alarm if a driver's irregular behaviour is detected.

- Fire suppression systems: A new water supply connection devoted only to fire fighting was built, complying with Spanish standard. The system has also a new water tank, separated from the former drinking water tank, avoiding both supplies to mix.

  There are two existing pumps, one at each portal. A new algorithm of pump starting has been designed in order to save energy and false starts. The protocol takes into account not only the pressure that the system needs, but also the water level in each tank.

  A new linear fire detection system based on fibre optics technology was deployed, substituting the old fusible bimetal type.

- Electric supply: According to Spanish standard, the tunnel is due to have a redundant power supply, besides a diesel generator (DG) and an Uninterrupted Power Supply (UPS). Every technical room is equipped with both a DG and a UPS to ensure a minimum emergency supply in case of electric fails.

  All the transformer stations were modified to allow electric supply from two different high voltage lines, along with a commutation system.

  The installed power capacity is increased due to the deployment of new equipment. So, new transformers and DG were installed in technical rooms.

- VMS: New panels have been deployed every 1,000 m. They show messages in a two-rowed alphanumeric area and a graphic area reserved for pictograms.

  Lane control signs are used above each traffic lane along with pictograms showing speed limit signals every 400 m. These speed limit signals allow up to 100 km/h of maximum speed and show their pictograms on a blank background, to improve visualization.

- Vehicle barriers: New vertical axis barriers were installed, along with the existing horizontal axis ones. Both barrier types working together allow a more efficient lane-cutting procedure, if necessary.

- Public Address (PA) system: A whole new PA system was installed, with new equipment and a new zone configuration. This feature allows conveying different messages for each zone, and also allows addressing to emergency galleries and tunnel portals.

- Radio Communications (RC): This system enables up four ways of communication, for different purposes. Firstly, it allows some radio frequencies to enter into the tunnel, which may be used for PA as well. Secondly, cell phone communications are also possible inside the tunnel. A radio channel for maintenance purposes is also available. Finally, the system also provides a mean of communication for emergency services through their private radio channels.

3. TECHNICAL CHALLENGES AND INNOVATIONS

Some detailed studies were necessary, given the tunnel's uniqueness and importance. Innovative solutions were developed in order to meet the safety requirements.

The main technical challenges and innovations are as follow.

3.1. Anti-glaring system

The tunnel of Folgoso is oriented from East to West. This fact leads into a rather uncomfortable and dangerous situation, since drivers are glared by the sunlight at dusk during certain periods of the year.

A theoretical approach to this issue was undertaken, since solar trajectories are well known and a geometrical study can determine when and how a driver is glared by sunlight.

Commercial code ECOTEC was used to study several road cross sections to assess which were the critical angles for glaring (Figure 3). The glaring angle is a variable angle formed between the sunbeam for every instant and the driver's visual plane. The anti-glaring system geometry will avoid each and every glaring angle during the year.

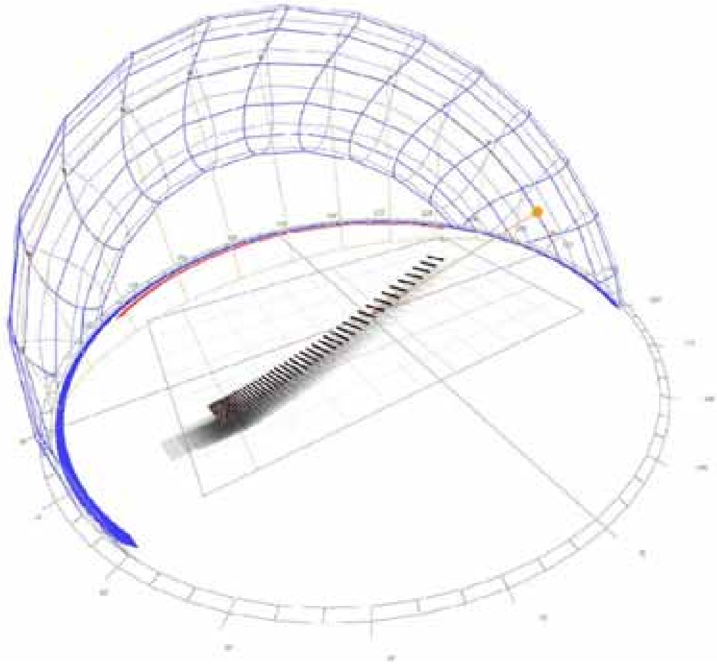

Figure 3: Map of solar trajectories and projected shadows

Once the ideal anti-glaring geometry has been determined, a structure that may resemble that geometry is designed. The structure must keep the road height and width free from obstacles.

Consequently the structure is formed by a series of equidistant gantries, with a cross beam structure on top. The beams hold a series of ellipsoidal lightweight aluminium blades transversal to the road, which avoid the sunbeams glaring the drivers.

3.2. Lighting system

The revamp of this system aims to upgrade lighting levels to new standards, but also to renew the equipment and taking advantage of new lighting control systems.

Given the length of the tunnel, a lighting optimization analysis was carried out during the design phase, considering several options on a cost-effective base. According to the study, a mixed solution of High Pressure Sodium Vapour (HPSV) and Fluorescent lamps was found the most convenient option for the tunnel.

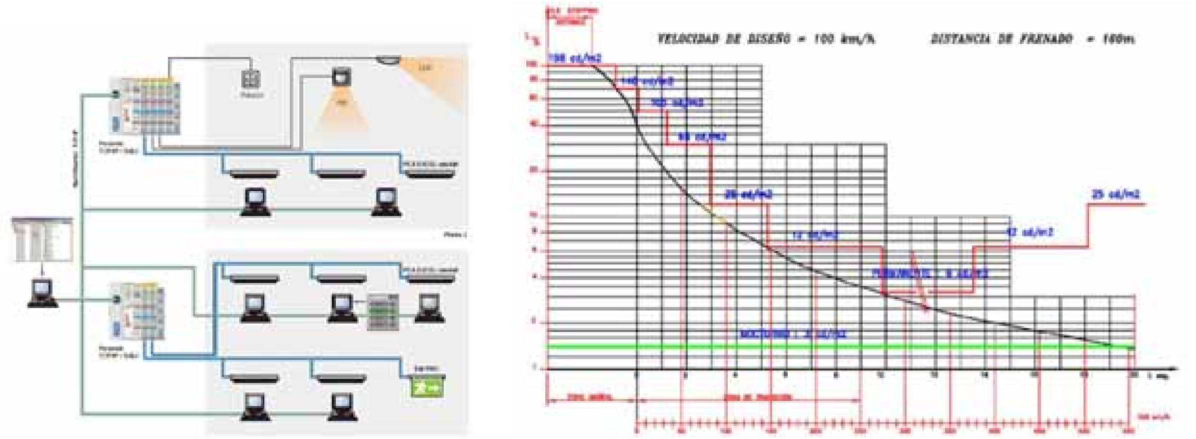

Figure 4: DALI scheme and lighting curve

The threshold zone and transition zone is lighted with HPSV lamps, while fluorescent lamps are deployed along the whole tunnel, providing with the interior permanent lighting. The permanent lighting regime is controlled with a Digital Addressable Lighting Interface (DALI), which enables to obtain a lighting curve that fits closely to the theoretical curve. So, energy savings are assured up to an estimated 25%.

3.3. Electric system

According to Spanish RD 635/2006, the tunnel of Folgoso must have a redundant electric supply, and the design project took that into account.

However, since the tunnel's surroundings are a low populated area and near the end of the power lines, the electrical supplier stated that the whole electrical power demand couldn't be provided. Thus, an electrical optimization study was developed in order to suit electrical demand and protocols to the actual power supply.

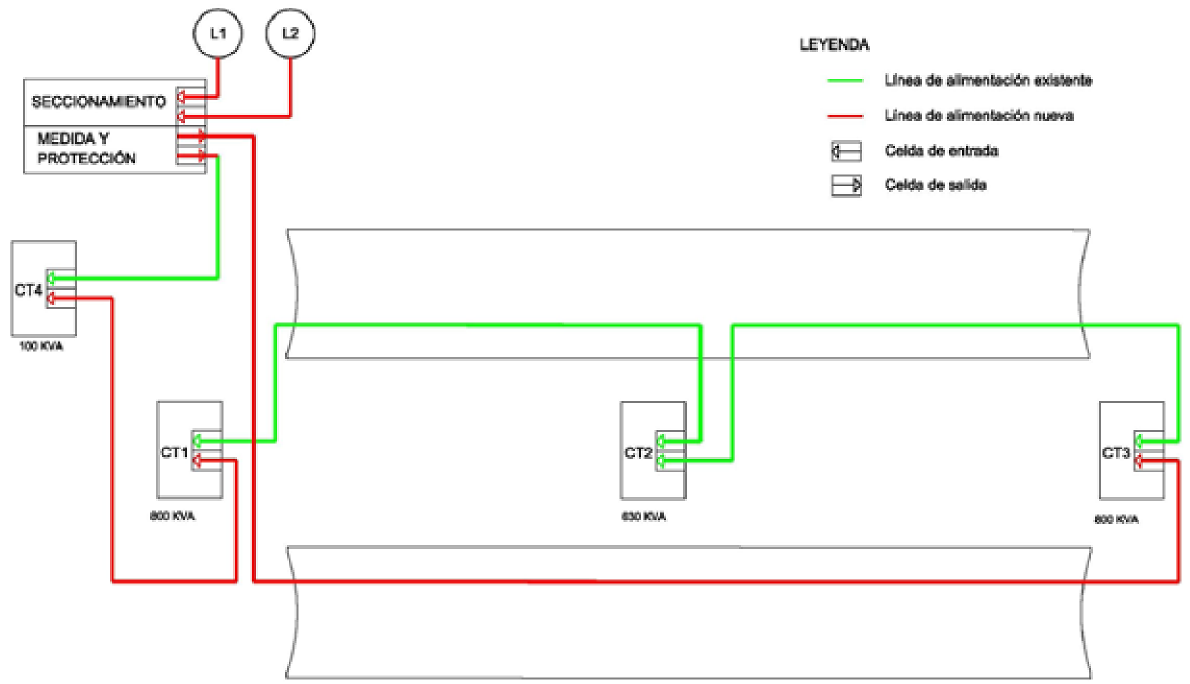

Figure 5: Electric scheme

Several hypotheses were studied, taking into account different fire sizes and lighting regimes.

- Normal operation conditions: this case involves the whole power capacity of the lighting system, but the ventilation system is expected to need only as much as 5 out of 14 fans for sanitary ventilation purposes, according to the CFD studies undertaken.
- Emergency conditions: this scenario includes a fire inside one tube. This situation needs the whole ventilation system switched on. Under these circumstances, the portal's lighting is unnecessary and the permanent lighting level is considered enough for the emergency purposes.

3.4. Tunnel Control Center

There are several tunnels in the province of Pontevedra, most of them in the by-pass surrounding the town of Vigo, some 50 km away of the tunnel of Folgoso. This tunnel network isn't monitored in a centralized Control Centre, but in small centres for each group of them.

Several new necessities for the already existing Control Centre rose in the design phase of the refurbishment project. The tunnels were not visible from the Control Centre, extra space for new equipment was needed and there was a lack of space for the maintenance and operation staff.

A new Control Centre was designed to suit all these needs, with extra space to host all the operation and maintenance staff. The possibility of a further centralization of all the tunnels in Pontevedra in this Centre is foreseen.

The Control Centre has a large control room with a video wall and a situation room annexed, which enables an access to SCADA application in slave mode.

Figure 6: Brand new Control Centre

A new 25 km long fibre optic network has been deployed to connect Folgoso's Control Centre and an existing Control Centre, aiming to a future centralization of the monitoring of Pontevedra's tunnels.

The Operation Centre of A-52 road also dwells in this same building. For this purpose a new annex building has been built to host a warehouse and shelter the road maintenance machines, and even a salt deposit for maintenance in winter conditions.

When it comes to architecture, the building merges both the concrete structure robustness and the lightness of the first floor volume which, shifted from the ground floor volume, provides with a direct vision of the tunnel's West portals.

The ground floor hosts common facilities and maintenance rooms, while the upper level houses offices for administrative work, the Control Center and the Situation Room.

3.5. Risk analyses for temporary traffic measures

One of the most difficult issues was to undertake the works without cutting the traffic in the tunnel. Anyhow, some tasks obviously needed a tube without traffic (mounting jet fans, coating, etc.) so, traffic had to be diverted through the other tunnel and the existing and winding county road.

Which was the best traffic diverting alternative in terms of safety was assessed through the well-known Quantitative Risk Assessment Model (QRAM) to evaluate the risks of dangerous goods transport through road tunnels.

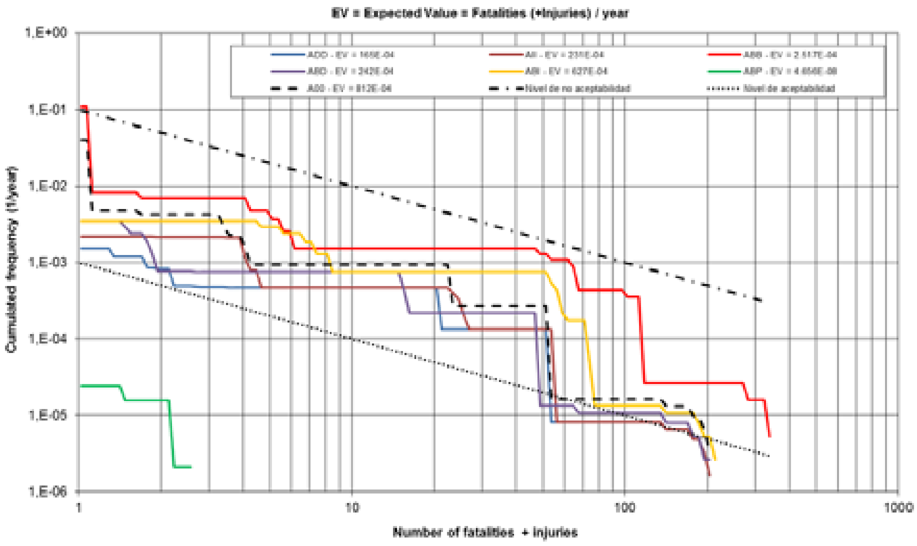

Figure 7: QRAM results showing the risk of every alternative route.

4. CONCLUSIONS

The tunnel of Folgoso is the longest Spanish highway tunnel that has been refurbished to meet RD 635/2006 standard. The refurbishment improved of several features concerning civil works and modernization of safety systems.

Due to its singular characteristics, this project was carried out by a multi-skilled team which could provide useful solutions to actual issues through their expert approach.

The main challenges undertaken were:

- Developing a novel anti-glaring system
- Lighting system optimzation
- Electric system optimization
- Designing a scalable Control Centre

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FIRE, RISK AND PROJECT GOVERNANCE

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ABSTRACT

The fact that deaths in a tunnel are possible can be confronting and politically difficult, therefore project decisions on risk can be difficult, even if the risks are very small. No one wants to be seen as 'compromising' safety, and so often there is a tendency to avoid responsibility for the final risk level.

The success of projects is related to the skill and dedication of people in design, construction and management and to the productive engagement with interested parties. But above all else, it is related to the framework set up for those people to work within. The project governance framework can either facilitate or thwart successful decisions on design and operation.

Governance reasons for success and failure are examined and a common approach is sought to project governance elements which will facilitate successful fire life safety design in any jurisdiction. Amongst other enabling characteristics, the key requirement is awareness of the role of risk decision maker and appropriate assignment of that role within the contractual framework.

Keywords: project governance, risk, decision making, risk acceptance.

1. INTRODUCTION

It may seem trite to note that a successful project requires a range of parties with different skills, in roles that complement each other and are within the capability of the people involved. There are of course many ways in which the management of roles can cause detriment to a project. Compared to other project disciplines, underground fire safety seems to have a high incidence of project issues which have root causes that are organisational rather than technical.

The interest in this paper is in the definition of roles on fire safety, how they have sometimes gone wrong, and how they might best be set up in order that the right outcomes are achieved and management of the various parties through the project is straightforward. That is; it is more about the high level governance of the roles than about the day to day management.

The issues can be quite different in different jurisdictions, although it is surprising how exactly the same issues arise in very different cultural and contractual contexts. It is hoped that an examination of the issues may assist in setting some projects on a more productive path.

2. PAST DIFFICULTIES

2.1. Separation of cost and risk

The most common difficulty is a real or perceived separation of the responsibilities for cost and risk. The cost responsibility for most major tunnel projects lies initially with an arm of government, either directly or through a project body. Once a contract is let, the contractor may be mostly or partly responsible for costs associated with subsequent design changes. The design work undertaken by both owner and contractor aims in some way to meet a desired standard or performance with reasonable cost. Through the contract, or by duty to the community, there is a cost-benefit, or cost-risk, balance to be found.

The role of the fire brigades may be loosely defined in the construction contract, but the fire brigade is mostly not a party to any contract. Fire service legislation is generally very clear on responsibility and authority when there is a fire, and often includes a regulatory role on building approval, but when it comes to major civil infrastructure, it is generally not clear that responsibility extends to determining an appropriate expenditure on risk reduction. Some legislation (e.g. in Queensland) provides for building approval on government projects to be handled internally by the proponent department of government. Of course, in practice, they will involve the fire brigades as advisors.

If there is no one else nominated to adjudicate on provisions made or omitted, and the contract as usual requires some approvals from the fire brigade, they are essentially put in the position of accepting risk. This can place the fire officers in a difficult position. If there is no defined risk acceptance route, and safety has priority, anything perceived as improving safety is likely to become required, no matter how marginally safety improves or at what cost.

A commercial corollary to this is that, if a fire brigade requests an additional feature to gain approval, it is not an instruction from the owner and so may not be contractually reimbursable. The power of the fire brigade to add cost to a contract, which has already been specified after consultation with the brigade, is interesting contractually. This is addressable by assigning the cost and risk decisions to a common party.

2.2. Authority of owner’s staff

A common issue is that the owner’s staff who are dealing with the project issues daily are not necessarily empowered to accept design when it includes acknowledging remnant risk. Those who are empowered (typically CEO or minister) may not understand the significance immediately if project personnel are ‘working through the issues with the fire brigade’ and are reluctant to admit to or point out a project roadblock. It can be very difficult for a manager to consider that application of their management skill may not be the best way of overcoming an organisational issue. In this way, a project may go for some time (years) without a nominated “Acceptor of Risk”. Any lack of remnant risk acceptance within the project allows that role to consolidate onto the fire brigades, as the only approval authority in the room.

2.3. Areas of technical understanding

Fire brigades everywhere have experienced officers to plan operational responses and review firefighting provisions in the light of those plans. The experienced firefighters have a clear understanding of the value of each provision and the consequences of its presence or absence. The level of understanding of risk and other engineering analyses is far more variable. A fire officer planning a fire response does not need to consider probabilities as the particular fire is assumed. That is; it is taken for that purpose as having a probability of 1.0.

In any particular jurisdiction, it may be many years between tunnel projects. For this reason, it is likely that staff from all parties will be relatively new to the issues.

If a fire service feels responsible for risk decisions, but has limited ability to engage in the technical arguments, the ‘caution margins’ increase and an emphasis on chasing risk even lower can be accentuated.

The lack of appreciation of risk and decision making can be project-wide. When this occurs, we can see safety ‘proven’ by deterministic analyses with somewhat arbitrary inputs and no resulting handle on risk or whether it meets any of the ‘ARPs’ (ALARP, SOFARP, ANARP, etc). The author discussed this aspect in 2012 [1].

2.4. Adherence to process

Around 2001, particularly in Victoria, there was a perceived problem with the standard of some fire engineering reports for buildings. The Australian Building Codes Board published a document which later became the "International Fire Engineering Guidelines" (IFEG). While the intention may have been to engender a more rigorous approach from the less scientifically inclined practitioners, it also became applied as a rigid approach by some of the less scientifically able practitioners. The parts of the IFEG which grant the engineer freedom to rearrange the process to suit the project are ignored by the rigid process adherents.

One manifestation of this issue is that the linear 'process' starts from scratch at each project stage. Specifications and provisions agreed between government and fire brigade at preliminary design stage are all opened up for re-'fire engineering' in a fresh 'process' at the start of a contract. In effect, the approach annuls the contract, in that the provisions above the collective signatures are no longer sufficient unless once again "agreed by stakeholders" through the 'process'. In addition to not being inside the contract, the brigades may have new staff between the two project phases.

Rigid process adherents can also generate logical nonsense when the progress or the facts don't fit the process. To paraphrase: "We can't review your risk report on how you want to use your smoke ducts because, in the process, we must first agree the Fire Engineering Brief. We don't agree the Fire Engineering Brief because of how your trial design uses the smoke ducts.

The above examples are Australian. In the US, projects often have a designated 'code engineer' whose job it is to identify and ensure compliance with any relevant codes, without necessarily having a grounding in the technical area described by the codes. This is a different layer of process, sometimes more technical than the Australian one, but still with its risk of producing poor results. One example result is dry sprinklers over a fire-sterile rail platform, isolated by valves that the fire brigade say they will never turn on.

Regardless of the jurisdiction, a rigid adherence to process, to the exclusion of common sense, can only serve to confuse the mechanism for acceptance of risk and cost. Besides the threat to sensible design outcomes, it can consume undue amounts of time from project directors on political matters which ultimately have little impact on the constructed outcome.

2.5. Unspoken realities

There is a non-zero risk in anything we do and the risk from fire in a tunnel seems to be amplified in the mind. Because it is difficult to be seen acknowledging that there is such a risk, it makes it doubly difficult to reach a conclusion that provides other than the absolute minimum risk, regardless of how tiny the remnant risk is. On many projects, the roles and responsibilities around achieving that safety also become taboo subjects, with the apparent mismatches in authority, responsibility and, sometimes skill, not discussed. The taboos will be overcome when funding and risk acceptance come together.

2.6. Lost opportunities

A consequence of the fire brigades becoming a de-facto design and risk acceptor, in isolation from costs, can be that conversations become skewed to a less collaborative style. A lack of design progress was once explained sufficiently by noting that everyone had been so busy with the politics, we had forgotten about designing. The fire brigades can be an invaluable design partner in planning the infrastructure and the response in a holistic sense. A successful project structure will capture the unencumbered inputs and advice from the operational fire brigades.

3. THE CHALLENGE

The challenge for projects, jurisdictions, and perhaps for the transport tunnel industry as a whole, is to work out how to govern the fire safety decision making to get to the right answer for the community and in a way that facilitates projects. This particular challenge is separate from questions about how to evaluate risk, or how to design deluge. It is about who has authority to decide such things, who wears the remnant risk, and who bears the cost. The 'R' in all of the 'ARPs' stands for 'reasonably', and so the challenge is also partly about nominating an arbiter of reason.

4. ESSENTIAL ELEMENTS OF A GOVERNANCE FRAMEWORK

4.1. Acceptor of Risk

The first requirement in setting up project governance of fire safety is to realise that the role of Acceptor of Risk is a critically important one and it matters who it is, for smooth and productive decision making. The realisation having been achieved, the Acceptor of Risk needs to be answerable to the community in some way and to have community interest as a primary driver. That really means that it needs to be an arm of government, or someone implicitly trusted by the government proponent. On safety matters, the fire brigade fits that description and for that reason they often are nominated into or assume the role.

The other quality that is important in the Acceptor of Risk is the ability to make rational cost-risk trade-offs. This is the characteristic most often missed. It is typically not part of the expertise of the fire brigades, who have no project cost connection at all. The requirement for the Acceptor of Risk to also be the approver of costs really restricts the role to the government proponent.

An alternative Acceptor of Risk is the government treasury or finance department. Economists in most government treasuries will be able to find an estimate for the economic value of life, although it will probably be called something more like; the economically justifiable expenditure to avoid a fatality. The reality is that government funds are limited and when making decisions about which remote hospitals to improve, which level crossings to grade-separate, and which intersection black-spots to fix, the cost-benefit ratio of each initiative has a value which is in units of $/life. The value may be compared to that for other initiatives and to the benchmark value.

The fact that deaths due to fire in a tunnel are a realistic possibility can be confronting. We can avoid that discomfort if we don't look at costs but just install every feature imaginable, such that there is the appearance of risk being absolutely as low as possible (ALAP?) rather than ALARP or SOFARP etc. It is the injection of reasonableness into the risk outcome that requires the funding decision makers to be involved. However, treasury officials usually do not want to get involved in the detailed decisions on a project, preferring to fund to an expected community outcome and budget.

Practically then, this means that the government project proponent, who also has the cost drivers, must stay centrally involved in the risk acceptance, and not pass it on or allow it to be usurped by others. This may seem like a really simple point, not deserving of elaboration in this paper. However, from the projects where this aspect has been seen to go wrong, the point that cost and risk acceptance need to be tied together in the government proponent warrants the exposure given.

4.2. Risk benchmark

This is not really part of the governance framework, but a criterion that can be passed on to the project team by the Acceptor of Risk. The 2012 Graz Tunnel Safety and Ventilation Conference had many papers on the evaluation of risk. It is suggested that, for modern road tunnels, quantitative risk analysis (QRA) will only show you that the risk from fire in the tunnel is vanishingly low. The risk is likely to be three orders of magnitude below the road traffic risk from all causes, or lower. QRA is unlikely to give design guidance in an absolute sense.

The Australian Standard on Tunnel Fire Safety AS4825 suggests a figure of two orders of magnitude below the prevailing road use risk. That benchmark was written with the express knowledge that it would take QRA, and all the arguments around it, out of the design decision process for new tunnels. A discussion on this was given in Graz in 2012 [1]. It is argued that, regardless of absolute risk, ‘reasonable’ efforts need to be made to prevent unsafe (stopped) traffic, facilitate self-rescue, control smoke, facilitate asset protection by the emergency services, and assist rapid resumption of operations.

In that context, the role of Acceptor of Risk requires the exercise of judgement on reasonableness more than it does the numerical comparison of a risk figure with a pass mark.

4.3. Clarity on other roles

When the responsibility for risk and cost is clarified, it will be clear that other parties do not have that role. There are still many interactions where early, documented definition and agreement can avoid parties working at cross purposes.

For a complex project, there may be road and/or rail operators separate from the project proponent. Rail is interesting because most rail operations maintain a ‘safety file’ or ‘safety case’ describing how their operation is run to keep risk appropriately low. Some roads do this also. The relationship between such safety files and the project design needs to be considered and preferably agreed beforehand.

The local government area of the project will most likely have building regulations or by-laws relating to fire safety. This will affect control buildings and other ancillary spaces and may affect the tunnel itself. It is best if the extent to which they apply to the project is clarified for all at the start. To the extent that building by-laws apply, a Building Certifier may be involved and have interaction with the fire brigades, the designers and reviewers. While perhaps already known, those interactions are worth describing briefly.

If there is to be a peer reviewer involved, it is most likely to be to assist the Acceptor of Risk to come to terms with the choices, by offering an additional view.

Of course there will be designers, possibly as consulting engineers, in the mix as well. They are typically contracted either by the owner or by the contractor and so for these purposes they are part of those entities.

4.4. Project Agreement

In Queensland, over the last several tunnel projects, the project governance with respect to fire safety has been recorded in an Intra-Governmental Agreement (IGA). This step has been a contributor to the projects running generally more smoothly over time. While IGAs are agreements between different arms of government, they also assist the contractors and other parties by clarifying for them how to approach matters and by providing a hierarchy and framework around the information they prepare and the responses they get from government.

It is important that a project agreement, or governance framework in some form, be prepared prior to any contract. A contract prepared before the issues above have been acknowledged can lock in some of the difficulties. With the inertia of contracts between large organisations, it is then hard to unwind.

5. CONCLUSION

Fire safety design on many projects is made more difficult than it need be by inappropriate assignment of responsibilities and authorities. Where this happens, with few exceptions, it is not by intent, but due to a lack of awareness of the problems. The solution is a governance structure which includes the government proponent funding the project taking the role of Acceptor of Risk. In some cases, this will be sufficient on its own. For more complex projects, there will likely be a need to extend the framework to describe the expected inputs, responsibilities and authorities of a range of interfacing parties.

In some ways this conclusion is so simple and self-evident that it is bit of an anti-climax. Based on my early experience, I suggest that when deep in a project, the existing organisational structures can powerfully restrict recognition of the obvious. Whatever the reason, projects do go wrong in the ways described. The hope is that this paper will help some to avoid the pitfalls and achieve greater value and creativity in fire safety design.

6. REFERENCES

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UPGRADING OF THE AUSTRIAN TUNNEL RISK MODEL TURISMO – METHODICAL AND PRACTICAL ASPECTS

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ABSTRACT

After publication of the EC Directive 2004/54/EC on minimum safety requirements for road tunnels Austria introduced a performance based approach to road tunnel safety. The Austrian Tunnel Risk Model TuRisMo was one of the first methods defining a quantitative approach to analyse and evaluate road tunnel safety. The risk model was published in the RVS guideline 09.03.11 in 2008. After more than 5 years of practical experience in applying this model an initiative was taken to upgrade the model for a wider application. The activities to improve the Austrian Tunnel Risk Model are focussing on the following aspects:

- to implement additional parameters influencing fire risk in the existing, standardized model – in particular for unidirectional tunnels
- to open the model for simulations to be able to study individual parameters for individual tunnels specifically
- to systematically evaluate the data collected on tunnel accidents and fires in Austrian motorway tunnels since 2006 in order to get a more realistic model and to improve the input data basis for the assessment of (alternative) safety measures

In 2014 a revised issue of RVS 09.03.11 (TuRisMo 2) will be published, including the modification of the standardized method as well an expansion towards a simulation-based approach for the detailed investigation of specific problems which are not covered by the standardized approach.

Keywords: Risk analysis, risk assessment, tunnel safety, Austrian Tunnel Risk Model TuRisMo

1. BACKGROUND

1.1. Experience in the application of the existing Tunnel Risk Model

In Austria the safety-relevant requirements regarding both – constructive design and equipment as well as operation of road tunnels – are defined in the Austrian Road Tunnel Safety Law (STSG) and in the tunnel guidelines (RVS 09-Tunnel) of the Austrian Society for the Research on Road-Rail-Transport (FSV). Whereas the framework for the application of risk analysis is defined in the Tunnel Safety Law, the guideline RVS 09.03.11; Tunnel – Safety – Methodology of Risk-Analysis (published in 2008) [1] is dealing with the risk based approach in detail. In this guideline a standardized risk-based approach for the assessment of accidents and fires in road tunnels is defined, including the risk analysis methodology as well as an approach for risk evaluation. This risk model (called TuRisMo) is the standard tool for the risk analysis of road tunnels in Austria.

During 5 years of practical experience in applying the Austrian Tunnel Risk Model the focus has changed; whereas in the first phase of its application the focus was on standard cases e.g. to define the danger class of a tunnel, the emphasis later shifted towards applying it as a decision making tool, thus addressing new and more complex problems.

As costs are becoming a more and more critical factor for investments in tunnel safety, risk assessment is increasingly applied to evaluate the effects of different design alternatives and / or additional risk mitigation measures on tunnel safety in a quantitative manner, to be able to optimize the cost / benefit ratio.

This may apply for the early design phase of new tunnels but is even more relevant for the upgrading of existing tunnels as in this case much more restrictions apply than for new tunnels. The topics which have to be addressed are often linked to fire risk and the performance of the ventilation system in combination with the self-rescue facilities. The existing risk model offered only limited options to deal with these topics, as for fire only limited input data for model tunnels with specific parameters was available [2]. Hence activities were initiated to improve the existing Austrian Tunnel Risk Model.

1.2. Organisation and objectives of the upgrading process

In Austria guidelines for road tunnels are elaborated by the Austrian Society for the Research on Road-Rail-Transport. On the level of this society working groups are established involving the relevant stakeholders as well as experts from University and practice. In the case of RVS 09.03.11 the Austrian Federal Road Tunnel Authority, the Federal Ministry for Transport, Innovation and Technology, the main Austrian tunnel operator ASFiNAG, the Federal Fire Brigade Organisation and experts from the University of Graz as well as from private companies were involved. ILF Consulting Engineers was commissioned to develop the core part of the model.

The development was initiated from two sides:

- The topics which came up in practice and could not be assessed so far due to limitations of the existing model; compared to other risk models – e.g. the German model (which includes a simulation module), the ability of TuRisMo to address complex problems with respect to fire and smoke propagation and evacuation were limited.
- The much more comprehensive and illustrative data now available on tunnel collisions, fires and all kinds of parameters influencing tunnel safety, which was collected systematically since 2006 (in particular by ASFiNAG) and which significantly improve the options for a quantification of many influencing factors.

Hence, the focus of the work in the working group was:

- to widen the range of application of the risk model taking the practical problems – brought in by the stakeholders – into account.
- to implement the existing data as far as possible in the new model. For parameters, where limited or no data at all was available, expert judgement should be used additionally for quantification.

2. CHANGES IN THE RISK MODEL

2.1. Basic Structure of the risk model

The Austrian Tunnel Risk Model combines a set of different methodical elements to analyse the whole tunnel system in an integrated approach.

The risk model covers the personal risk of tunnel users. The result of the risk analysis is the expected value of the societal risk of the tunnel investigated. The respective shares of risk due to mechanical effects, fires and hazardous goods are shown separately.

The method consists of two main elements: A quantitative frequency analysis and a quantitative consequence analysis.

- Frequency analysis
  An event tree analysis is applied in order to evolve a set of characteristic incident scenarios (collisions and fires) and to calculate the frequencies of these scenarios.
- Consequence analysis – collision
  To estimate the damage of collisions, the method provides default values for individual collision scenarios (depending on vehicle involvement), which were derived from statistical data of tunnel collisions.
- Consequence analysis – fire
  To estimate the damage due to fires the method provides default values for different fire scenarios, which were calculated on the basis of simulations (smoke propagation and evacuation).

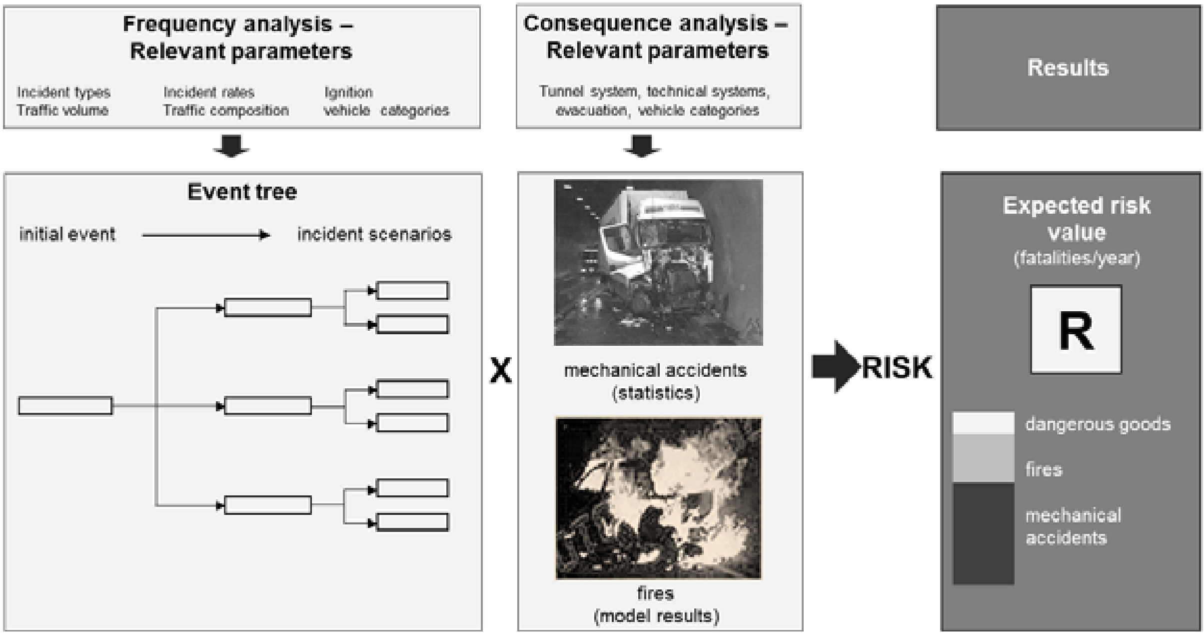

Figure 1: Structure of the Austrian Tunnel Risk Model

No changes apply to the basic structure of the risk model, as well as to the consequence analysis of collisions. However the other two methodical elements of the risk model are partly modified, in particular the consequence analysis of fires.

2.2. Structure of the event tree

In the event tree, the development of potential incidents is depicted addressing relevant parameters like traffic and vehicles. In the modification of the risk model special attention was paid to scenarios with congested traffic, because this traffic situation may have major influence on fire risk of unidirectional tunnels with longitudinal ventilation. Furthermore, these scenarios have to be addressed separately with respect to fire risk. Two types of congestion are distinguished:

- Congestion due to traffic overload
  In the new model, this type of congestion is addressed separately and introduced as individual independent branch in the event tree, because specific conditions occur with respect to airflow as well as exposure of people in case of a fire.
- Congestion as a consequence of a previous initial event (collision or break down)
  This type of congestion is relevant because it develops suddenly and can cause collisions and fires as a consequence. It is addressed separately for two reasons: There

are measures which may influence this type of collisions and – once again – specific conditions occur with respect to airflow and exposure of people in case of a fire, which differs from the other congestion type. For this type an additional branch is introduced in the event tree, which is linked to the previous initial events, collision and breakdown.

Furthermore the steps of the event tree analysis were expanded from 6 to 9, thus allowing for a clearly structured modelling of fire scenarios.

2.3. Basic incident rates and relative frequencies in the event tree

For the calculation of frequencies for the various incident types quantitative input data is needed. With respect to quantification of the event tree the general principle applies, that in the guideline default values are defined which may be modified, if significant specific data for a individual tunnel is available. The changes in the model with respect to the quantification of the event tree are based on tunnel incident data collected by ASFiNAG since 2006 (and before). Whereas relative frequencies referring to collisions (type of collision, vehicle involvement) are not changed, the basic collision rates as well as the relative frequencies related to fires were modified for the following reasons:

- There is a general decrease in the rates of collisions causing casualties in Austrian motorway tunnels [3].
- With respect to tunnel fires, a detailed analysis of data and information collected by ASFiNAG in the period 2006 – 2012 [4] covering 68 tunnel fires was executed to establish a basis for the definition of quantitative input data for the event tree.

All default values provided in the new guideline were defined after discussion in the working group, including expert judgement. Some characteristic examples are presented to illustrate the changes:

Supported by statistical tunnel incident data the basic collision rates were reduced by appr. 30% to stay abreast of the general increase in traffic safety (table 1)

Table 1: Basic collision rates for motorway tunnels in Austria

Basic collision rates		
	Unidirectional	Bidirectional
RVS 09.03.11 – 2008	0,112 / 10^6 veh-km	0,077 / 10^6 veh-km
RVS 09.03.11 – 2014	0,078 / 10^6 veh-km	0,054 / 10^6 veh-km

In the 2014 edition of the guideline – like in the original version – the basic collision rates are modified by parameters referring to traffic load and tunnel length, hence it is not admissible to conclude on the basis of the basic collision rates, that unidirectional tunnels have a higher frequency of collision with casualties than bidirectional tunnels (because the two basic rates refer to different average tunnel lengths and traffic loads).

With respect to fire, fires after a breakdown (caused by various kinds of technical failures in the vehicle or in the load) and fires as a consequence of a collision are addressed separately.

For fires after breakdown, a significantly higher frequency was found for HGVs in comparison to passenger cars. However, only a share of 38% is developing to a size which may endanger people; the majority expires by itself or is extinguished by simple means (data see table 2).

For fires initiated by a collision the relative frequency is depending on the type of collision; this type of fire typically is developing faster, hence it is assumed that 100% are reaching a critical size (data see table 2).

Table 2: Relative frequencies of vehicle fires

Vehicle category	Type of fire: Fire after breakdown
Passenger car	0,015 / breakdown
HGV	0,01 / breakdown
Type of collision	**Type of fire: Fire after collision**
Single car accident	0,012 / collision
Front – end collision	0,006 / collision
Head – on collision	0,020 / collision

Another aspect taken into account much more specifically in the new model is the development of HGV fires. Experience shows [4] that typically the fire takes some time to reach the maximum heat release rate, thus offering options for intervention. As the data allowed for a certain correlation between fire size and intervention time of fire brigade, an approach was implemented in the model which allows an assessment of the influence of the intervention time.

2.4. Consequence modelling of fire risk – modification of the standard model

In the standard risk model default values are applied for the quantification of damage in fire scenarios. These default values were calculated during the development of the risk model by applying simulations for different fire sizes to model tunnels, with variation of a predefined set of parameters (ventilation system, tunnel length, length of escape route). The range of model tunnels covered by default values corresponds more or less to practicable combinations of parameters admissible according to the Austrian guidelines, so that standard tunnels in most cases can be investigated by applying the standard approach. If parameters relevant for fire risk are not in line with requirements defined in the guideline, the standard approach cannot be applied; this applies for instance, if the capacity of a smoke extraction system is not corresponding to the values defined in the guideline. The reason is, that the simulations for the calculation of the default values were performed with these standard values and hence do not cover deviations.

Although the implementation of an approach including specific simulations as presented in chapter 2.5 was the main focus of the upgrading process, there was a consensus as well, that the standard approach should be retained and improved as well. This was done on the basis of the new detailed approach to take advantage of its increased potential.

With respect to the default values of the standard model the focus was on unidirectional tunnels with longitudinal ventilation for the following reasons:

- The predominant majority of tunnels on the Austrian (motorway) network are unidirectional tunnels; only a few bidirectional tunnels are left
- Many of the bidirectional tunnels are so specific that they cannot be covered by a standard approach anyway; to cover a rather small number of bidirectional tunnels would have required a high number of simulations and calculations for different types of model tunnels.

Hence for bidirectional tunnels the existing default values were kept, thus accepting a certain level of inconsistency in the standard model.

For the unidirectional tunnels different types of scenarios with respect to airflow and exposure of people were taken into account:

- Primary fire scenario:
  Fire in a situation with flowing traffic where the first vehicle is burning and all vehicles downstream of the vehicle on fire can leave the tunnel.

- Secondary fire scenario:
  Fire as a consequence of a collision at the end of a stopping convoy of vehicles, which is caused by a previous incident (high longitudinal airflow at the beginning; limited queue downstream of the fire, where vehicles cannot leave the tunnel).
- Tertiary fire scenario:
  Fire in the middle of a congestion, which has been caused by traffic overload; (low initial longitudinal airflow, all vehicles downstream of the vehicle on fire are trapped).

For these 3 types of scenarios default values were calculated, including a variation of the following parameters:

- Fire size: 5MW / 30MW / 100MW
- Tunnel cross section: vaulted / rectangular with 2 lanes
- Tunnel length: 0,5km – 4,0km (rectangular cross section); 0,5 - 8,0km (vaulted cross section); 0,5 - 1,0km (natural ventilation)
- Gradient: -3,0% / horizontal / +3,0%
- Escape route length: 125m – 500m

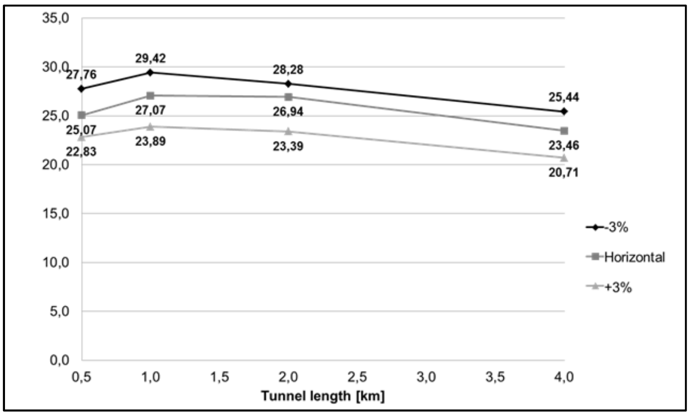

Figure 2:
Model values for damage in a secondary fire scenario of a 30MW fire
(example for rectangular cross section)

2.5. Consequence modelling of fire risk – the detailed model

The most relevant limitation of TuRisMo was so far, that with respect to fire risk it was limited to the default values defined in the standard model and hence to the underlying conditions. Therefore, it was often not possible to investigate tunnels with specific characteristics with respect to fire risk with the existing model. In principle, the application of simulations was also possible with the old model and in several risk assessment studies related to practical projects first steps were undertaken towards a simulation based calculation of damage values for fire scenarios. However, no specifications were available for this kind of approach.

The core element of the new detailed model integrates a 1D and a 3D CFD model and an evacuation simulation model. The application of the detailed model for consequence modelling of fire risk includes three different model fires (a 5MW fire scenario for passenger cars, a 30MW and a 100MW fire scenario for HGV's) and all relevant parameters (related to infrastructure, equipment and traffic) for the specific tunnel under investigation. When applying the model various parameter variations are performed in order to cover a broad range of different initial states as well as different possibilities of scenario evolvement.

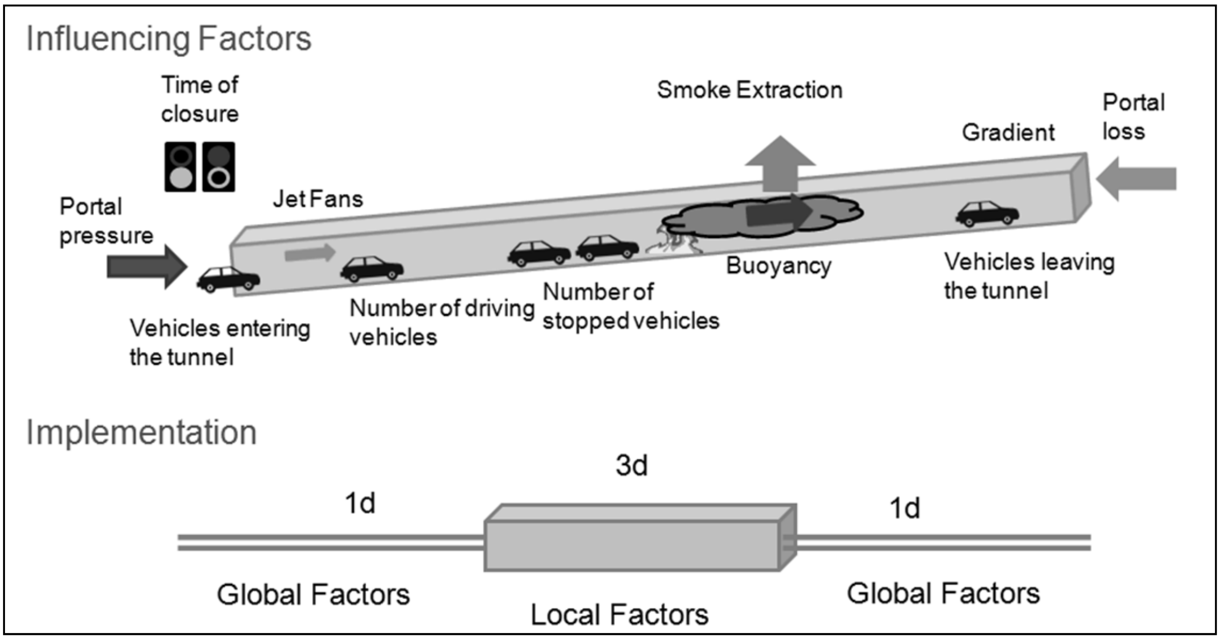

Figure 3: Relevant influencing factors in the transient 1D/3D smoke propagation model

As first step a one-dimensional simulation is carried out, which creates the boundary condition for the corresponding scenario in the 3D simulation. To model the time-dependant input parameters adequately a transient approach is applied.

All parameters influencing the longitudinal air flow conditions are covered in the 1D simulation such as:

- Movement and stoppage of vehicles in the tunnel
- Number and configuration of stopped vehicles in the tunnel
- Parameters influencing flow conditions like portal loss, drag at tunnel walls etc.
- Buoyancy depending on longitudinal inclination
- Development of effects of ventilation with respect to time

A relevant section of the tunnel around the fire site (can be longer than the actual tunnel length) is modelled in the 3D model, covering the following parameters:

- Detailed tunnel geometry (cross section, local gradient)
- Traffic configuration (local turbulence due to vehicles)
- Heat transition to tunnel walls, smoke stratification
- All local effects of ventilation

The output of the 3D modelling – the extinction coefficient (describing the visibility conditions) and the flue gas concentrations (describing the tenability conditions) at a height of 1,6m – is transferred directly into the egress model influencing the movements of escaping people in the tunnel. The visibility influences walking speed, whereas the accumulated flue gas concentrations may cause immobility, if defined thresholds are exceeded [5] [6].

In a next step the fire site is shifted systematically along the tunnel axis, in order to cover all emergency exit configurations relevant for the scenario under investigation. The result can be described as zones with different survival probabilities, which in the final step are superposed with those areas, where vehicles are present (close to the fire site as well as in all tunnel zones located next to a location, where the traffic can be stopped). The damage values of the individual scenarios multiplied by the respective probabilities are finally summarized to calculate the statistically expected damage value for a basic fire scenario. This procedure is applied for all scenarios investigated.

Furthermore, the variation of the following parameters shall be covered to some extent, depending on the specific situation of the tunnel under investigation:

- Unidirectional tunnel: separate investigation of each tube
- Traffic: three different traffic scenarios, representing low, average and high traffic situations, thus covering varying exposure as well as well as different flow conditions; in case of bidirectional tunnels the symmetry of the traffic is covered by three sub scenarios for each basic traffic case; a method is defined how to deduce these representative traffic scenarios from statistical traffic data
- Fire location: depending on gradient, changes in cross section and tunnel length 2-5 fire locations should be investigated
- Meteorological influence: if relevant, representative portal pressure differences shall be taken into account

3. CHANGES IN THE APPLICATION OF THE MODEL

3.1. Risk evaluation

For the final step of the risk assessment process, the evaluation of the results of the risk analysis, a twofold approach is applied:

- The absolute risk level is taken as basis for assigning the tunnel to one (out of four) danger classes. In the Austrian Tunnelling Guidelines a categorisation system consisting of 4 danger classes is applied to determine the levels of performance for parts of the civil design as well as the equipment of the tunnel.
- Risk evaluation by means of a reference tunnel; this reference tunnel is defined as a characteristic tunnel which assures, that all minimum safety requirements subject to the Austrian Tunnel Safety Law (which are applicable to the tunnel under investigation) are fulfilled. For this reference tunnel a reference risk profile is determined, applying the same risk analysis method (and the same parameters except those which are different in the reference case), which hence represents an acceptable safety level.

In the updated guideline this approach was not changed, however, the requirements for the reference tunnel are specified much more in detail in order to overcome ambiguities. The definitions for the reference tunnel include traffic parameters, some aspects of the tunnel system and geometry as well as requirements for the ventilation system.

One specific aspect in Austria is, that the technical requirements according to the RVS-guidelines are stricter and more specific than the minimum safety requirements according to the Austrian Tunnel Safety Law. Hence the risk level of a tunnel in line with the guidelines is normally below the reference case. However traffic parameters or other special characteristics may cause additional risks which have to be compensated by additional safety measures. For instance a slip road belonging to an interchange connected to a tunnel is not considered in the reference system hence the additional risk has to be compensated.

Temporary phases with bidirectional traffic are addresses separately: The risk of such situations has to be assessed, but the requirements with respect to the reference tunnel are less strict.

Another new element in risk evaluation is the inclusion of activities of the rescue services. In addition to the parameters already involved in the risk model, specific positive or negative conditions can be included in the final evaluation of the results in a qualitative way. In this context, an intervention time of the fire brigade of 15 minutes is defined as characteristic reference value.

3.2. Risk mitigation measures

The updated model, in particular the detailed version, is enhancing the options for a quantitative evaluation of the effects of risk mitigation measures a lot, in particular with respect to fire risks; however, with respect to measures influencing the frequency of tunnel collisions, a certain need for further research is remaining.

For the selection of the most suitable risk mitigation measures two principles are defined:

- The measures should specifically address topics, where specific problems were identified in the risk analysis.
- The ALARP (As Low As Reasonably Practicably) principle is established thus introducing a cost-effectiveness approach for the selection of measures

4. EXPANSION OF THE RANGE OF APPLICATION OF THE RISK MODEL

It was a key objective of the upgrading process from the very beginning to widen the range of application of TuRisMo to be able to address various kinds of specific problems as well as measures to mitigate these problems in a quantitative manner. In particular the owners and operators of tunnels are interested to display investments into tunnel safety in a quantitative way in the risk balance, including the option to bring in innovative solutions. Hence, a short summary of typical questions is presented which can be addressed on the basis of the enhanced model.

Tunnel geometry and tunnel system:

- In the detailed model, the individual detailed structure of a tunnel is taken as a basis; hence all characteristics and irregularities of an individual structure are implemented in the study, such as varying emergency exit distances (real configurations), changing tunnel cross sections, changing gradients etc.
- The effect of a continuous emergency lane can be assessed as well as the distance of lay-byes.

Traffic and operational aspects:

- In the detailed model, a transient approach is applied. Hence the influence of vehicle movements and all kinds of influencing measures can be addressed, such as a speed regulation or location and type of facilities for stopping the traffic in front of and / or inside the tunnel.
- Specific traffic situations and special traffic characteristics can be assessed.
- Time delays in detection as well as the reaction of relevant safety systems (like ventilation) can be taken into account.

Fire and smoke control:

- Combined ventilation systems can be studied as well as all kinds of unconventional ventilation solutions (e.g. local extraction or injection).
- The specific capacity of a ventilation system (including local anomalies like varying extraction capacities or leakages) as well as the operational strategy (e.g. operation mode over time, modification of airflow velocities) can be assessed.
- As secondary fire scenarios are also included, the effects of a longitudinal ventilation system in a long tunnel can be studied in detail.
- Specific meteorological situations (like strong winds or barometric pressure differences at tunnel portals) can be studied.
- The effects of fixed firefighting systems can be implemented in the model; however, this requires specific data form real fire tests and a modification of the 3D-model.
- Early intervention for firefighting can be assessed.

5. CONCLUSIONS

After more than 5 years of practical experience the Austrian tunnel risk model TuRisMo was upgraded by implementing new data and additional parameters. In addition to the standard model a new detailed model with a simulation based approach was developed, thus increasing in particular its capabilities for a detailed investigation of factors influencing fire risk.

The standard approach is easily and quickly applicable by implementing default values in an event tree based on a spread sheet approach whereas for the application of the detailed model a complex simulation environment has to be set up, which requires much higher resources and specific knowledge and experience of the user.

TuRisMo 2 is well suited to perform all kinds of risk-based studies such as

- Select the best design alternative or combination of risk mitigation measures available to minimize risk.
- Identify the most cost-efficient solution to fulfil the minimum safety requirements
- Quantify the effects on risk of specific shortcomings in existing tunnels (e.g. in the ventilation system).
- Quantify the effects on risk of potential compensation measures and identify the most cost-efficient combination of compensation measures.

TuRisMo 2 will be published in 2014 in a revised issue of RVS 09.03.11, including the modification of the standard method as well as a guidance to the new detailed approach.

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DEVELOPMENT OF A RISK ASSESSMENT METHOD FOR FIRE IN RAIL TUNNELS

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1. ABSTRACT

In the field of rail tunnel fire safety the concept of risk analysis plays an important part in the creation of a fire safety design that meets the objectives of the different stakeholders. For rail tunnels, there is very little information available about how to perform a quantitative risk assessment. Therefore, research on this topic has been conducted in order to develop a risk assessment methodology able to quantify the risk for people present in a tunnel.

The problem is approached by means of an extensive literature study in which the deterministic cause of fires in tunnels is investigated. From this, the major contributing factors leading to disastrous events are determined. Next, a bow-tie structure was chosen for representing the risk assessment model. For the construction of the event tree part of the bow-tie, a closer look is taken at past accidents. From these experiences, the most important factors are determined to be: Human behaviour, fire growth curve, ventilation conditions, safety systems and population distribution. These factors are incorporated into the event tree by using pathway factors. After determining these factors, the frequencies are calculated for each branch outcome. The data obtained for these frequencies is based on European research projects, fault tree analysis and engineering judgement.

For the determination of the consequences, the method is assisted by three integrated models: The Smoke spread, Evacuation and Consequence model. The models can take all types of geometry and materials, human behaviour and different susceptibilities of people for smoke into account. Together, they determine the possible number of fatalities, by means of a FID value, in case of a fire in a rail tunnel.

The final risk is presented by the expected number of fatalities, the individual risk and the societal risk. The societal risk is demonstrated through visualisation of an FN-curve.

Keywords: Quantitative risk assessment, risk analysis, rail tunnel, FID, sensitivity study

2. INTRODUCTION & OBJECTIVE

For tunnels in general, the concept of risk analysis plays an important role to create a fire safe design that meets the objective of the different stakeholders. For road tunnels, many regulations, standards and directives are available as guidance. For rail tunnels however, the amount of reference documents is much scarcer, which leaves an important role for the designer. Relying solely on engineering judgement may lead to different safety levels for different rail projects. As a significant part of designing fire safety systems is based on extreme events, it is of crucial importance of making the process of risk analysis more objective. As the probability of having a fire on a train in a tunnel is reasonably low, but the consequences can be extremely high. That is why the need for an appropriate risk analysis methodology for rail tunnels would contribute to making an acceptable fire safety design with consensus of all the stakeholders more objective.

When dimensioning safety systems in an underground infrastructure, the main influencing parameter is the design fire. There is a wide range of possible fire scenarios occurring in underground structures and one can always think of a scenario that is more worst-case. In recent years some very extensive measuring campaigns [1] & [2] have been performed that show the possibility of reaching really high peak heat release rates for rail carriages under specific boundary conditions (e.g. ignition source and reaction to fire of materials).

A question that automatically comes to mind is, should we be designing all tunnels where trains are allowed based on a 55 or 70 MW design fire? The problem of a purely deterministic approach is that the design will have an acceptable result for the design fire scenario the design team considers "realistic worst-case". In order to add a more objective way of dealing with the safety level, there is a need to add a probabilistic element in the analysis, in the form of a distribution curve. Therefore, research on this topic has been conducted at FESG and further developed into a tool during an IMFSE or International Master in Fire Safety Engineering thesis in cooperation with the University of Ghent.

The purpose of the study is to develop a quantitative risk assessment methodology able to quantify the risk for people present in the tunnel. The main objectives within this requirement is that the methodology:

- Should be developed in a way that it enables the user to compare different alternative solutions with each other;
- Should compare these alternative solutions with predefined acceptable risk criteria.

The research focuses only on passenger transport and is divided in four main parts. The literature study, the development of the methodology, the case study and the sensitivity analysis.

3. LITERATURE STUDY

As a means of determining the most optimal approach for the quantitative risk assessment model, research has been conducted regarding risk assessment methodologies used for tunnels in European countries and in other types of infrastructure. The study showed that within near future possibilities of computational capacity, statistical data acquisition, etc. the bow-tie model (Figure 1) could be a suitable method to approach this problem.

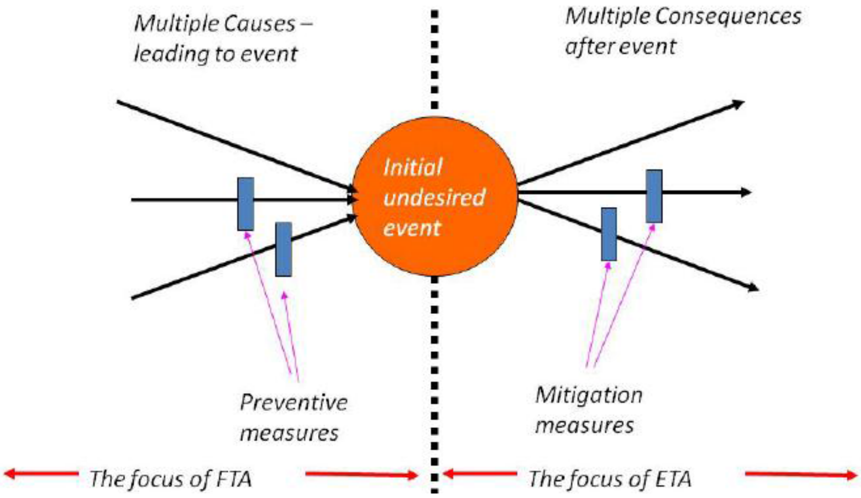

Figure 1: Concept of the bow-tie model. Taken from [1].

The bow-tie model is a combination of the fault and event tree analysis (FTA & ETA) with a critical event in the middle. This technique requires formation of fault structures at the left side and branch scenario's at the right side of the critical event. In this respect, risk is analysed from an engineering point of view by multiplying frequency and consequences. Every branch scenario has its own frequency and consequences in terms of fatalities per year. By providing preventive safety measures in the FTA and mitigation safety measures in the ETA part it will be possible to reduce the negative effectives from fire situations.

4. DEVELOPMENT OF THE METHODLOGY

The bow-tie model for fire situations in rail tunnels was constructed by analysing past accidents. The most important factors which may lead to the sequence of events were determined to be: Human behaviour, fire growth curve, ventilation conditions, safety systems and population distribution. With this information, it was possible to indicate the most critical events which should be taken into account in the fault & event tree structure. In this case, two events are chosen to be the most crucial: the “Fire initiation” and “Stop in tunnel & fire in train” of which the second event is considered the most crucial one because in the first event the train has a significant probability of stopping before or driving through the tunnel.
The “Fire initiation” event is considered as the start of the event tree. Instead of developing a fault tree structure for this event, fire frequency data is collected from national governmental institutes and international research projects to determine the initial fire frequency in trains. After this initial event, six pathway factors are used to determine the second crucial event of “Stop in tunnel & fire in train”. These pathway factors give multiple branches of which several have the same outcome of a stop of the train in the tunnel. In order to reduce the number of possibilities, the outcomes are taken together and initiate the second event tree (Figure 2). In the second event tree five pathway factors are used for obtaining different outcomes. These pathway factors determine the fire growth scenario, detection & activation times, ventilation performance, the smoke free zone and the population density.

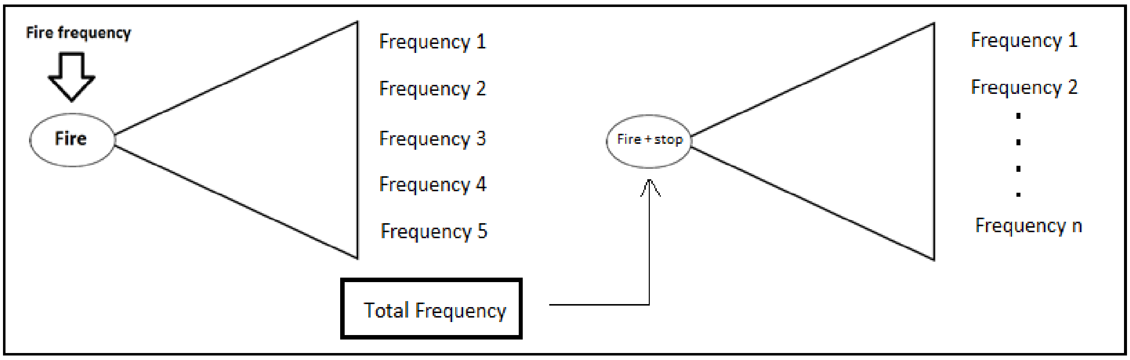

Figure 2: Concept of two event trees.

The quantification of probabilities of the pathway factors are determined by using [3]:

- Historical data: Incident data (i.e. accident), failure rate data (i.e. equipment failures) and failure probability data (i.e. human error).
- Fault tree analysis: Structured method to quantify initiating fire occurrence events by using technical specifications or failure rates.
- Engineering judgement: Probabilities based on expert judgement.

After determining the branch probabilities, the consequences for each branch outcome are evaluated. As a means of achieving the result in terms of fatalities per year, the methodology is assisted by three models: The Smoke spread, Evacuation and Consequence model.

The smoke spread model is needed to model the physical movement of products from the fire such as heat and smoke spread. The model should be able to take the following configurations into account:

- Complex tunnel and train geometry must be modelled. 3D-effect should be taken into account.

- It should hold the state-equations of conservation of mass, energy and momentum.
- Proper pressure losses should be modelled or imposed at the boundaries.
- The transient effects of fire development are of importance in evacuation circumstances.
- The model should be able to take different types of fire safety systems such as smoke and heat exhaust systems, different detection devices, train localisation systems, etc. into account.
- Proper output data must be provided for the evacuation model.

Two types of models are investigated. A 1D-model and a 3D CFD model. In order to obtain more realistic result the 3D model FDS [4] is considered to be more accurate, especially for larger and more complex cross sections. By comparing simulations of 1D and 3D models, it was found that 1D models tend to underestimate the smoke concentrations above the evacuation path. Secondly, the output of the 3D model was found to be more appropriate to use as input for the evacuation model.

The smoke spread model requires various input factors of which the most important regarding toxicology of products of combustion for fire in trains are studied. According to Purser [5], the CO and HCN asphyxiant gases are the most relevant toxic product of combustion relating to incapacitation and death. Therefore, these product were studied together with soot products for visibility.

For the CO-yield, Babrauskas [6] stated and confirmed by [7] that the generation of CO is largely determined according to the oxygen available for combustion (Figure 3). Depending on the fuel, the yields could vary between 0.13-0.18 g/g. However, in German guidelines [8] lower values between 0.02-0.08 g/g are advised. The difference can be due to fact that the higher values are from bench-scale and the lower German values are advised based on large scale experiments.

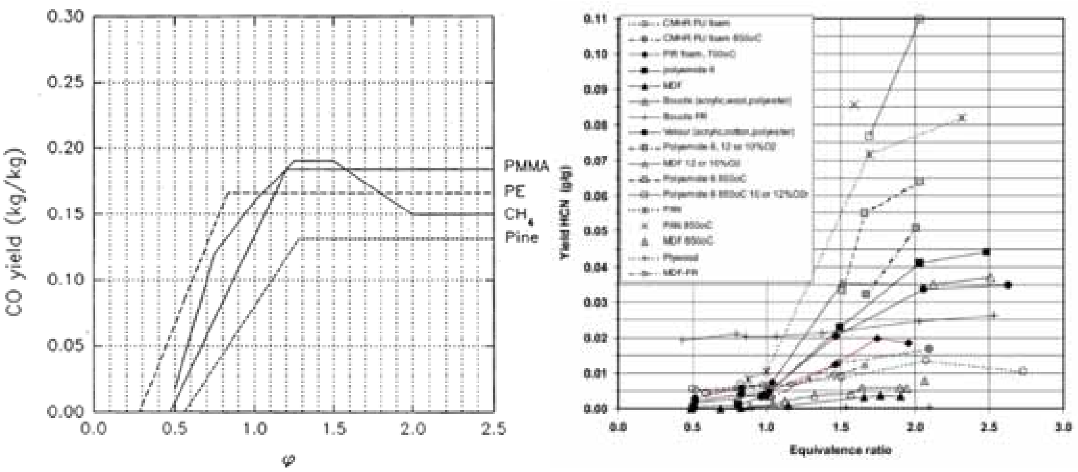

Figure 3: CO yield in terms of equivalence ratio measured in catcher hood experiments (Left) [4] and in the tube furnace (right) [7].

HCN concentrations are more material dependent. HCN can only be created if nitrogen is incorporated into the fuel. According to Purser [9] the HCN-yield is as well related to the equivalence ratio. However, the spread is higher due to material dependency. Consequently, it is advised to determine the materials which are likely to burn in case of fire in a rail car and link the corresponding average weighted value to HCN-yields.

The third component taken into account is the soot-yield. The German guideline [8] advises values between 0.03-0.15 g/g for rail cars.

The output data obtained from the smoke spread model is used as input for the evacuation model, which is able to take complex interactions between evacuating passengers and products of combustion into account. The purpose of the model is to determine the heat and toxic gas doses of the different products of combustion for each person which is exposed to the fire and smoke during evacuation.

In order to choose an optimal evacuation model, the main parameters which should be taken into account for rail tunnel fire circumstances include modelling the following configurations:

- Tunnel and train geometry should be able to be taken into account.
- The evacuation transition from the train to the emergency walkway and from the walkway to the emergency doors or tunnel portal.
- The model should determine the optimal way of evacuation without predefining necessary evacuation routes.
- Distributions of pre-movement times, walking speeds, population types, etc. should be taken into account. Especially, walking velocity variations will have a large impact on evacuation times because it has been encountered that, in smoke filled tunnels, people tend to walk in one row behind each other next to the wall in order to have a guidance from that wall during evacuation [10]. This means that slower people will tend to hold other people up.
- Aspects of human behaviour should be taken into account, e.g. people and place affiliation, keeping interpersonal distance between one another, reduces walking velocities in case of high people densities.
- The time dependent effects of smoke should be taken into account. The effects of visibility and irritant gases should have an impact on evacuation flow.
- The model should take different types of safety systems into account such as voice communication, passive and dynamic evacuation signalling, improved walkways, handrail, etc.
- The output data obtained from the model should in a useable form in order to determine the effects on each person.

Additionally, in case of an evacuation out of train into the tunnel towards an emergency exit, the effect of merging flow phenomena can be of importance. Several experiments have been performed in the past. A paper by Oswald [11] showed the effect of merging flows when evacuating the train. The figure below shows people flows at the different doors of the trains. The horizontal lines at the different doors in the graph indicate that people need to wait until a large part of the carriage in front of them is emptied. This could mean that merging becomes a less dominant factor. However, this was not the case for every train carriage (door 7 and 8).

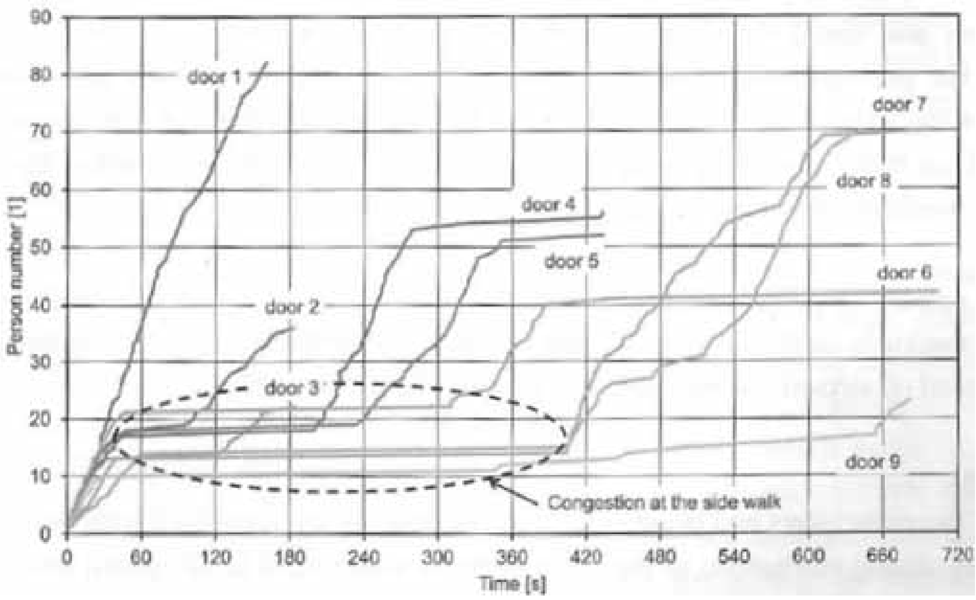

Figure 4: Person flows at doors 1 to 9 at the evacuation of a train in a simulated tunnel situation [11]

Taking these attention points in mind, the model STEPS [12] is chosen to model the evacuation circumstances in the tunnel because it takes the most important above mentionned phenomena into account.

The third model used is the consequence model. This model is developed to convert the concentrations, obtained from the evacuation model, corresponding to each person in the tunnel to a fatality rate per scenario. In order to estimate the effect of fire on people in the tunnel the main sources of hazard should be investigated. These are heat, radiation, irritant and asphyxiant gases. In case of a fire in a tunnel, the most significant factor for incapacitation is likely to be asphyxiant and irritant gasses. Heat and radiation will be less significant due to the ventilation conditions, the fact that fire is shielded for a large part inside the train and the large distances people have to travel inside the tunnel.

In the model, the effect of asphyxiant gases (CO, CO_2, HCN and low O_2) and irritant gases are taken into account by means of correlations formulated by Pursers [7]. In contrast to the ISO 13571 [13], these correlations take the non-linearity of different types of concentrations into account. Purser combines the correlation and uses one value in order to determine whether a person becomes incapacitated or not. This is the FID or Fractional Incapacitation Dose. The FID is in principal the ratio of the dose for a gaseous toxicant produced in a given test to that dose of the toxicant that has been statistically determined from independent experimental data to produce incapacitation in 50 percent of test animals within a specified exposure and post exposure time. The FID is determined for each person exposed to the fire and smoke. When the value becomes unity it is assumed that the considered person will incapacitate and is likely to result in a fatality [7]. The visibility is taken into account by use of the Yin Yamada correlation [14] which takes the walking velocity as function of the extinction coefficient into account.

The use of the above mentioned correlations represents the population of healthy young men. However, in reality, not only these type of persons but also children, elderly, pregnant women, etc. take the train. Additionally, the chosen parameters in the correlations carry a large degree of uncertainty. Therefore, the susceptibility of different types of people is taken into account by varying the exposure dose for incapacitation in the FID correlation for CO:

$$F_{ICO} = 3.317 \cdot 10^{-5} \cdot [CO]^{1.036} \cdot V \cdot \frac{t}{D}$$

Where:

[CO]	CO concentration [ppm].
V	Volume of air breathed each minute [l/min].
t	Exposure time [min].
D	Exposure dose for incapacitation [%COHb].

The D value is varied by using data statistical data from primates which correspond closely to human properties suggested by Purser. The curves showed in **Figure 5** are a Normal and Beta distribution based on the same data. In the model the normal distribution is used because it is slightly more conservative. The volume of air breathed can be approach similarly. However, it will not only depend on age but also on walking speed and stress.

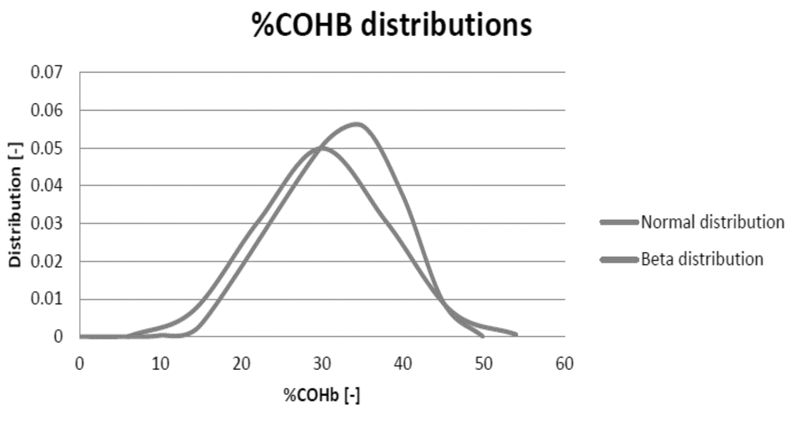

Figure 5: Normal and Beta distribution for the exposure dose for incapacitation.

Every person in the tunnel must be assigned one D value from the curve. This is done by random choice using Monte Carlo simulations. Each subject is assigned a D value which determines the final FID value. If the FID value is higher than unity, the person is considered to be incapacitated. This is done for every person evacuating and every run will give the estimated amount of fatalities. By running the model a large amount of times the final value will be an average fatality rate for each scenario.
The advantage of the above described models is that it can take all types of geometry and materials, human behaviour and different susceptibilities of people for smoke into account. Together, they determine the possible number of fatalities, by means of a FID value, in case of a fire in a rail tunnel. The final risk is presented by the expected number of fatalities, the individual risk and the societal risk. The societal risk is demonstrated through visualisation of an FN-curve (See following section).

As with all risk analysis methodologies, the importance of having the right probabilistic data is large. In order to address the uncertainty from the proposed input parameters, a sensitivity analysis must be performed. Two types of analysis are chosen (See case study):

- An individual sensitivity analysis is implemented in which the sensitivity of the most important input parameters is determined. The results are visualised in a tornado diagram.
- A collective sensitivity analysis is structured in which all significant input parameter are varied at once. The purpose is to determine the uncertainty of the end results. The results are visualised in an FN-curve.

5. CASE STUDY

The purpose of the study was to make a methodology which is able to be used in practical applications. Consequently, a case study is performed on an existing underground rail link. The goal is to show the possibility of comparing alternative solutions with each other. The part of the rail link studied is the combination of a 500 m tunnel section and a station. The tunnel contains 6 tracks and has a cross section of about 32 x 5.2 m². The traffic type chosen are 26 m long double-decker rail-way cars (Figure 6).

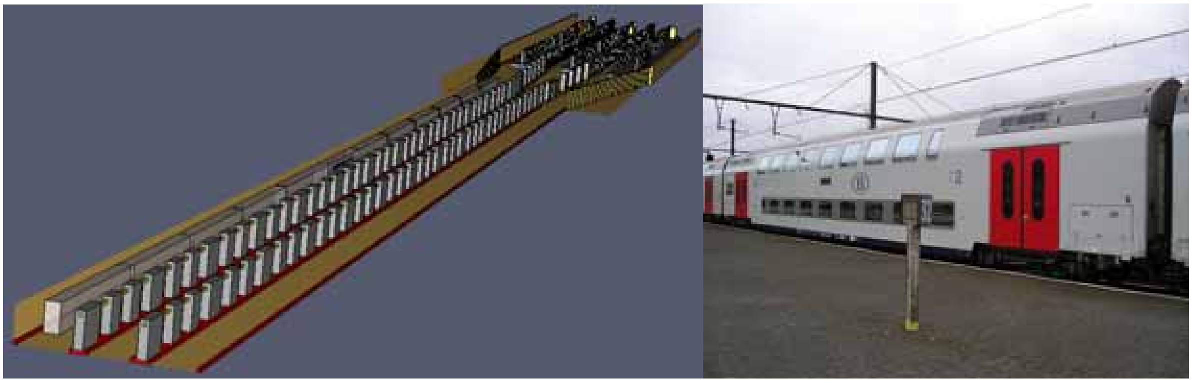

Figure 6: CFD model tunnel and station (Left) and Double-decker railway-car (Right) [15].

In order to compare different alternative solutions, several safety systems can be proposed. The systems are divided in two types: systems that are incorporated and systems which can be added in order to show the impact on the risk level. In the case study, the following safety systems are always taken into account: automatic brake stopping system, emergency response, alarm and voice communication system. The following systems are compared in alternative solutions: a linear heat detection system, a train localisation system, a longitudinal ventilation system and a brake overrule system.

In Figure 7, these safety systems are compared with each other and against two predefined limits, from Sweden and the Netherlands (straight lines). The Reference FN-curve shows the reference curve with no longitudinal ventilation, linear detection nor train localisation system.

The FN-curve below presents the effect of linear detection and longitudinal ventilation. The next FN-curve shows the effect of also adding train localisation. The last curve presents the consequences of adding additionally a brake overrule system.
The curves show a clear shift downwards when multiple safety systems are added to the concept. This is because basically the failure frequencies of each branch in the event tree are adjusted. In case all systems are provided, scenarios with high consequences will have lower probabilities than scenarios where few safety systems are chosen. Then higher consequences will occur more easily. When, in this case study, the two limits are take into account, then the FN-curve with linear detection, longitudinal ventilation and train localisation system could be considered acceptable.

Note that no horizontal shift is observed because only reliability data are taken into account which only changes probabilities. No efficiency data is used because no measures were applied which have an impact on for example smoke spread or evacuation times. In case different SHE systems would be applied, also the deterministic part of the FN curve will shift. In this way the effectiveness of the systems can be determined which in engineering terms is reliability times efficiency.

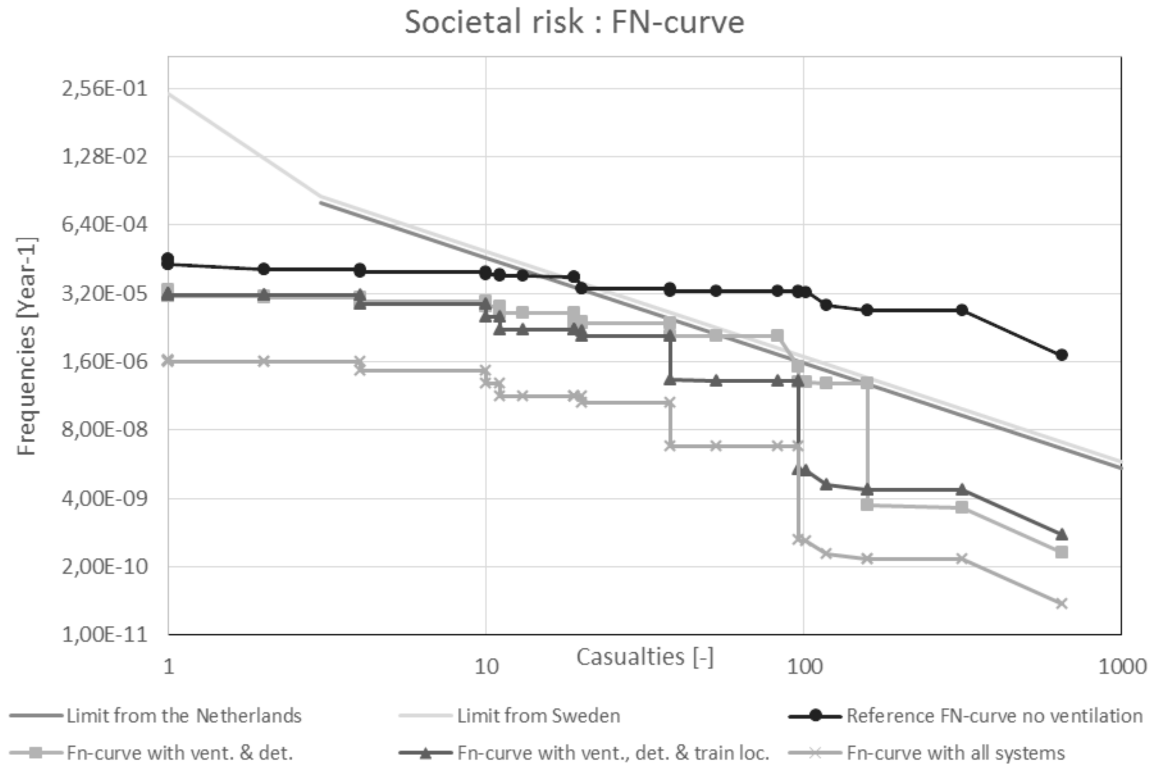

Figure 7: FN-curve case study with different alternative solutions.

As mentioned above, a sensitivity analysis is performed and divided in two parts. The first part studies the sensitivity of each parameter within certain ranges. In the second part, all parameters are varied at once and the overall result is compared with the Dutch and Swedish limits. The aim of the first sensitivity analysis is to show the influence on the outcome of varying each parameter individually. A range of input parameters have been studied. The most important input factors are assigned a possible range of frequencies and probabilities based on, fault tree data, historical frequencies and engineering judgment. The purpose is to show the sensitivity of each parameter by means of a Tornado-diagram. The Y-axe shows each parameter and the X-axe shows the standard deviation of the final risk value when each parameter is varied. By means of the diagram, the designer is able to determine the most sensitive input parameters which are useful when discussing the results with the end client and proposing additional measures.

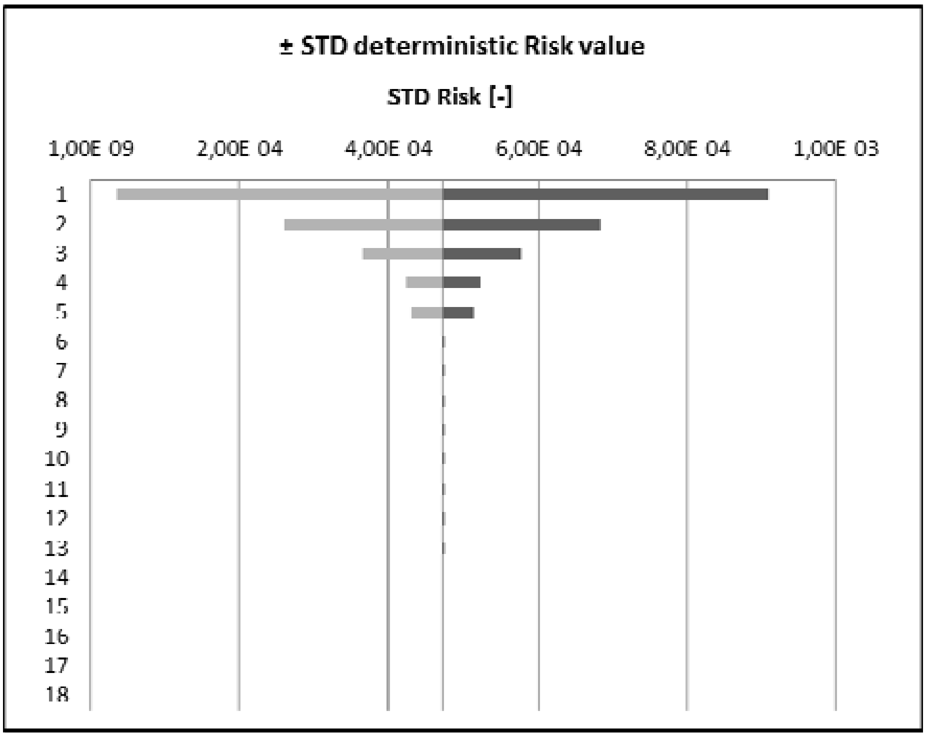

Figure 8: Tornado diagram of the sensitivity analysis.

The aim of the second sensitivity analysis is to determine the sensitivity of the concept when all parameters are variable. Depending on the type of input: uniform, normal or beta distributions are applied. The results in **Figure 9** show the effect of the sensitivity analysis. The upper bound (red curve) shows 2 times the standard deviation of the results. The figure shows that 2 points peak above the curve which means that within the chosen reliability interval the upper limit is not acceptable anymore. When these points are lowered by decreasing the standard deviation and thus the reliability, then the results will come at a certain point within acceptable limits. This means that a statement could be made about the reliability of the results and therefore about the reliability of the applied safety system. For example, in the applied case study, it could be said that the results are within the acceptable limits with an 84% reliability interval taking the predefined assumptions into account.

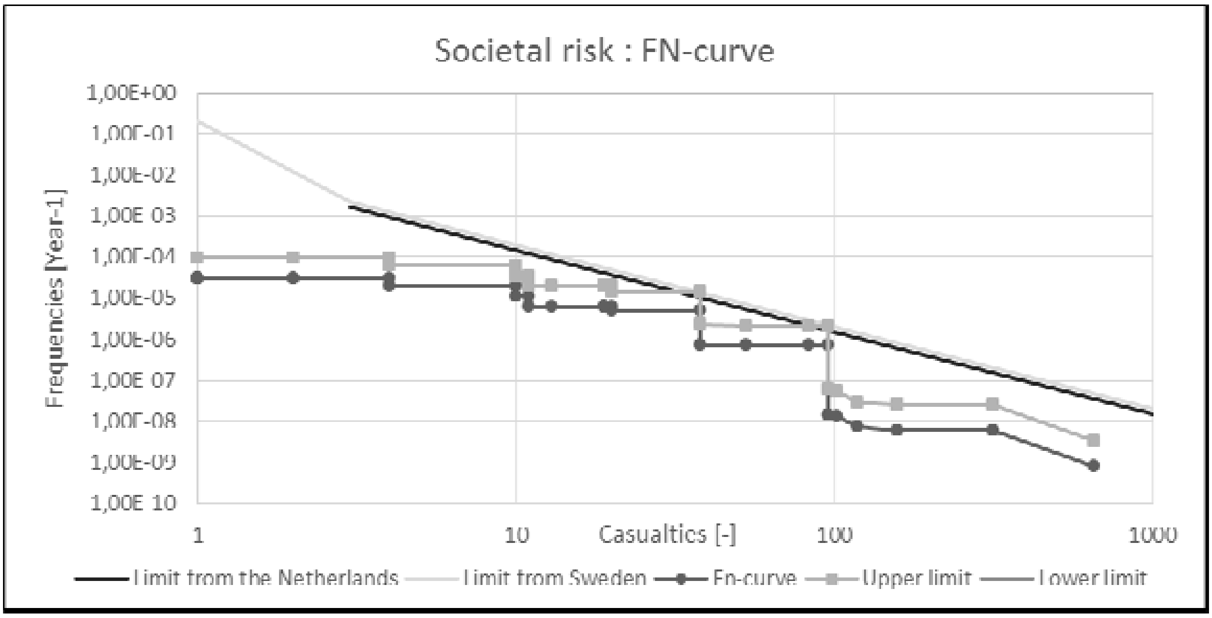

Figure 9: FN-curve for societal risk

6. CONCLUSION

The results show that the developed tool can be useful in, both new and upgrading tunnel projects, in order to determine what combinations of different fire safety systems (each time a different FN-curve) achieve which safety level. This way it is possible to select the most cost-effective combination of measures that lead to an acceptable safety level. The method backs-up the results by showing the effect of uncertainty on the reliability of the safety system.

7. ACKNOWLEDGEMENTS

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FIXED FIREFIGHTING SYSTEMS IN ROAD TUNNELS - GENERAL REQUIREMENTS AND CAPABILITIES

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ABSTRACT

Firefighting systems are increasingly being constructed and operated in road tunnels in a wide range of countries. However the reason for use is varies greatly from system to system; in the end it comes down to the choice of system. In 2014, ASFINAG is constructing the first firefighting system on the highway network in Austria in the City Tunnel near Bregenz. By 2017 at least one more system will be constructed – the one in the Arlberg Road Tunnel. So far two systems have already been fitted in Austria, one in the Felbertauern Tunnel and one in the Mona Lisa Tunnel.

The plans and choice of system have been discussed and decided with a focus on the latest guidelines and technologies; parameters such as route availability, maintenance frequency, pressure levels, water volumes, the drainage system, etc. were the crucial basic factors. Since the "Fixed Extinguishing Systems" data sheet did not set any binding guidelines in Austria, the new RVS 09.02.51 Fixed Firefighting Systems was created for ASFINAG's efforts based on the previous data sheet.

1. ASFINAG AND FIXED FIREFIGHTING SYSTEMS

In future, ASFINAG – the constructor and operator of the major road network in Austria – will construct firefighting systems in tunnels due to cost-efficiency issues. The first system will go into operation in 2014 with the City Tunnel near Bregenz, which is approx. 1.3km in length. In years to come, the intention is to investigate and assess more tunnels in accordance with the prevailing requirements – a further project has already been secured with the Arlberg Road Tunnel.

The reasons for constructing firefighting systems are complex. In addition to general points such as improving self-rescue and supporting firefighters in their fighting of fires, the detailed principle of operation is as follows:

- Reducing temperatures
- Reducing heat radiation
- Preventing fires from spreading
- Reducing the heat release rate
- Influencing the concentration of smoke gas

In its projects, ASFINAG primarily strives to improve fire safety for the structure in question, whereby any added value (rescuing people, etc.) will of course also be used for positive assessment.

The cost-effectiveness of a project is assessed by comparing active (firefighting system) and passive (fire protection panels) fire prevention. The costs of the entire life cycle are referred to here – so not just the construction costs, but also the costs for operation (staff, energy, maintenance, repairs, etc.).

2. CLASSIFYING FIXED FIREFIGHTING SYSTEMS

On an international scale there is a very wide range of manufacturers with very diverse philosophies regarding the design and technique behind firefighting systems. The following classification may help to develop a system here:

Table 1: Classifying Fixed Firefighting Systems

System	Extinguishing agent	Water-foam requirement	Nozzle pressure
Water deluge	Water	8-15mm/min	1-5bar
Water mist	Water	4-7mm/m² per min	Low pressure P < 12.1bar
			Medium pressure P > 12.1 bar and < 34.5bar
			High pressure P > 34.5 bar
Air foam	Mixture of water and foam	~ 6mm/m² per min	1-2bar

Classifying the water mist systems into low, medium, and high pressure corresponds with classification in accordance with NFPA 750.

A differentiation is made between water deluge systems and water mist systems in accordance with DIN CEN/TS 14972 and NFPA 750.

According to NFPA 750, the $DV_{0.99}$ characteristic diameter describes the diameter of the drops that fall below the size of 99% of the released volume of water. The CEN is defined in accordance with the $DV_{0.9}$ diameter with a proportion of 90%. Water mist systems are associated with cases where $DV_{0.9}$ < 1mm; where $DV_{0.9}$ > 1mm, it is a sprinkler- and/or water spray system. NFPA 750 differentiates between three classes of water mist systems based on the $DV_{0.99}$ characteristic diameter.

Table 2: Differentiation between water mist- and sprinkler/water spray systems

Class I	Class II	Class III
DV0.99 ≤ 200µm	200µm ≤ DV0.99 ≤ 400µm	400µm ≤ DV0.99 ≤ 1000µm

3. REGULATION AND GUIDELINES

The construction of firefighting systems in tunnels is fundamentally not regulated in Austria. The revised RVS 09.02.51 Fixed Firefighting Systems thus specifies how they must be constructed and what should be taken into account in the process. The important thing here is that in Austria only high-pressure water mist systems may be used in accordance with this Guidelines. The following points are also cited:

- Design principles
- Adding additives
- Spray specifications
- Criteria
- for release
- Operational aspects
- Verifying and testing

Thus RVS 09.01.45 Construction Fire Protection is significant if a firefighting system is constructed for fire prevention in structures. It cites the procedure for calculating the necessary level of protection – in other words, the amount of time in which the structure must stand firm in a fire.

Table 3: Overview of the various levels of protection

Level of protection	Duration of exposure to fire
0	None
1	30 min
2	90 min
3	120 min

In this guideline, a heavy good vehicle tank accident involving diesel fuel, within which a pool size of 100m² is used, is taken as a basis for fire load. Therefore, as a result of these standards, a firefighting system for use in construction fire protection in Austria must be measured beyond the standards stated in RVS 09.02.51.

Controlling this fire load using a firefighting system (in this case, a high-pressure spray mist system) was verified in 2008 in the Runehamar Test Tunnel in Norway. During these trials, solid- and liquid fires with various fire loads were created. Among other things, it was possible to successfully complete a trial with a 100m² diesel pool (corresponding to a fire load of 200MW) and an applied volume of water of approx. 4L/min and m².

Moreover, it must be verified in Austria that the measures also achieve the desired success and justify substituting passive construction fire protection methods using risk analysis in accordance with RVS 09.01.31 – Tunnel – Risk Analysis Model.

It goes without saying that we at ASFINAG are also guided through the planning stages by other international standards and guidelines and/or studies, such as:

- SOLIT^2 – Safety of Life in Tunnels
- DIN CEN/TS 14972 – Fixed Firefighting Systems
- NFPA 750 - Standard on Water Mist Fire Protection Systems

4. CITY TUNNEL FIREFIGHTING SYSTEM

The City Tunnel in Bregenz is a 1,311m-long tunnel on the approach road to the A14 Rheintal highway for Bregenz, the regional the capital of Vorarlberg. The tunnel was approved for traffic in 1984. The traffic operates in this single-tube tunnel in a bi-directional way. The standard section includes a 7.50m-wide lane with 0.85m-wide shoulders on both sides; it has a clearance of 4.70m.

The ventilation system consists of longitudinal ventilation (jet fans) with exhaust air extraction in a ventilation cavern which is positioned about a third of the way up the tunnel section.

The need to adapt the City Tunnel with fire protection is a result of the EU-Directive (in Austria STSG) which has set a deadline for 04.30.2019 at the latest. The reason for this is that the tunnel is being overbuilt, in particular in the section of open cut tunneling. This is why a significant amount of the neighboring buildings have been put at risk should a major incident with fire occur.

After the technical and safety equipment was completely redeveloped in 2007, a conceptual study revealed that subsequently installing a firefighting system was the most economic option. If passive construction fire protection had been installed, all of the tunnel equipment would have had to be dismantled and reconstructed – this is no longer necessary in the current system.

The implemented investigations have resulted in protection level 2 for the City Tunnel in accordance with RVS 09.01.45, which means designing a 90-minute service life for the firefighting system. With water exposure of 4L/min and m², this means:

- Constructing a 450m³ water container
- Constructing a pumping station with a motor capacity of 430kW
- The required volume of water in operation is approx. 60L/sec
- Constructing the water distribution system in the tunnel
- 23 remotely-operated valve stations for actuating the sections
- Adapting the tunnel drainage system

5. ARLBERG ROAD TUNNEL FIREFIGHTING SYSTEM

The Arlberg Road Tunnel is the longest road tunnel in Austria. The tunnel system, which is approx. 15.5km in length (including galleries) was put into operation as a bi-directional traffic tunnel in 1978. The Arlberg Road Tunnel has transverse-ventilation with supply air- and exhaust air ventilators in a total of 6 ventilation zones.

Between 2014 and 2017, the supply air duct was also fitted as an escape route in addition to the existing 8 escape and emergency routes between the road and rail tunnel – a similar design to the Felbertauern Tunnel. This requires constructing a total of 37 sets of collectors from the driving area into the channel above. It is also intended that the tunnel will be fitted with a firefighting system in order to curb the risk of the subceiling collapsing in the event of a fire.

The standards set in RVS 09.01.45 – Construction Fire Protection, SOLIT[2] and RVS 09.02.51 – Fixed Firefighting Systems are used as a guide when designing the minimum firefighting system's operating time. These standards specify that it should be designed for 120 minutes. This is also confirmed by fire fighters' working times as they arise in practice. During a fire incident on January 16th, 2013, the emergency services took approximately 12 minutes to get to the tunnel portal and a total of 22 minutes to reach the location of the fire. The entire chain of events was as follows:

Table 4: Estimating the emergency services' penetration time

Step during the incident	Time
Detecting the fire and alerting the emergency services	0 min
Triggering the firefighting system (delayed in accordance with RVS 09.02.51)	5 min
Time until the firefighters reach the tunnel portal	12 min
Reaching the start of the traffic congestion	16 min
Reaching the fire location and beginning of the extinguishing works	59 min
TOTAL TIME TAKEN FOR FIREFIGHTERS TO REACH THE FIRE	**59 min**

In accordance with the SOLIT² planning guide, the water supply must be enough to last double the timespan that the emergency services require to reach the fire (with due regard to the most unfavorable conditions such as traffic jams, etc.). In the Arlberg Road Tunnel's case, this timespan is therefore 118 minutes; this is covered by the requirements stated in the Guideline for Construction Fire Protection.

The water is supplied via both portals due to the extraordinary length of the Arlberg Road Tunnel. In turn, the following are details of what is required with water exposure of 4L/min and m²:

- Constructing 2 water containers, at 350m³ each
- Constructing 2 pumping stations with a motor capacity of 280kW each
- The required volume of water in operation is approx. 60L/sec
- Constructing the water distribution system in the tunnel
- 147 remotely-operated valve stations for actuating the sections

Once the tunnel drainage system in the Arlberg Road Tunnel will be completely renovated, the additional volumes of water do not need to be adjusted as a result of the firefighting system.

6. CONCLUSION

When comparing international standards, it is clear that the basic approaches for the use of firefighting systems varies widely. Some countries, such as Australia, already specify an obligatory construction. Due to differing systems, in ASFINAG's experience the focus during the development stages is above all on the safety objective. For example, several systems are possible for supporting firefighters in the event of a fire; this is not the case if the focus is on protecting the structure.

From the operator's perspective, it would be preferable if the standards and guidelines could be made more internationally uniform. On a national scale, there are still great differences and differing approaches to the function and operation. This in turn has significant impacts on the individual manufacturers on the market, who need to adapt to the respective standards; this involves high levels of effort and spending.

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IMPROVING VENTILATION AND PASSIVE PROTECTION WITH FFFS

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ABSTRACT

This paper discusses the efficiency of fixed fire fighting systems (FFFS) in combination with other safety measures, particular tunnel ventilation systems and passive fire protection in road tunnels. This is done by referring to the experimental data from full scale fire tests of the SOLIT² (Safety of Life in Tunnels) project. The SOLIT² project was carried out 2009 - 2012, having so far the largest fire test program, focusing on using FFFS in combination with other safety measures.

The presented results in the paper demonstrate that ventilation systems can be compensated by FFFS within certain limits. Test results from the comparison of 30 MW and 100 MW heat release rate (HRR) of class B fires with semi-transversal ventilation are used to demonstrate the effect of FFFS to the ventilation design criteria.

The experimental results show that a ventilation system designed for 30 MW HRR without FFFS can control even a 100 MW fire with FFFS. The reasons for this are discussed in the paper. Additionally other important aspects of FFFS in conjunction with passive fire protection will be shortly discussed in the paper as well.

Keywords: Fixed firefighting systems (FFFS), ventilation systems, SOLIT² research program

1. EXPERIMENTAL RESULTS

1.1. SOLIT² Research Project

The experimental results shown in this chapter have been measured as part of the SOLIT² research project. Test program included over 31 full scale fire tests in order to test the efficiency of FFFS in combination with the fire ventilation system in road tunnels. Half of the test fires were executed as class A (solid) fires involving complete lorry-loads (fire load consisting wooden pallets with a potential heat release rate [HRR] of over 100 MW) and the other half as class B pool fires (fire load consisting diesel fuel with HHR ranging from 30 MV to over 100 MW).

The research project “Safety of Life in Tunnels 2” (SOLIT²) started in 2009 with the aim of investigating the interaction between FFFS water mist fire suppression systems and other road tunnel safety equipment as e.g. the fire ventilation. The project ended in 2012 and was partly funded by the federal Ministry for Economics and Technology as a result of a decision by the German Bundestag. The results and reports are publically available from www.solit.info.

1.2. Fire tests arrangements

Fire test tunnel

Used TST test tunnel is only built for test purposes and has got a total length of 600 m. The shell construction has a horseshoe cross-section, typical for road tunnels (9,55 m wide and 8,10 m high). But for the almost whole length of the tunnel, an intermediate ceiling is arranged, which limits the height to 5,2 m. This ceiling serves to build up an exhaust duct for the semi-transversal ventilation system.

In order to unify the naming of different measurement areas, the middle of the fire load was defined as “zero” for all distances along the tunnel axis. In the direction of the prevailing longitudinal ventilation direction, all positions were called “D” for downstream plus the corresponding distance in “m”. Against the direction of the air flow, all positions were called “U” for upstream plus the corresponding distance in “m”.

Ventilation system

The test tunnel is equipped with systems for longitudinal and semi-transversal ventilation. The longitudinal one is powered by six jet-fans attached to the tunnel ceiling within the horseshoe section in the beginning of the tunnel, velocities between 1 to 6 m/s can be achieved. The semi-transversal ventilation system is built up in a ventilation station with two axial fans, which can extract 120 m³/s. This air flow will be extracted through 14 dampers, which are installed in the intermediate ceiling between the tunnel and the exhaust duct above; each damper has a cross-sectional area of 1,5 m². This set up of the semi-transversal ventilation is designed to exhaust the smoke volume of a fire with a HRR of 30 MW.

FFFS

For the tests a fixed firefighting system, type high-pressure water mist, was installed in the test zone over a length of 60 m covering the tunnel from D30 (30 m downstream) to U30 (30 m upstream of centre of fire load). The two nozzle branch lines of the system were fixed to the intermediate tunnel ceiling and were fed via a main supply line. The water supply was achieved by diesel driven pumps, set up in a container beside the tunnel fed by a 500 m³ water storage. The pressure and the flow rate of the pump were adjustable by controlling the rpm’s of the diesel engine. However, all major layout parameters of the water mist system were corresponding to a real installation in a similar tunnel, as e.g.:

- Type of the nozzle (Shape, K-factor, etc.)
- Nozzle layouts
- Angle of the nozzles regarding the vertical axis
- Distance of the nozzle to the fire load/carrier
- Pressure at the most remote nozzle

Measurement system

In order to measure and register all relevant parameters during a fire test, a measurement system with a total of 152 sensors was set up. Measurement values from following type were recorded every two seconds:

- Air humidity
- Air speed
- Air temperatures
- Gas concentrations (CO, CO_2, O_2)
- Heat Radiation
- Material temperatures
- Flow rate of the water mist system
- Pressure of the water mist system

In order to measure the influence of a FFFS on material temperatures, a concrete specimen, containing five thermocouples with different distances to the specimen surface, was installed underneath the ceiling. This specimen was positioned 7 m behind the fire load.

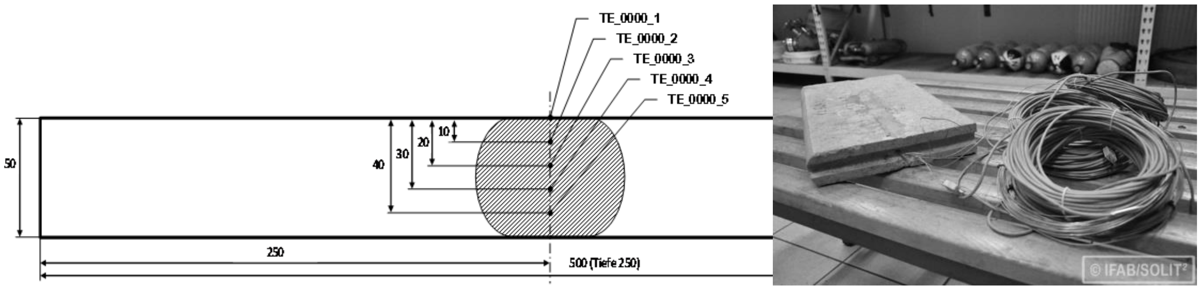


Figure 1: Sketch and photograph of a concrete specimen and assembled material thermocouples

Class B / pool fire load

In order to obtain a uniform class B fire with a predictable HRR, multiple steel trays were arranged together to form one continuous surface. Depending on the required HRR (e.g. 30, 60 or 100 MW) the according number of 40 cm high pools were arranged together and pre-filled with a 30 cm layer of water in order to protect the steel trays. The required amount of diesel oil was put on top of the water and 1 litre of petrol was used to enable the ignition procedure.

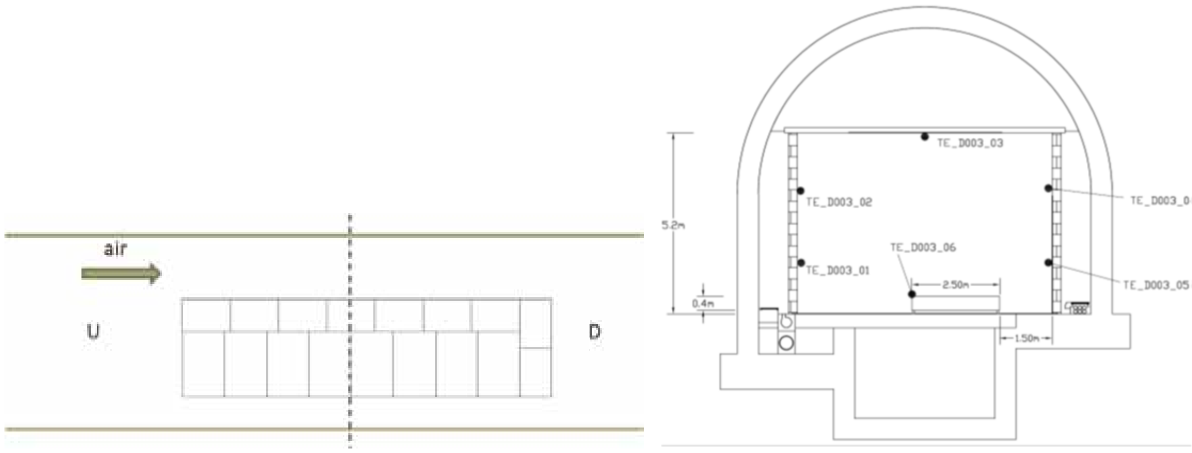


Figure 2: Pool arrangements for exemplary 100 MW fire test

Class A / HGV fire load

The geometry of this certain class A fire scenario was created to reproduce a typical heavy goods vehicle or especially a trailer. Wooden euro pallets were stacked on a 1,5 m height platform. The fuel load was covered with a truck tarpaulin. In total 408 pallets were arranged and totaling to approximately 9600 kg and 140 GJ energy content. The ignition of the fuel was done with two pans of gasoline representing a fire breakout at an overheated brake in the front part of the fire load. In that case the FFFS was activated approx. 11 minutes after ignition regardless of the measured HRR.

1.3. Test Results Class B fire - influence on ventilation

In the following the effectiveness of a water mist FFFS in conjunction with emergency ventilation is demonstrated with test results of a class B fire, which had an actual HRR of 100 MW. This certain fire load was not intended to extinguish, it was intended to have a constant energy output to show the influences on ventilation. The dimensioning of the ventilation system was configured to cope with a 30 MW fire.

After the ignition of all the 17 pools, the fire developed fast as known for pool fires. The HRR reached the 100 MW after 90 seconds, the delay occurred because of the traveling time of gases from the fire location to the gas concentration measurement in D45, where the HRR calculation was executed. The temperatures underneath the ceiling rose up to 1000 °C in the fire zone within 60 seconds after ignition.

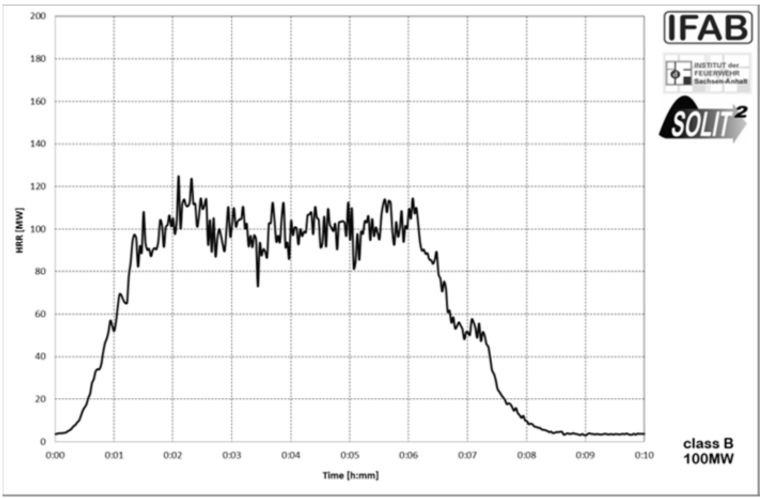


Figure 3: *Heat release rate for a 100 MW class B fire test*

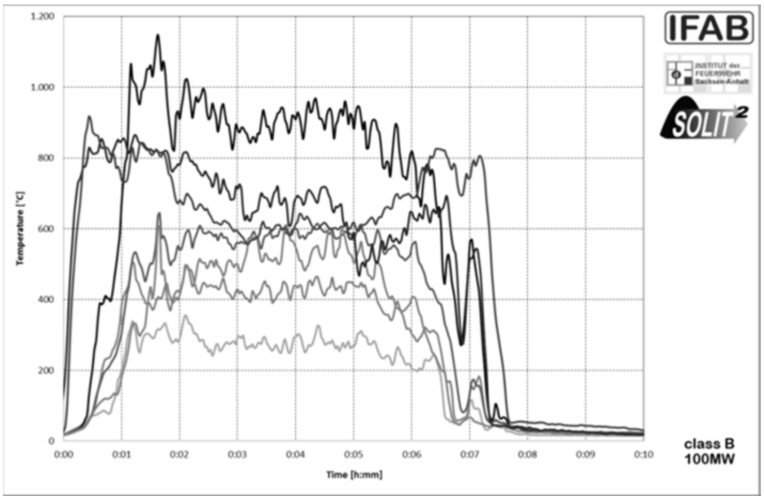


Figure 4: Temperatures near the fire zone at different heights during a 100 MW class B fire test

In that time, the smoke volume produced by the fire was higher than the volume, which could be managed by the combined ventilation system, although the extraction via the semi-transverse ventilation was already running as the fire was ignited. The longitudinal ventilation velocity was slower than the critical velocity, which resulted in the observed "back-layering" phenomenon. This means that hot fire gases moved against the longitudinal flow of 3 m/s and caused a thick layer of black smoke in the upper sector of the tunnel on the upstream side of the fire. This observation could be further documented by the increased temperatures in the upper section (in 5 m height, just underneath the tunnel ceiling in 5.2 m) of the tunnel cross section in 15m distance (upstream) of the fire load centre.

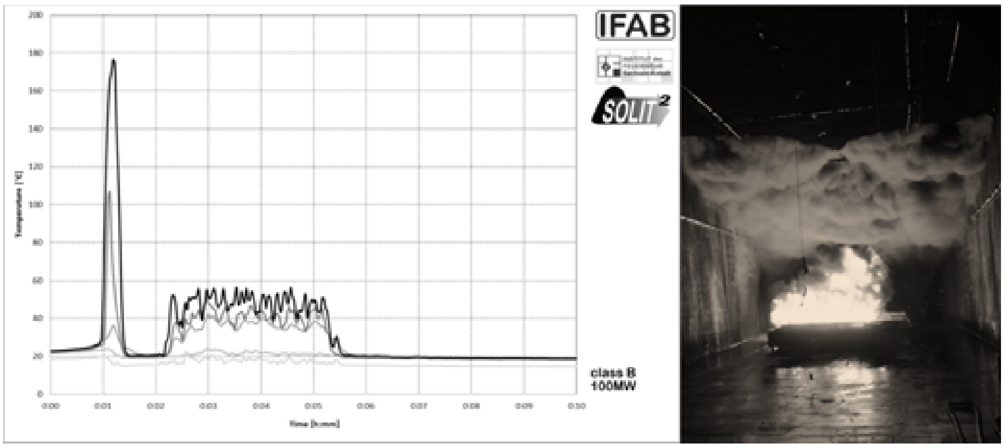


Figure 5: Temperatures 15 m upstream due to “Back layering” during a 100 MW class B fire test

Furthermore, most of the smoke was led throughout the main tunnel, which was documented by the measurement in D215. The air flow direction was positive and directed downstream with the longitudinal ventilation, the temperatures were higher than the ambient temperatures, which means that hot smoke was led to the end of the test tunnel and out through the portal.

The activation of the water mist FFFS was 60 seconds after ignition of the first pools and reached its full flow rate and system pressure after 100 seconds. After activation of the FFFS; the 100 MW pool fire was now within a very short time manageable with the combined ventilation system designed for 30 MW fires. The smoke output of the supressed fire was now lower than the extraction flow rate of the fire ventilation system (120 m³/s), which was documented by the fact that back-layering disappeared and negative and upstream air flow occurred on the downstream side of the fire at D215 near to the end of the tunnel. This means that the exhaust volume was adequate to discharge the produced smoke volume and even more fresh air, which was drawn into the tunnel.

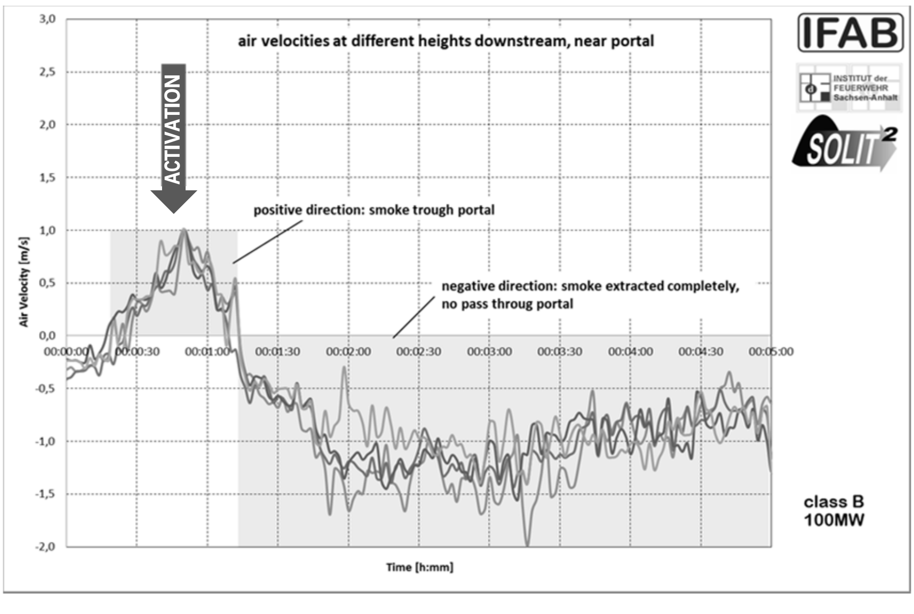


Figure 6: Air velocities near the downstream tunnel portal during a 100 MW class B fire test

1.4. Test Results Class A fire - influence on concrete specimen

The figures 7 and 8 illustrate the released heat during a class A fire and the gas temperatures under the ceiling right behind the fire load. Additionally, the material temperatures in the arranged concrete specimen at different material depths can be seen.

The material temperature directly below the concrete surface (0,2 cm below the concrete covering) reaches a maximum of 320 °C after 32 min. The other material temperatures, particular the temperature with a concrete cover of 1cm) do not reach the critical temperature of 300 °C at any time. It can be assumed that the higher temperature increase gradient, just before the activation, will develop with more serious consequences for the material if the FFFS will not be activated.

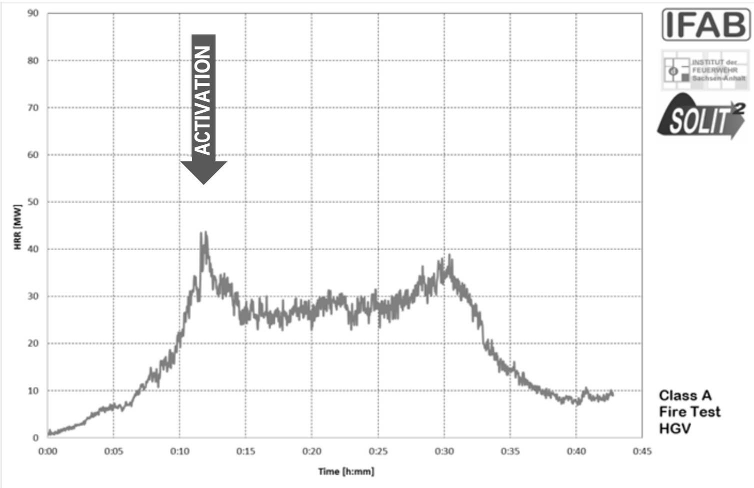


Figure 7: HRR during a class A fire test with activated FFFS

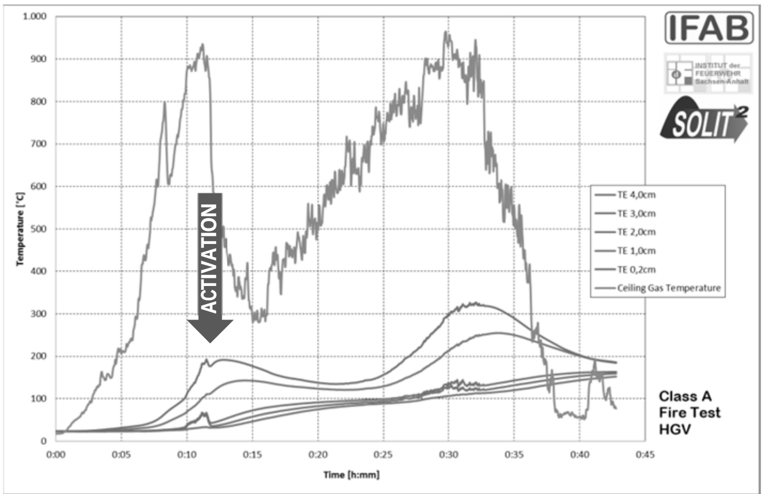


Figure 8: Material temperatures of a concrete specimen and ambient gas temperature

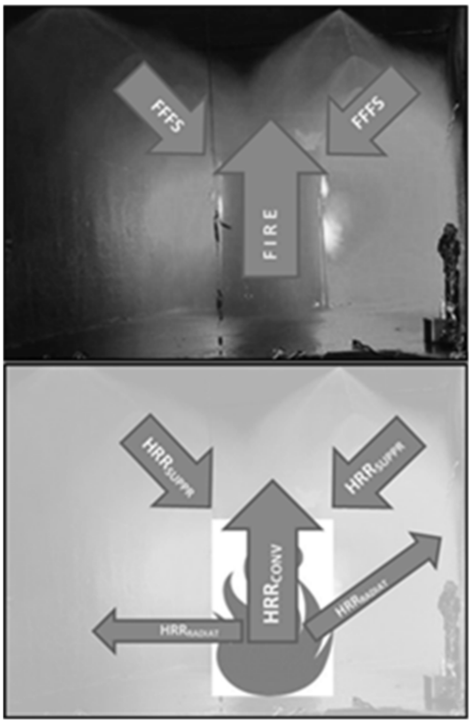
2. INTERFACE BETWEEN FFFS AND OTHER SAFETY MEASURES

The interface between FFFS and ventilation is relatively well studied with experimental tests. The positive impacts have been presented for example by Leucker & Kratzmeir („Brandversuche zu Wassernebel-Brandbekämpfungsanlagen“, Tunnel 8/2011). The possibility is given to downsize ventilation system design in new built tunnels or upsize the capacity of existing ventilation in refurbishment project when FFFS is applied. This is also accepted by e.g. NFPA 502, 2014 edition. When the interface between ventilation system and FFFS is discussed, it can be divided into two aspects, FFFS impact to design fire size and FFFS impact to convective heat transfer. These are shortly explained in the following.

2.1. FFFS and impacts to convective heat transfer

The total heat release rate, $HRR_{TOTAL,}$ can be divided into sub parts, which define the portion of HRR that the entire tunnel system, particular the ventilation needs to be able to cope with it.

The total HRR is also often called a chemical HRR that is created during the combustion of fuel. A part of the total heat release rate will be absorbed by the environment, this part of HRR is generated in the form of heat radiation and is therefore called HRR_{RADIAT}. In the moment the FFFS is started, a second part, much more significant, will be absorbed by the firefighting agent. This part is called HRR_{FFFS} . The FFFS can absorb a significant part of the energy depending on the flow rates used and portion of evaporation. The now remaining energy of combustion will be transferred by combustion gases and further by surrounding air. This convective HRR_{CONV} is the effective HRR, which is used to size the ventilation system and to choose any structural protection measures.



$$\mathrm{HRR_{TOTAL}}\ (\mathrm{HRR_{CHEM}}) = \mathrm{HRR_{RADIAT}} + \mathrm{HRR_{FFFS}} + \mathrm{HHR_{CONV}}$$

The impact of FFFS in terms of cooling and absorbing the energy depends on the FFFS type and flow rates. The most important one is the evaporation rate of the system as it defines the cooling energy.

The evaporation of water absorbs the most energy; therefore, water evaporation mass rate is in the decisive factor when the effect of a particular FFFS is calculated for the total HRR. When different FFFS are compared, smaller droplet sizes provide much larger reaction surface and therefore provide more effective evaporation. This implies water mist systems are more effective in cooling because of higher evaporation rate. It can be partly compensated with considerably higher flow rates of deluge systems.

2.2. FFFS and the ventilation design fire size

Previous research projects have shown that FFFS are very effective to fight and suppress class A fires to a portion of size compared to sizes of fires being unsuppressed. This is the most important impact for the ventilation system as the initial design parameter in terms of HRR can be significantly reduced. For example, SOLIT[2] research project results have shown that heavy goods vehicle (HGV) fire loads with over 150 MW potential HRR were suppressed with FFFS to maximum 20 - 40 MW HRR. If a design fire is suppressed to a smaller HRR value, this can be utilised when dimensioning the ventilation. The design HRR can therefore be significantly reduced compared to fires without FFFS. A very important aspect is that a typical design HRR for ventilation systems is given assuming that only one vehicle is involved in fire. There is a very likely possibility that fire will spread to other vehicles during the self-rescue phase in tunnels. Then the design fire had to be adapted. When applying a FFFS, it is noticed that the fire spread onto other vehicles can be limited when dimensioned correctly.

3. SUMMARY

FFFS can reduce the potential HRR by suppressing and controlling fire size to a portion compared to a free burning fire. Furthermore, FFFS fights against the output of fire, especially convective heat transfer, which is the primary design aspect for other safety measures like ventilation or structural protection. FFFS can therefore impact positively the ventilation system design. A favourable influence on material temperatures can be demonstrated as well.

FFFS, especially water mist systems, have been tested experimentally in full scale fire tests for demonstrating the theory in practice. Presented results from SOLIT research projects showed that ventilation system design for a 30 MW design fire was able to cope with 100 MW pool fire when FFFS was applied. FFFS will be seen more in future as the mitigation method to assist ventilation designs.

Common FFFS apply water, and their performance is strongly related to used application rates, nozzle characteristics (droplets sizes) and lay-out. Water mist systems generally use far less water and work more in gaseous level, whereas deluge system apply more water and work on surface basis. Both systems have been used in real tunnels for longer times.

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COMPARISON OF DELUGE AND WATER MIST SYSTEMS FROM A PERFORMANCE AND PRACTICAL POINT OF VIEW

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ABSTRACT

Fixed fire fighting systems (FFFS) are a relatively new technology in tunnels that has been researched intensively in the recent years. European approaches have strongly focused to water mist systems, but especially Asian and American approaches have traditionally focused to deluge systems, often also called as “sprinkler” systems. There has been lots of full scale fire test data available about how water mist systems perform with tunnel fires, but deluge systems have undergone only very few full scale tests.

This paper will show full scale fire test experiments with both systems. This unique test series is the first one in the world where deluge and mist systems are compared in tunnels with full scale HGV fire scenarios. The tests were carried out in 2011 with a Class A HGV fire load.

The paper summarises the differences and similarities of deluge and water mist FFFS in theory and practice. Both systems have important parameters like nozzle type, droplet distribution, flow rate and lay-out to determine that are greatly affecting to the performance.

Keywords: Fixed fire fighting systems (FFFS), deluge, water mist, HGV full scale fires, HRR (heat release rate)

1. INTRODUCTION OF FIXED FIRE FIGHTING SYSTEMS (FFFS)

Fixed fire fighting systems (FFFS) are an active way to fight fires in tunnels. Such systems are often called water based fire fighting systems or simply fire suppression systems. There are two main streams technologies that are applied in tunnels. Low-pressure deluge systems (often called as “sprinklers”) and water mist systems (normally applying high-pressure). The terminology often differentiates deluge and water mist systems as both systems work in deluge operation, dividing the tunnel into groups of open nozzles that are activated by opening the section valve. The technologies apply partly different fire fighting methods, which are explained later in this paper.

Low-pressure deluge systems have been applied for longer time e.g. in Japan, USA and Australia. The background of deluge systems is coming from standard sprinkler applications. Pipes, connecting methods, nozzles and valves are often the same as used in buildings [1]. Water mist systems are primarily used in European tunnels and they have been developed as a result of research work e.g. UPTUN, and SOLIT research projects [2][3]. The used technology has been developed specifically for tunnels following best practice engineering guidance [.

Figure 1: Deluge system in the Mount Baker tunnel

1.1. Low-pressure deluge

Low-pressure deluge systems are normally using open sprinkler heads (called as nozzles afterwards), applying typically less than 12 bar pressure. Low-pressure deluge systems operate with a relatively large droplet sizes with low kinetic energy when discharged by the nozzle.

Droplet size can be reduced if higher pressure and special nozzles are used. Every nozzle type has a different spray characteristic in terms of droplet distribution and coverage area. Both are important parameters when different nozzle types are compared. The common misunderstanding is to dimension deluge systems only with their application rate without evaluating the droplet distribution and the nozzle lay-out. The design application rates are given only on surface based rates as lpm/ m^2 or mm/ min.

1.2. High-pressure water mist

High-pressure water mist systems work with a pressure of over 35bar. The nozzle type is open and a group of nozzles is activated at the same time similarly to low-pressure deluge systems. High-pressure water mist systems apply water with significantly smaller droplets than deluge systems. Additionally, the droplets are discharged with a high velocity and momentum to fill the complete protected volume. Droplets will reach both the road level but at the same time fill the entire protected cross section, therefore also reaching the space above the nozzles. Droplet distribution and lay-out are important parameters also for the dimensioning of a water mist system. Every nozzle type has different spray characteristics and the systems are normally designed as volumetric based in lpm/ m^3.

Figure 2: Water mist system in the M30 tunnels

2. THEORETICAL COMPARISON OF DIFFERENT FFFS

2.1. Tunnel fires and effects of FFFS to combustion

Tunnel fires, as other fires, can be described in a simplified way by using the fire (combustion) triangle. A fire always requires the following three components to start and continue chemical process:

- Fuel, which may be a solid, liquid or vapor
- Oxygen
- Heat (energy) to initiate and maintain the oxidation process which is called as fire.

If any of the three critical elements are limited or eliminated or if the chemical process is disturbed, the fire will be suppressed/controlled and / or finally extinguished. Since normal design fires for tunnel applications are often large deep seated solid fires (Class A), a full extinguishing is difficult with all FFFS types. Therefore the term fire suppression or control is a better description compared to the term extinguishing systems which is sometimes also used. The fire suppression effect in the tunnel applications is slightly different to the definitions normally given in the fire protection literature. A suppression of a fire in a tunnel does not necessarily require that the HRR would be immediately reduced when the FFFS is activated. It also does not mean that the HRR would stay in the same level (control) as at activation of the FFFS, but that the HRR can still grow afterwards. This is due to the fact that Class A fuels are deep seated fires that are often obstructed and cannot be reached by the fire fighting agent. Additionally, the fire load is often covered with a tarpaulin as e.g. in real trucks and therefore the water has very limited access to the seat of the fire before the cover has opened up due to the effect of the heat. However, the fire development as well as the maximum peak of the HRR with FFFS is considerably lower compared to a situation without a FFFS. For example the SOLIT fire tests programs have shown that over 100MW potential HRR fires have been regularly been limited to less than 40MW with FFFS [2].

FFFS in tunnels do not only fight the combustion process but also - and this is the dominant and in protection terms the most important property of well-designed FFFS – mitigate the output of the fire. This mitigation effect refers to the smoke volume, smoke temperatures, heat radiation and absolute temperatures. In consequence the effects of the fire on people, vehicles and the tunnel itself are severely mitigated or even avoided. These effects are not (fully) covered by the fire triangle model. As it is very important to suppress and limit the HRR, it is obviously even more important that the effects of the fire are mitigated. By this fire services are enabled to operate in the tunnel, life safety conditions are enhanced and damages to the tunnel are limited. Again, limiting the effects of the fire is often the primary target of FFFS as these systems are operated rather as suppression than extinguishing systems. The mitigation effect of FFFS is nowadays taken into account for example when design fire sizes for ventilation systems (convective HRR can be portion of total HRR) are chosen or time temperature curves for the specification of structural measures are defined.

2.2. Comparison of low-pressure deluge and high-pressure water mist systems

The droplet sizes, primary fire fighting methods and flow rates, are the main differences between low-pressure deluge and high-pressure water mist systems. As the deluge systems have larger droplets, their evaporation is not as complete at the fire or in the gas phases. Larger droplets work more on the fuel surfaces by cooling and so suppressing the fire. Wetting fuel surfaces also prevents the ignition. The fire fighting ability per litre of water of deluge systems compared to water mist is reduced, which can be compensated by applying higher flow rates. The ratio in previous tests is known to be 3…5 times higher. Water mist systems work with significantly smaller droplets with higher kinetic energy, filling the whole volume of the tunnel in an almost three dimensional manner. This means that water mist droplets are able to directly interact with the flames of a fire disrupting the chemical reactions in the gaseous phase [6]. The smallest droplets do not pass through the flames to cool the involved fuel directly, which is achieved by the larger droplets. These larger droplets work in the same way as in low-pressure deluge systems, but they are produced to a lesser amount. Additionally, continuous vaporisation expands the water volume by 1640 times creating a continuous stream away from the fire seat. This works against the access of air/oxygen to the fire seat and thus inert the fire and increasing the performance of water mist systems. Especially water mist systems have traditionally been used also to fight flammable liquid fires, but both system types can be enhanced with AFFF (Aqueous film forming foams) when a special focus is given to the risk of flammable liquids.

It is often seen that there is a tendency to categorize both deluge and water mist FFFS differently, but the fact is that deluge systems also cool the flames by vaporisation and water mist systems also wet fuel surfaces. Deluge and water mist systems overlap with the fire fighting methods, although they represent different approaches.

2.3. Comparison table of FFFS

Based on the main fire fighting effects and system functions of low-pressure deluge and high-pressure water mist systems, the following comparison can be made:

Table 1: Theoretical comparison of deluge and water mist systems*

		Low-pressure deluge	High-pressure water mist
Fire fighting principle	Cooling – flames/gases	Minor	Major
	Cooling - fuel	Major	Minor
	Displacement of oxygen (locally)	Minor	Major
	Isolating fuel from oxygen	No	No
	Interrupting chemical combustion process	Minor	Minor
Main mitigation measures	Mitigation of effects of covered class A fires	No (limited)	Minor
	Suppression of uncovered class A fires	Major	Major
	Suppression of class B fires	Minor (with AFFF major)	Major (with AFFF major)
	Blocking heat radiation	Minor	Major
	Smoke washing/sooth binding	Minor	Minor
	Prevention on reigniting by wetting surfaces	Major	Minor

* Notice! This table highlights the differences between the system types in a very generalised way. The actual performances are however related to a specific nozzle characteristic (droplet distribution/spray momentum/lay-outs) and flow rates of a specific system.

3. COMPARISON OF FIRE TESTS

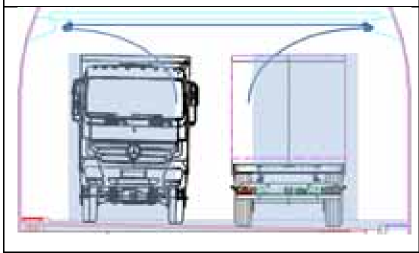
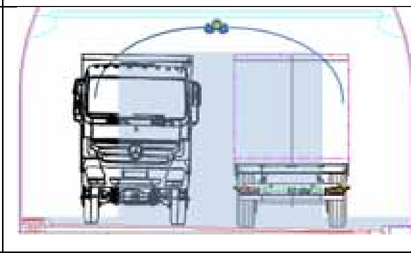
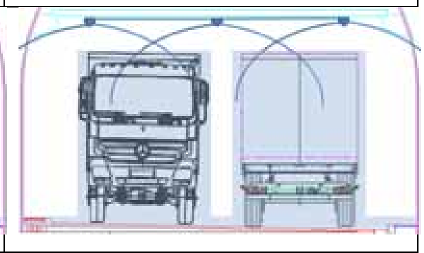
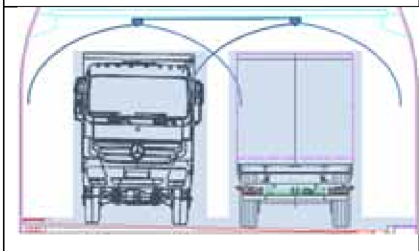
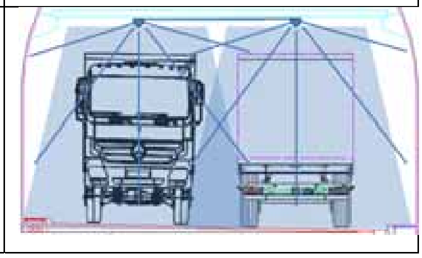
This chapter describes results of full scale fire tests that were carried out in 2011. All measurements in the tests were carried out by IFAB together in cooperation with the Institute der Feuerwehr Sachsen-Anhalt. The tests were ordered by FOGTEC in order to compare different technologies and design criteria used in other countries. The testing included various application rates, whereby for the purpose of this paper only results with 12 lpm/ m^2 are presented ***Notice! Results with lower flow rates 6/8/10 lpm/ m^2 were not as good as with the selected 12lpm/m^2***. Deluge system results are compared with those of high-pressure water mist systems for the same fire scenarios, with a flow rate of less than 30%, ~0,65lpm/ m^3 (< 3.5lpm/ m^2) of the flow rate of the deluge system. All tests were carried out in the TST test tunnel in Asturias, Northern Spain.

3.1. Nozzle lay-out selection

In order to define a suitable deluge system and nozzle lay-out, a pre study was carried out to evaluate the most effective nozzle lay-outs and water distributions. As deluge systems are not that well known in scientific terms, it was important to find a nozzle lay-out combination that could spray onto the complete fire load, avoiding obstructed surfaces. HGVs were chosen as the risk for evaluating spray patterns. Both side wall and pendent type nozzles were evaluated.

Table 2 summarises that only pendent nozzles above the fire load could spray water equally on all the sides of the fuel in used geometry. One of the reasons was also that the test tunnel ceiling height of 5.2m did not leave a lot of head room space above the fire load (HGV mock up). The 2 nozzle row option D (one nozzle row per lane) was chosen for the testing of the deluge system. The water mist system was tested with a 2 nozzle row option (one nozzle row per lane) accordingly. It was known from previous fire tests that this lay-out with the right nozzles was effectively able to fill the whole protected volume with water mist.

Table 2: Theoretical comparison of deluge and water mist systems

A. Deluge lay-out: Side walls on sides	B. Deluge lay-out: Side nozzles in the center	C. Deluge lay-out: 3 pendent nozzle rows
		
D. Deluge lay-out: 2 pendent nozzle rows (selected)		E. Water mist lay-out: 2 pendent nozzle rows (selected)
		

3.2. HGV (Class A) fire load and measurement system

Figure 3: HGV fire load [2]

The HGV fire scenario was developed during the SOLIT projects and explained in detail in the Annex 7- *Fire Tests and Fire Scenarios for Evaluation of FFFS* of the SOLIT2 document “Engineering Guidance for a Comprehensive Evaluation of Tunnels with Fixed Fire Fighting Systems” [2]. The geometry of the mock-up corresponds to a typical HGV. Euro wood pallets were stacked with steel frames on 1,5m high platform as is the case on real HGV trailers. The fuel was covered with a truck tarpaulin. In total 408 pallets per test were used (approximately 9600 kg and 140 GJ energy content). A longitudinal ventilation velocity of 3m/ s (+/- 0,5m/ s) was applied. The fuel was ignited with two pans of gasoline representing a fire with an overheated break in the front part of the fire load. The FFFS was activated 4 minutes after ignition regardless of the measured HRR. Typically the HRR varied between 2 and 5 MW at this point of time.

The measurement systems in the fire tests were very extensive, but only some of the most relevant results are presented in this paper. These are following:

- HRR – impact to fire size (suppression/control)
- Damage of a second (part) HGV mock-up as a fire target, 5 m downstream of the main mock up to detect and evaluate the fire spread
- Temperatures at fire target mock up, 5 m downstream
- Temperatures above the fire load in the rear (flame temperatures)

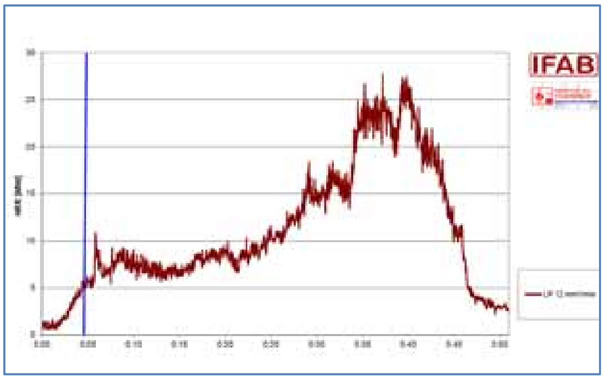
- Temperatures at 40m downstream of the fire mock up at 2m height (life safety)
- Heat flux next to fire load
- Smoke backlayering
- Fire damage

Additionally, subjective reports of fire fighters present in the test tunnel during testing were collected, which is commented later.

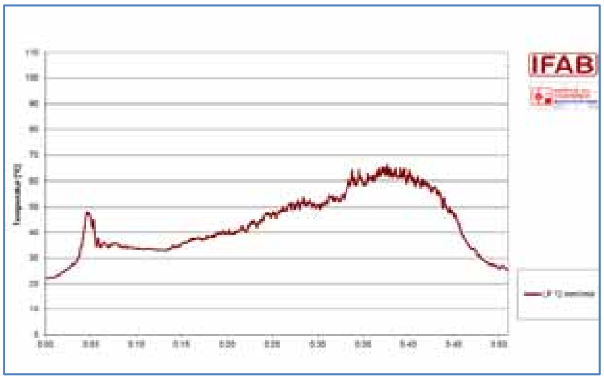
3.3. Test results with the deluge system

This chapter shows results of the deluge system.

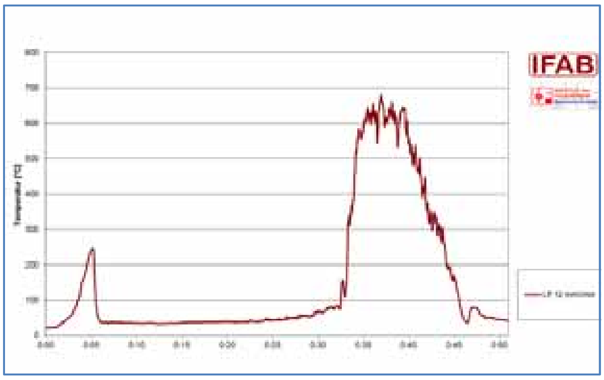
Table 3: Full scale results with the deluge system



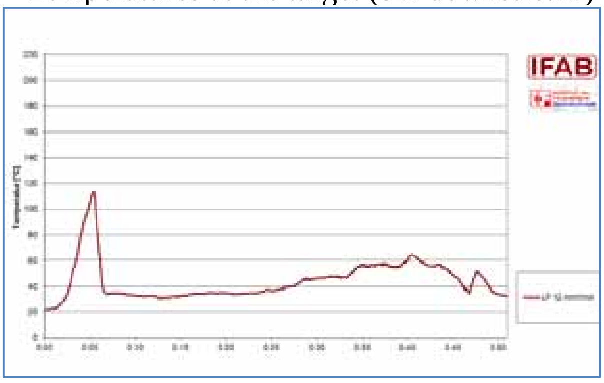
HRR



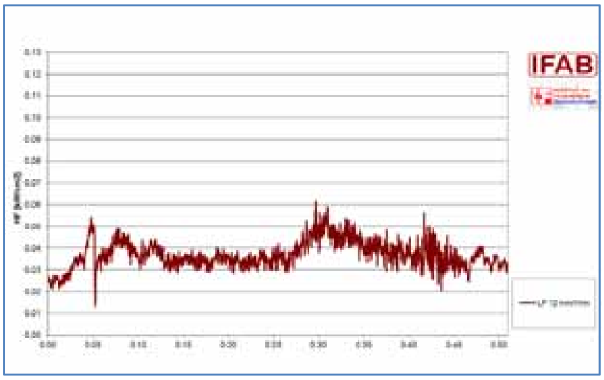
Temperatures at the target (5m downstream)



Temp. at the flame zone (rear of the fire load)



Temperatures 40 m downstream side



Heat flux

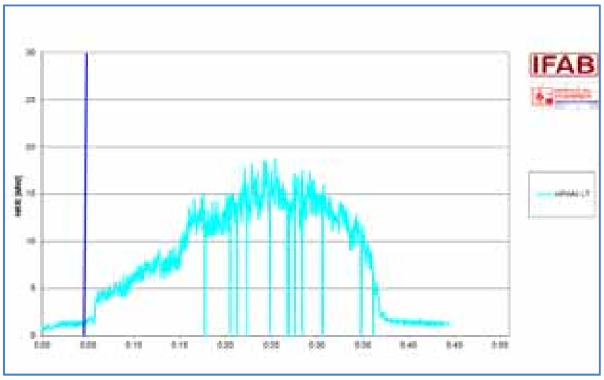
Fire damage

According to the reports of the fire fighters, the manual fire fighting was safe and easy to perform in the end of the test. The heat radiation was very minor and it was easy to approach the fire. Manual extinguishing of the fire took in all tests only a few minutes. The visibility was well sufficient for manual fire fighting.

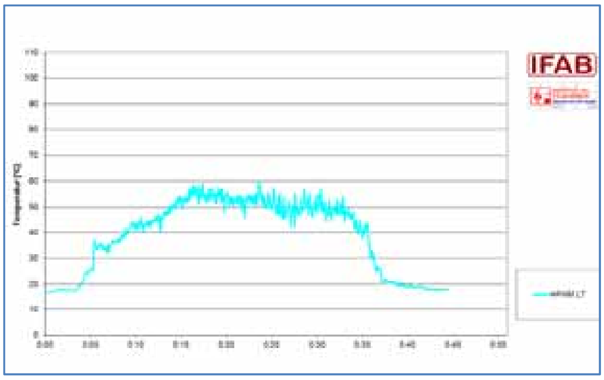
3.4. Test results with water mist system

This chapter shows results of the water mist system.

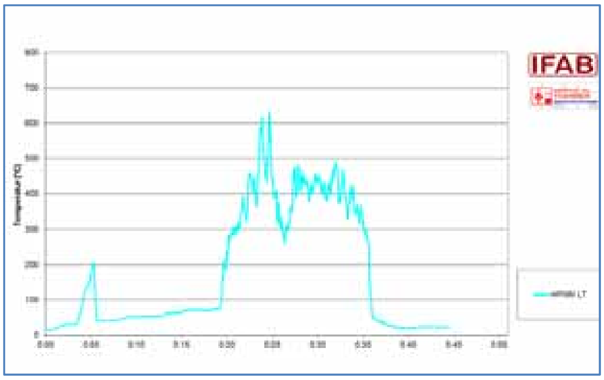
Table 4: Full scale results with the water mist system



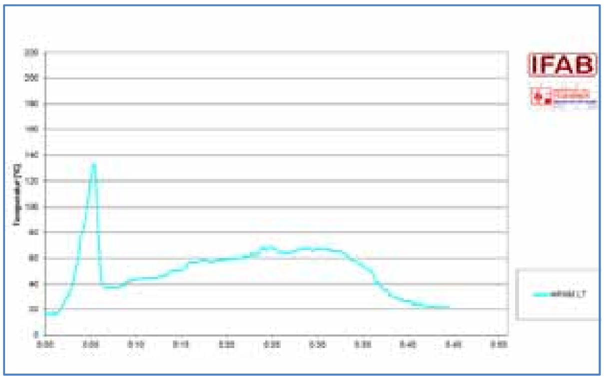
HRR



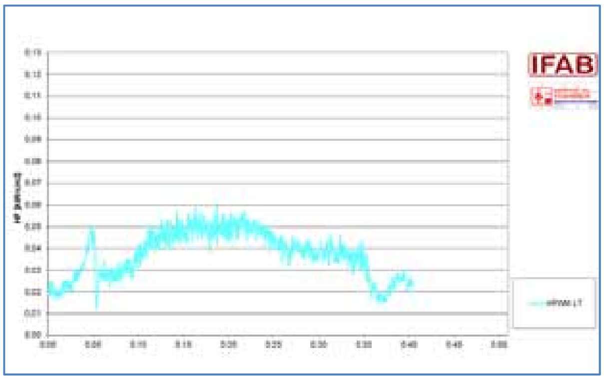
Temperatures at the target (5m downstream)



Temp. at the flame zone (rear of the fire load)



Temperatures 40 m downstream side



Heat flux

Fire damage

According to the reports of the fire fighters, manual fire fighting was safe and easy to perform in the end of the test. The heat radiation was very minor and it was easy to approach the fire. Manual extinguishing of the fire took only a few minutes in all tests. The visibility was well sufficient for manual fire fighting.

3.5. Comparison of experimental results

The tests showed very comparable results for the deluge and the water mist systems. These results suggest that the flow rate ratio of approx. 1:3.5 can lead to similar results. The suppression effect is very similar whereby the water mist system results were slightly better.

The difference can be explained also with normal test deviation Class A fires behove always slightly differently. Fire grew in tests until the tarpaulin had burned and the water started to get to the seat of the fire. The fire target was well protected by both systems; also temperatures at the target were kept well in control. All other temperatures were controlled in a similar way, especially in the lower areas of the tunnel. The maximum temperatures were measured directly above the fire. These were about 400…700°C depending on the system, but these temperatures were only temporary achieved (e.g. for 10 minutes) for a specific location since the fire propagated from upstream into downstream direction. The water mist generally cooled better in the upper area of the tunnel, which is logical as it works more three dimensional compared to a deluge system. Accordingly videos and photos showed flames reaching the soffit continuously in deluge tests. The heat flux measurements showed very comparable results with the tested system types. Both systems together with the tested ventilation concept prevented well any backlayering. In addition, the fire damage after the tests was very comparable for both systems leaving a lot of unburned fuel load.

The generated test data were analysed and evaluated by IFAB in a standardized way. Further, fire brigade professionals were interviewed regarding their experiences during the tests. As a result of this the following table was generated. The most important design aspects of FFFS are evaluated. These are *A. Life safety, B. Fire services and C. Tunnel protection*.

Table 5: Comparison of deluge and water mist systems with different design aspects*

		Low-pressure deluge	**High-pressure water mist**
Life safety	**Suppression of fire**	Major	Major
	Cooling environment under 2m height	Major	Major
	Reduction of heat radiation	Major	Major
	Prevention fire spread to further vehicles	Major	Major
	Impact to the visibility	Minor	Minor
	Toxic gases (downstream) under 2m height	Minor (tenable conditions)	Minor (tenable conditions)
	Smoke backlayering	No	No
Fire services	**Reduction of heat radiation**	Major	Major
	Impact on visibility	Minor	Minor
	Suppression of class B fires	- (not tested)	Major (previous tests)
	Breaking of fire fighting foams	Major	Minor

Tunnel structure	**Temperature/time curve reduction**	Major	Major
	Prevention of fire spread (catastrophic fire)	Major	Major
	Protection of tunnel ceiling	Minor (limited)	Major
	Reduction of heat radiation	Major	Major
	Wetting surfaces	Major	Minor
	Distribution of water	Equal	Equal

* Notice! The conclusions shown above are derived from fire tests with two specific systems / manufacturers. They may heavily vary for other specific designs and products.

3.5.1. Temperature tolerance/damages of normal deluge system materials

As the deluge system fire tests were one of the first ones ever carried out with modern design fires in tunnels, interesting other information was collected. One of important finding was that normal deluge nozzles were in some tests severely damaged by the heat. This was noticed especially during tests with delayed activation. The conclusion was that brass alloy, which is typically used for deluge nozzles, is by not suitable for a tunnel fires.

Figure 4: Damaged sprinkler - Brass made sprinkler nozzle

It is also logical that nozzles cannot be fixed with Teflon tape or any other normal method when used in tunnels. The pipe connecting method of deluge systems was also evaluated before the test series as normal “sprinkler” fittings/couplings have a maximum temperature rating of 120 to 180 °C, which is reached during a tunnel fire often in less than 120 seconds. This was the reason why only welded pipe connections were used in the section pipes above the fire. No damages were reported for the pipes, neither for the water mist nor for the deluge system tests. Some pipe supports were however damaged, but these were replaced between the tests. It may be that pipes could tolerate higher temperatures – even when traditional fittings are being used - when the system is being activated early enough. It is however very difficult to predict at which point of time traditional fittings will be damaged. Especially low ceiling tunnels can be problematic since the flames will reach the ceiling quickly.

4. CONCLUSIONS

The two most popular types of FFFS in tunnels are low-pressure deluge and high-pressure water mist systems. Water mist engineered systems that have undergone dramatically more full scale fire tests. Designs and layouts of deluge systems have been often adopted from other application fields like the building industry. This equally applies to the used system components used in tunnels.

Both system types work similarly in deluge operation with open nozzles and applying in most cases pure water. The main difference is in the flow rates, the droplet distribution and their kinetic energy of sprays. Deluge systems work more by cooling and wetting the fuel surfaces whereas water mist works (almost) three dimensional in the gases of the fire. The very efficient cooling abilities of the tested water mist systems make them more efficient in terms of the applied flow rate. This has a direct influence on design aspects such as pipe diameters, pumping capacity, water storage and drainage.

The full scale fire tests delivered positive results for both deluge and water mist systems. Flow rates and nozzle type/characteristics were part of the preliminary study and therefore it cannot be concluded that all system types with similar flow rates would perform equally. For example it was noticed that a proper water distribution (minimum one nozzle per lane) with a deluge system is very essential if two vehicles in parallel are involved to the incident. The fire test results for both systems were very comparable in general. The main differences were found in the cooling of the upper area of the tunnel including the ceiling.

Both tested FFFS are able to significantly improve *life safety, the safety of fire services and the protection of the tunnel structure*.

It was a surprise to experience a limited tolerance of normal deluge nozzles against heat and high temperatures. Nozzles in the fire zone were damaged already during the preburn stage of the test. Additionally, conventional connecting methods were found to be not suitable.

5. FUTURE WORK

Deluge systems provide potentially a good alternative for water mist systems, especially when the length of the protected tunnel is relatively short. Longer tunnels make hydraulic systems very large as the total flow rates of deluge system often reach 10 000…14 000 lpm for three zone activation. On the other hand, it has been seen in previous fire test series, e.g. by Swedish SP, that the performance of deluge systems can be significantly improved by increasing the pressure and thus decreasing the droplet sizes [7]. FOGTEC developed a smaller droplet deluge system, or water spray system, that was tested in full scale fire tests in 2012 and further improved in 2013. The system has been optimized in combining the innovations from water mist systems but operating in a traditional deluge system pressure range. The test results with the new approach of higher pressure deluge systems will be published later in 2014.

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VENTILATION AND ESCAPE FACILITIES FOR SHORT CUT-AND-COVER URBAN TUNNELS

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ABSTRACT

Cut and cover tunnels or enclosures of existing highways in urban areas are typically rather short (up to 600 m) and have a high number of lanes. Due to high traffic frequency in urban areas such tunnels have a high probability for congested traffic. In case of incident the number of trapped persons in the tunnel is high and the risk for incidents with high severity grows. A scenario analysis, investigating self-rescue process and self-rescue conditions due to ventilation in such tunnels has been performed. The results of this scenario analysis reveal that common ventilation and self-rescue strategies, as defined in various normative documents should not be applied to these tunnels. A better safety level can be obtained by increasing the number of emergency exits, which can be built cheaply in cut and cover tunnels, and choosing a passive ventilation strategy in case of congestion.

Keywords: urban road tunnel, egress facilities, ventilation strategy, incident detection

1. INTRODUCTION AND OBJECTIVES

Cut and cover tunnel are frequently built in urban environments for mitigating the negative impacts of traffic, particularly air pollution and noise. Such tunnels are increasingly built also for recuperating or saving valuable surface space. They are frequently short or very short (in the range of 300 to 600 m), have often three or more lanes for every traffic direction and suffer from frequent traffic congestion. In case of fire a large number of persons and vehicles could be trapped in the tunnel due to the high number of lanes. Self-rescue means and strategies need to be adapted to these circumstances. These characteristics are also essential for ventilation design and for selecting the ventilation strategy. An adequate level of smoke management should be provided, while preventing as much as possible smoke destratification. Limited space and large aspect ratios of the tunnel cross section have finally a very large impact on the design of several safety elements, including fire detection and ventilation.

Recent design experience allowed identifying a number of specific issues which require a special treatment and adapted solutions in case of cut and cover tunnels:

- Capacity and layout of egress facilities
- Ventilation design and operation
- Congestion and fire detection
- Protection of the safe tube against smoke penetration (doors and portal smoke recirculation).

While several issues apply also for tunnel with bidirectional traffic, this paper will focus on the more frequent situation, with two tunnel tubes and unidirectional traffic. All examples presented herein are based on recent real-life investigations. Nevertheless, the focus will be on principles and investigation methodology rather than on specific examples and there will be no reference to specific projects.

2. NORMATIVE REQUIREMENTS

The unusual characteristics of cut and cover tunnels in urban environments are not always entirely accounted for at the normative level. This shall be illustrated based on self-rescue facilities. An informal overview of the international state-of-the art for the maximum distance between emergency exits for twin-tube tunnels shows that there is no clearly defined "international state-of-the-art" for the maximum allowable distance between emergency exits, but the following indications emerge quite clearly:

- Minimum requirement: 500 m (EU's directive 2004/54/EC)
- "Standard" requirement: about 300 m (CH, DE, FR, IT, AT and USA)
- Maximum requirement: 100 m (NL and UK).

Also concerning applicability of longitudinal ventilation systems, different national and international regulations provide quite heterogeneous prescriptions.

Norms and recommendations are focused mainly on medium and long bored tunnels, as they pose the more relevant safety risks. The concepts and solutions provided are not readily applicable to cut and cover tunnels, for both technical (see e.g. [1]) and economic reasons. The low investment required for additional emergency exits coupled with technical issues related to fire detection and ventilation call for safety concepts which are different from conventional excavated double-bore tunnels.

3. TUNNEL CHARACTERISTICS AND SCENARIOS

The issues are illustrated based on a short urban cut-and-cover tunnel of 580 m length with varying number of lanes and cross-passages. Peak-hour traffic around 2050 vehicles per hour and lane with around 10% HGV are expected. This real-life example is merely used for illustrating general issues and the technical details of this specific tunnel are not relevant. Different tunnel setups with different number of lanes and number of emergency exits are considered for investigating in a systematic manner ventilation and self-rescue. All representative fire scenarios with and without congestion are analyzed in detail in terms of smoke propagation and person movements. The list of scenarios is given in Table 1, which does not include traffic conditions. The number of scenarios is doubled by considering congested and moving traffic.

Table 1: Tunnel characteristics of investigated scenarios

Scenario	1	2	3	4	5	6
Number of cross-passages	1	1	3	3	4	4
Number of lanes	3+1	5	3+1	5	3+1	5
Tunnel width	17 m	20.5 m	17 m	20.5 m	17 m	20.5 m
Tunnel height	5.2 m	5.2 m	5.2 m	5.2 m	5.2 m	5.2 m

The self-rescue distance is varying with the number of cross-passages. In case of one cross-passage a maximum self-rescue distance of 290 m results. In case of three cross-passages the maximum self-rescue distance can be reduced to 145 m. Increasing of cross-passage width has been preliminary judged as no effective mean to reduce self-rescue time. Although the high number of lanes does lead to increased number of persons per meter of tunnel length, the main driving factor for long self-rescue times in wide cut-and-cover tunnels still is the self-rescue distance and not the emergency exit capacity.

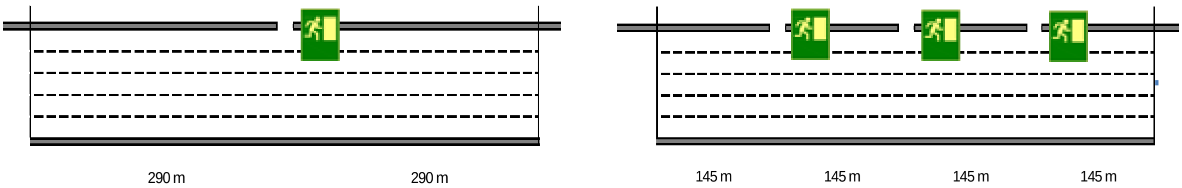

Figure 1: Illustration of 5 lane tunnel layout for 1 and 3 cross-passages

The ventilation system for this tunnel consists of two groups of jet fans, installed in a distance of 100 m to the portals. Limited space for jet fans leads to fans with rather small diameter, but high in number (about 8 per group). The rationale between this selection of the ventilation system is related in particular to redundancy requirements (at least two jet-fan groups are needed in every tube for redundancy in case of fire) and for the pressurization of the opposite tube. Moving the jet fan groups to the portals lowers the probability of disturbing smoke layering in case of fire incidents. However, the jet fan groups could be operated only in one direction and thus redundancy is lost and the total number of installed jet fans is slightly increased (group at entrance portal must generate total thrust for incident ventilation and group at exit portal must be sufficiently equipped to ensure over-pressurization).

The scenario analysis is based on a timeline of events. An identical timeline has been assumed for free-flowing traffic and congested traffic (see Table 2). Detection of fire within 1 minute is a requirement of the Swiss guideline for fire detection in road tunnels [4]. Tunnel closure and activation of ventilation would start immediately after fire detection in modern tunnels which are equipped with automatic control system. The slight delay is introduced to consider late detection and special cases where the tunnel reactions do not follow immediately. For the beginning of self-rescue a distinction is made between persons close to the fire and further away in order to account for different perceptions of specific situations.

Based on traffic frequency and time between traffic blockage in the tunnel and tunnel closure a congestion length of about 400 m can be expected in the tunnel in case of free-flowing traffic.

Table 2: Scenario timeline for free-flowing traffic

Time [min]	Event / Description of scenario
0	Start of fire and blockage of traffic in whole fire tube
1	Fire detection
1.5	Closure of tunnel
2	Activation of ventilation system and alarming of tunnel users
2.25	Start of self-rescue for persons close to the fire location (distance up to about 30 m)
2.75	Start of self-rescue in whole tunnel

The effectiveness of different safety concepts can be evaluated using a scenario-based approach, such as described in [2]:

- Global assessment of evacuation process based on NFPA 130
- Detailed simulation of evacuation process, taking into account individual persons and vehicle locations (with the dedicated software ASERI)
- Investigation of fire development and smoke propagation (CFD).

The results can be compared in terms of visibility conditions and self-rescue time. A fair chance of self-rescue only exists, if sufficient smoke control can be provided during the whole self-rescue phase.

4. VENTILATION AND SMOKE PROPAGATION

4.1. General objectives and design criteria

The general objectives of fire ventilation are as follows:

- Keep escape way free of smoke during the whole self-rescue phase
- Support the selected intervention strategy with a proper smoke-management strategy
- Prevent smoke penetration into the rescue tube
- Prevent smoke recirculation through the tunnel portals.

In case of longitudinal ventilation, the resulting requirements for ventilation design are:

- The ventilation system shall be designed for attaining the critical velocity
- An overpressure shall be maintained in the rescue tube at all emergency exits.

4.2. Ventilation strategy

Ventilation design depends largely on the ventilation strategy to be adopted in case of fire. The optimum ventilation strategy depends on both fire location and traffic conditions:

- In case of fluid traffic the critical air velocity shall be attained in the fire tube, preventing smoke backlayering over the vehicles stopped upstream of the fire
- In case of congestion downstream of the fire flow inversion should be prevented and a moderate longitudinal air velocity (typically 1-1.5 m/s) can be useful for improving self-rescue conditions
- Exceptional conditions with bidirectional traffic are handled analogously to congestion
- Portal smoke expulsion, depending on local conditions, in case of fire in the immediate vicinity of one portal, depending on air velocity.

Smoke penetration into the parallel tube must be prevented. This can be achieved with:

- Same flow direction as in the fire tube, for preventing smoke recirculation at the portals and generating similar pressure distributions in both tunnel tubes
- Overpressure generated by using part of the jet fans opposite to the flow direction.

In case of congestion downstream of the fire or bidirectional traffic, no jet fans shall be used in smoke-filled areas, where they would instantly destroy smoke stratification. During self-rescue this requirements is generally far more important than a proper control of smoke propagation since escape is impossible without adequate visibility. As shown in the section below, for short tunnels the use of jet fans should generally be prevented in case of congestion.

4.3. Scenario analysis

Congested traffic is coupled with low longitudinal air flow velocities, as there is no piston effect and meteorological effects for short, urban tunnels can in most cases be neglected. Assumption for the scenario analysis is a longitudinal velocity of 0 m/s at the start of the fire incident. Smoke propagation will evolve on both sides of the fire, at the beginning in a stratified manner. If the stratified smoke layer propagates into the influence area of jet fans, stratification will be destroyed and destratified smoke propagation will occur along the tunnel. The self-rescue conditions are worse than without ventilation (example is given in Figure 2).

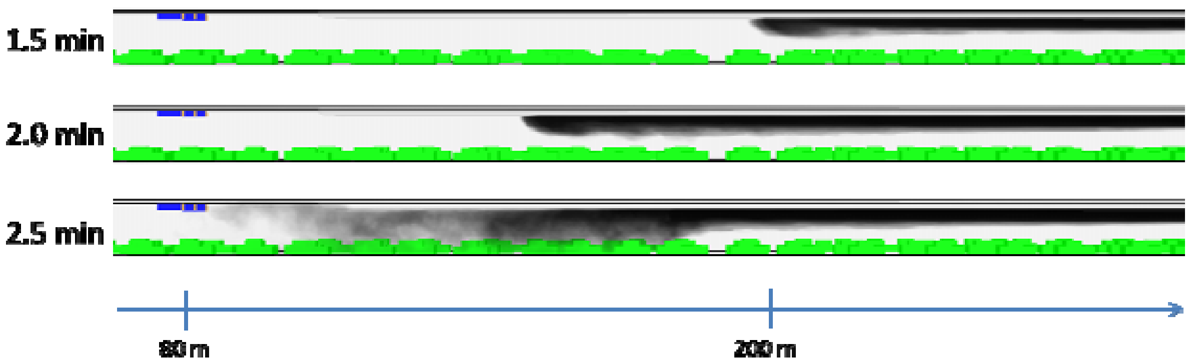

Figure 2: Destruction of stratified smoke layer by activation of jet fans (in this example the jet fans shown above are started at 2 minutes according to scenario timeline)

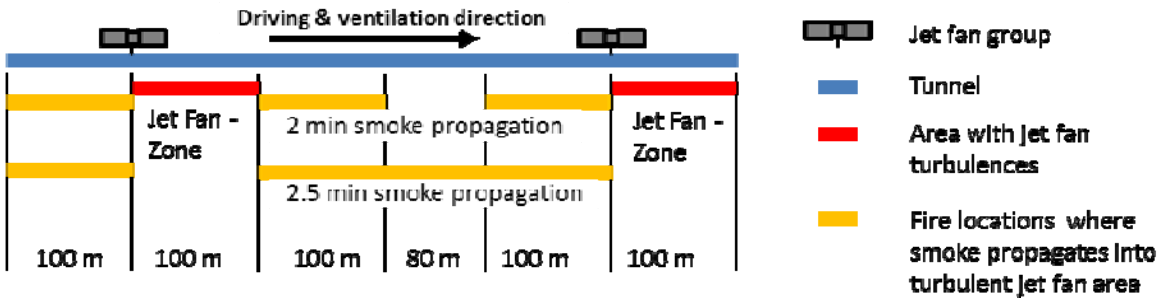

Figure 3: Illustration of fire locations where activation of jet fans would result in destratified smoke propagation for fan installation in the tunnel

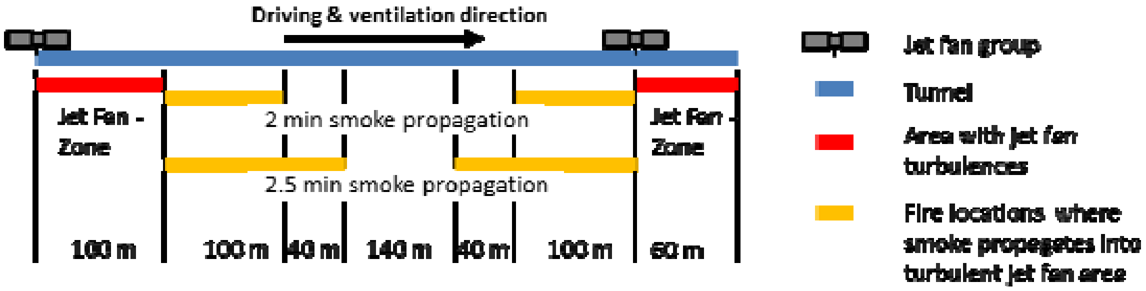

Figure 4: Illustration of fire locations where activation of jet fans would result in destratified smoke propagation for fan installation at portals

In the analysis, the smoke-propagation distance till fire detection (2 minutes according to scenario timeline), has been evaluated by 3D simulation. This allows to evaluate the fire locations for which the ventilation system can be activated without destroying a stratified smoke layer. The result is illustrated in Figure 3. Tunnel sections around jet fan groups are marked red. Activation of jet fans for fire locations in the red sections will certainly lead to destratfied smoke propagation, as smoke is conveyed through jet fans or the turbulent jet impinges on the smoke layer. Yellow marked sections indicate fire locations from where smoke propagates into the influence areas of jet fans (red section), which will lead to destratified smoke propagation. The length of the yellow marked sections is dependent on time between start of fire and acitvation of jet fans.

Figure 3 shows that for short urban tunnels activation of jet fans is problematic for about 85% of the fire locations in case of congested traffic. If activation of jet fans is delayed (2.5 minutes after start of fire), activation of jet fans will cause destratification for all fire locations.

Jet fan location can be optimized. Moving them closer to the portal increases the tunnel sections which are not problematic for longitudinal ventilation. Figure 4 illustrates the situation with optimized jet fan location. Still 60% of fire locations are problematic concerning destratification of smoke layer by activation of jet fans.

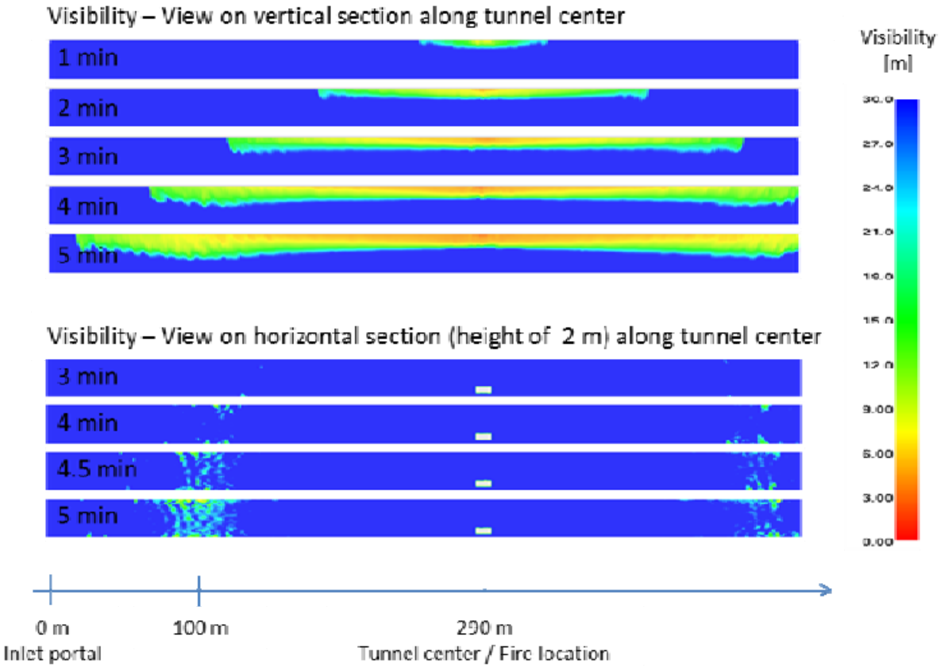

Figure 5: CFD results for fire situation with congested traffic and natural ventilation

Activation of jet fans in short urban tunnels leads with a high probability to destruction of stratified smoke layer and worsens self-rescue conditions. The CFD-analysis shows, that if no longitudinal ventilation is used in case of congested traffic, smoke propagates symmetrically, in a stratified manner along the tunnel ceiling (see Figure 5). The analysis shows additionally, that acceptable conditions for self-rescue can be expected for a duration of about 5 minutes, if no jet fan is activated. After 5 minutes, stratification is gradually lost and areas with a visibility range below 20 m may occur.

Instead of installation of comprehensive ventilation equipment, the means for self-rescue must allow for a fast rescue (within 5 minutes from start of fire) of the incident tube. This allows for safe and reliable operation also in case of congested traffic.

4.4. Means for detection

Detection of congestion in case of wide tunnels with a high number of lanes has to be more sensitive than in common two lane tunnels. The number of vehicles and persons involved in congestion grows fast to a considerable number (50 m of congestion on 5 lanes correspond to 60 persons). The spatial resolution of detection equipment for congestion and fire should allow for accurate detection in the order of at least +/-50 m. Additionally, fire detection must account for the high aspect ratio of wide and comparatively low tunnels, which in most cases requires an increased sensor density. The author's recommendations are as follows:

- The use of CCTV for detection and localization of congested areas
- The use of CCTV for fire detection is not widely accepted due to comparable high number of false alarms. Using common means for fire detection (smoke sensor, heat detector), CCTV data could be used for a more exact localization of fire incidents after alarm of a common sensor. Such an approach would combine the strengths of the different systems.

5. ESCAPE FACILITES

The general requirement for escape facilities according to analysis of smoke propagation is to enable self-rescue within 5 minutes after start of fire. Egress calculations have been conducted for different constellations of escape facilities (1, 3 and 4 cross-passages) and vehicle occupancies. The egress calculations have been performed using the simple approach described by NFPA 130. Validation of some specific cases with the well-established software ASERI has shown excellent agreement (deviations in total egress time of 1% to 3%).

Relevant for the egress time is the person density (number of persons per tunnel length), or the vehicle occupancy respectively. A low person density means that only the distance to the next emergency exit determines the egress time. For high person densities the capacity of means of egress becomes relevant. The limit value for door widths of 1.25 m is 0.853 Persons/s. The mean occupancy for private vehicles in Switzerland is about 1.6 Persons / PCU [5]. This results in following person densities:

- 3 lanes (1.6 Pers/PCU):0.720 Pers / m
- 5 lanes (1.6 Pers/PCU):1.200 Pers / m

Higher person densities are of course possible, either because of an higher general occupancy of cars or owing to the presence of busses. Both have not been considered in the analysis, but would increase the egress time. Buses with up to 55 persons would lead to a capacity-determined egress process and extend the egress time by maximum 35 s.

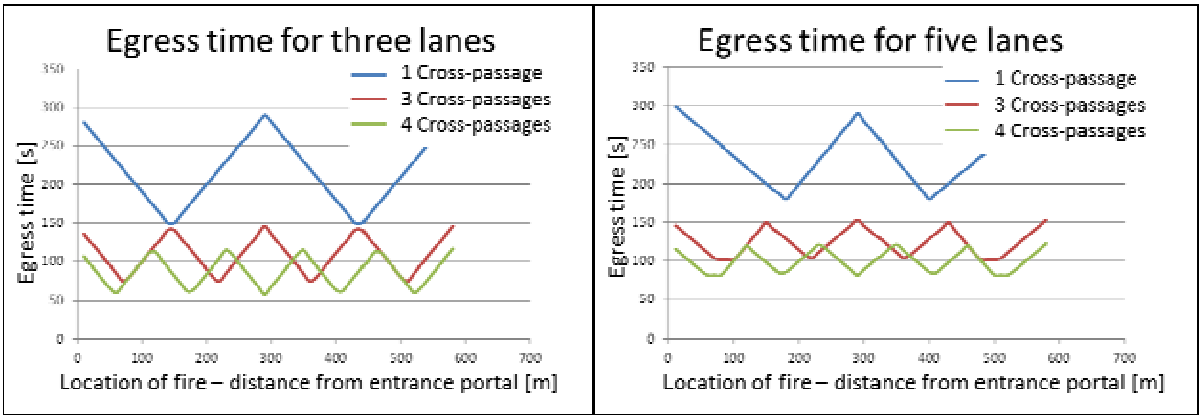

Figure 6: Total egress times as a function of fire location

Figure 6 illustrates egress times for a fully congested tunnel tube in dependence of fire location. Assumption is that fire blocks the tunnel and the fire location cannot be passed. Only the time required to leave the tunnel is accounted for. Time lost through alarming and perception of tunnel users is not included in the illustrated egress time. Egress time peaks occur for fire locations in the proximity of cross-passages and portals as either the nearest cross passage or the path to the close portal is blocked. The egress times for three and five lanes differ little. Larger differences become visible for higher person densities.

According to chapter 3, 2.25 minutes (135 s) for alarming and perception have to be added to the "walking" time in order to get the total egress time from start of the fire incident. The maximum total egress time is presented in Table 3. The main impact on egress time arises from self-rescue distance. Door capacity (width of 1.25 m) is not an issue for common car occupancies, as the self-rescue time for 3 lanes and 5 lanes is almost identical.

Table 3: Total maximum egress times

Variant	3 - Lanes	5 - Lanes
1 Cross-passage	4.8 + 2.25 min = 7.05 min	5.1 + 2.25 = 7.35 min
3 Cross-passage	2.4 +2.25 = 4.65 min	2.5 + 2.25 = 4.75 min
4 Cross-passage	1.9 + 2.25 = 4.15 min	2.0 +2.25 = 4.25min

The design of emergency exits require some attention. Users could reach the emergency exits before the traffic in the safe tube is blocked. In a few European countries, emergency exits are locked under these conditions. This is in the author's opinion inacceptable. As stated by PIARC [3] "emergency exit doors should not be locked".

6. CONCLUSIONS AND RECOMMENDATIONS

This paper showed that normative requirements for road tunnels are not always applicable in a straightforward manner to cut and cover tunnels in urban environments. These are usually characterized by high traffic loads and frequent congestion. A scenario-based approach was presented for analyzing the requirements in terms of ventilation and emergency exits for any specific configuration. The results and conclusions are case dependent, but a few general indications clearly emerge from the analysis of several cases:

- A distance of 300 m between emergency exits is likely to be insufficient in case of short tunnels with natural or longitudinal ventilation
- A door width of about 1.2 m is likely to be sufficient for tunnels with high number of lanes, as egress time is mainly determined by self-rescue distances
- In case of congestion and short tunnels the risk of smoke destratification is high and the best possible ventilation strategy is likely to be natural ventilation (no activation of the jet fans in the fire tube) complemented by providing short self-rescue distances
- Ventilation design must take into account smoke recirculation and over-pressurizing the opposite tube (used for self-rescue)
- Congestion detection must be fast and accurate and thus needs a dense net of point sensors or support from CCTV
- Fire detection needs special attention in case of large numbers of lanes and high tunnel aspect ratios.

7. REFERENCES

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[2] Bettelini, M., Rigert, S. (2013) Scenario-oriented safety design of underground traffic infrastructures. Paper presented at the World Tunnel Congress 2013, Geneva, "Underground – the way to the future!", G. Anagnostou & H. Ehrbar (eds), © 2013 Taylor & Francis Group, London, ISBN 978-1-138-00094-0, pp. 267-274.

[3] PIARC: Road Tunnels Manual, 2011.

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HIGH TEMPERATURE TESTING AND CERTIFICATION OF FANS FOR TUNNEL VENTILATION

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ABSTRACT

In case of a fire incident the axial fans used for smoke and heat extraction in European road tunnels should be capable to handle air and smoke with temperatures of 250 ºC or 400 ºC for a period of 90 to 120 minutes. Increasingly authorities and tunnel operators require certification of such fans in accordance with European Standard EN 12101-3. The Zitron Group has tested and certified numerous axial fans at different testing institutes.
In the paper Zitron Nederland will share their views, experiences and lessons learned during the design, installation and certification of large axial fans for high temperature smoke extraction in road tunnels.

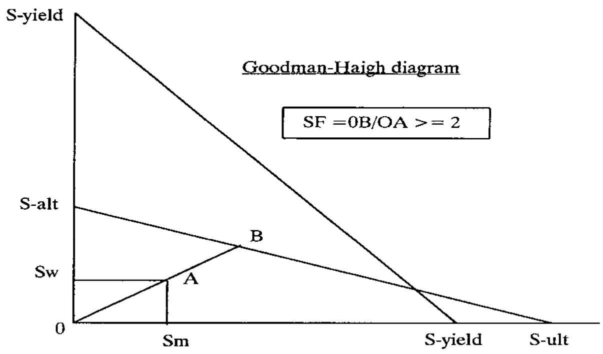
1. INTRODUCTION

One of the main functions of a ventilation system is to create sufficient time for self-rescue in case of a fire incident. Therefore it is important that smoke extraction fans are able to operate for a certain time at elevated temperatures. Contrary to fans for fresh air supply, the fan exhaust fan design has to be based on the high temperature requirements specified by the customer. The performance of the exhaust fan at high temperature operation needs to be verified. This can be done by carrying out a high temperature test in a certified test facility.
Alternatively the fan maker can demonstrate suitability for high temperatures by determining the stresses in the critical parts of the fan and compare these stresses with the high temperature properties of the materials applied. The latter option is considerably less costly.

2. HIGH TEMPERATURE FAN DESIGN

Mechanical design of high temperature extract fans

In general tunnel ventilation systems require a minimum fan design life time of 40 years. To achieve this a design safety factor for combined (static and dynamic) stresses in normal operation of 2 is used by Zitron, see Figure 1.
High temperature material properties vary significantly for short operation compared to continuous operation. Emergency operation in case of a tunnel fire is usually limited to 90 to 120 minutes.
It is generally accepted that after emergency operation critical parts such as blades and drive motor may have to be replaced. Because of this and the limited emergency operating time lower safety factors can be allowed for the high temperature design.
For the high temperature design Zitron uses a safety factor for combined stress of 1.5, see table 2 below.
Correct application of material properties over time is essential for high temperature design. Especially for aluminium alloys there is a large difference between the material properties at high temperature for continuous operation and those for one and a half or two hours.



S-yield: Design yield stress of the material
S-alt: Design alternating stress of the material
S-ult: Design ultimate stress of the material
Sm: Average stress of the fan part
Sw: Dynamic stress of the fan part
SF: Safety factor for combined stress

Figure 1: Safety factor definition

Table 1: Safety factors and the materials used for fan parts

Part	**Material**	**Safety factor Normal operation**	**Safety factor Emergency operation**	**Safety factor based on:**
Blades	EN-GJS-400-15 EN-GJS-500-7	2	1.5	Static and dynamic load
Blade shaft	34CrNiMo6	2	1.5	Static and dynamic load
Hub	EN-GJS-400-15 EN-GJS-500-7 WStE460	2	1.5	Static load
Static parts	S235JR	2	1.5	Static load

2.2. Cooling and thermal isolation of the inner tube(s)

To limit the temperature in the inner tube during a fire emergency, the fan can be equipped with thermal isolation and an external cooling fan, see figure 2. This combination of a cooling fan and thermal isolation reduces the temperature of the parts in the inner tube (motor, hydraulic hoses and oil supply head) during emergency operation significantly.

2.3. Electric motor and cabling.

The design of the E-motor and supply cabling is primarily the responsibility of the motor supplier. Nevertheless it is important to pay attention to the following aspects

- The bearing design for the high temperature operation (e.g. larger clearance and lubrication)
- Insulation class of the windings
- High temperature test certificate of the motor.
- Power supply cable (including the connections) suitable for the high temperature operation.

3. VERIFICATION OF HIGH TEMPERATURE OPERATION CAPABILTY

3.1. Verification by tests in circuits and furnaces in accordance with EN 12101-3.

Recently Zitron Nederland fans as given in table 2 were tested in accredited test facilities.

Table 2: Recent high temperature fan certification tests

	Road tunnel project			
	Bosruck (A)	Bosruck (A)	Gernsbach (D)	Meistern (D)
Test facility	Tunnel Safety Testing, Spain	Tunnel Safety Testing, Spain	Materialprüf-anstalt (MPA) TU Braunschweig	Tunnel Safety Testing, Spain
Temperature	400 °C/135 min.	250 °C/120 min.	250 °C/90 min.	250 °C/90 min.
Impeller diameter	2512 mm	2512 mm	1884 mm	2113 mm
Blade adjustment	Hydraulic	Hydraulic	Hydraulic	Hydraulic
Installation	Horizontal	Horizontal	Vertical	Horizontal
Test Set-up	Fan connected to furnace by recirculating duct system	Fan connected to furnace by recirculating duct system	Fan mounted inside furnace	Fan connected to furnace by recirculating duct system
E-Motor Power	450 kW	450 kW	710 kW	400 kW
Fan drive during the test	Frequency converter	Frequency converter	Frequency converter	Frequency converter
Fan speed	1000 rpm	1000 rpm	1500 rpm	1500 rpm
External cooling	Yes	No	No	No

Besides the cost of and the time required for the actual test and certification procedure, the cost and lead time of an additional fan-motor-unit has to be taken into consideration. This makes verification of high temperature capability a costly and time consuming method.

3.2. Verification by design calculation

Because of the cost and time required to certify an exhaust fan according to EN 12101-3, customers and authorities often accept a design report as an alternative means of verification.
In this method the stresses of the rotating fan parts are determined with the finite element method. The calculated stresses are then compared with the high temperature properties of the materials. If the calculated safety factors are equal or better than mentioned in table 2 above, the fan meets the high temperature design conditions. In the last 10 years Zitron Nederland supplied over 80 exhaust fans for road and rail tunnels in Germany, Austria, Switzerland and Benelux countries where high temperature capability was verified by comparing the calculated stresses with laboratory tests of the high temperatures properties of the materials used.

3.3. Type approval for a range of large axial exhaust fans

Annex A of standard EN 12101-3 gives a possibility to obtain type approval for a range of fans. It is not required to test each and every fan of a product range provided that a list of criteria is met. These criteria relate to number of tests, stress levels, mounting arrangement, drive motor size and speed and geometric similarity.

As far as fans for tunnel ventilation are concerned, certification of a range of jet fans considering these criteria, is very well possible and has been done by various fan suppliers.
However, this is not valid for large axial exhaust fans.
Large axial exhaust fans are selected and designed to meet the required duty points and operating regimes as dictated by tunnel geometry, traffic parameters and EU/national guidelines. Fan suppliers optimize fan selection by considering various parameters such as:

- Impeller diameter, hub diameter
- Number blades, blade material, blade chord width
- Blade profile uni-directional, (partly or fully) reversible
- Blade adjustment hydraulically during operation or manually at standstill
- Nominal powers and rotating speed(s) of drive motors

The optimization is aimed at low energy consumption. This is an important factor as apart from the operational cost, exhaust fan power consumption influences installation cost of power supply systems and cabling considerably.

The result of this optimization process is that the chance that a tested and EN 12101-3 certified large exhaust fan design can be used for a future tunnel requirement is very small. Insisting on application of an already certified fan may result in sub-optimal fan design and higher installation cost. Furthermore it is our experience that certifying bodies are hesitant, if not unwilling to issue EN 12101-3 certificates for large axial fans for tunnel applications when the fan is similar but not identical to a tested fan.
This applies especially to large exhaust fans with blade adjustment during operation.

3.4. Evaluation of test certificates

Currently the version EN 12101-3:2002 is in force. The version EN 12101-3:2010 is expected to be released shortly. In case the validity of a fan test certificate has to be evaluated for use in new installations, following aspects should be considered:

- Impeller diameter, hub diameter, blade adjustment mechanism and number and geometry of blades of selected fan have to be identical to tested fan.
- Nominal motor power should not be higher and be no less than 80% of the power of the tested fan.
- Drive motors should be identical, use of an alternative drive motor makes the certificate invalid.
- When the fan is to be equipped with a variable speed drive (VSD), the tested fan should also be driven by VSD. When a fan is tested without VSD the thermal load on the drive motor is lower, making the certificate invalid for VSD drive. It is possible to get around this problem when the VSD is by-passed after start-up of the fan.

- A certificate based on a test in horizontal position is not valid for a fan in vertical position
- The EU-MEPS directive regarding minimum efficiency of electric motors up to 375 kW will result in drive motor construction changes. A certificate of a fan tested with a lower efficiency class motor will not be valid for a fan with a high efficiency class motor.

4. EFFECT OF THE USE OF AN EXTERNAL COOLING FAN.

Large exhaust fans can be equipped with or without auxiliary cooling systems, with corresponding high temperature certificates. To reduce installation and operating cost designs may choose not to install such a cooling system.
The cooling fan provides cooling to the inner tubes with the motor and to the inner tube with the rotating oil supply device and the hydraulic hoses, see figures 2 and 3. To reduce the heat flow into the inner tube these inner tubes are equipped with thermal isolation.

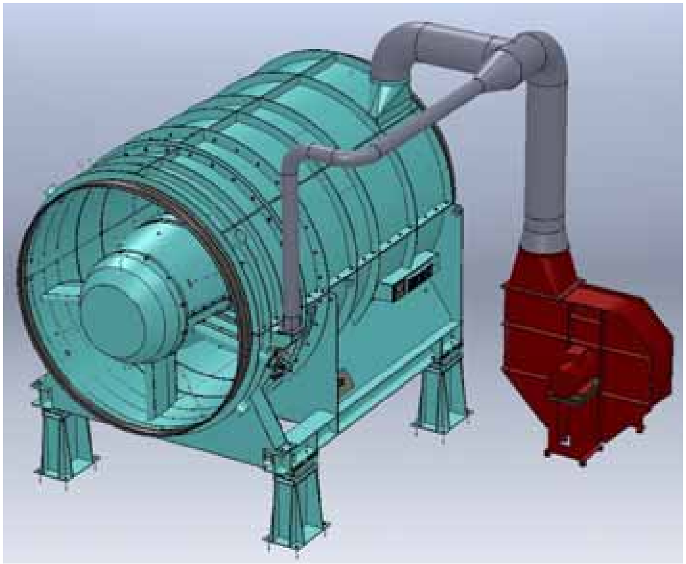


Figure 2: Exhaust fan with auxiliary cooling fan

To demonstrate the effect of auxiliary cooling Zitron Nederland performed the 400 °C test on the exhaust fan for the Bosruck tunnel with cooling air and repeated the test at 250 °C without cooling air.

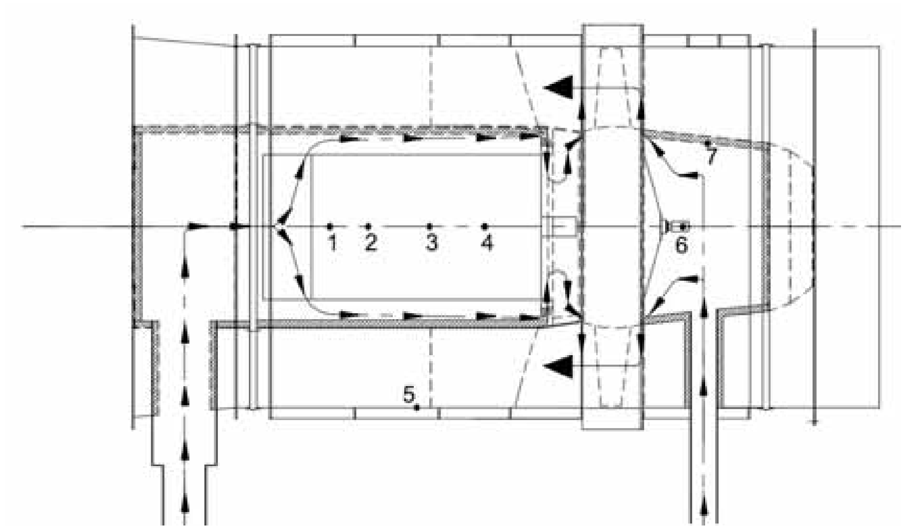


Figure 3: Cooling air flow with auxiliary cooling fan

Test set-up

To measure the temperatures in the inner tubes 7 thermocouples type K were installed:

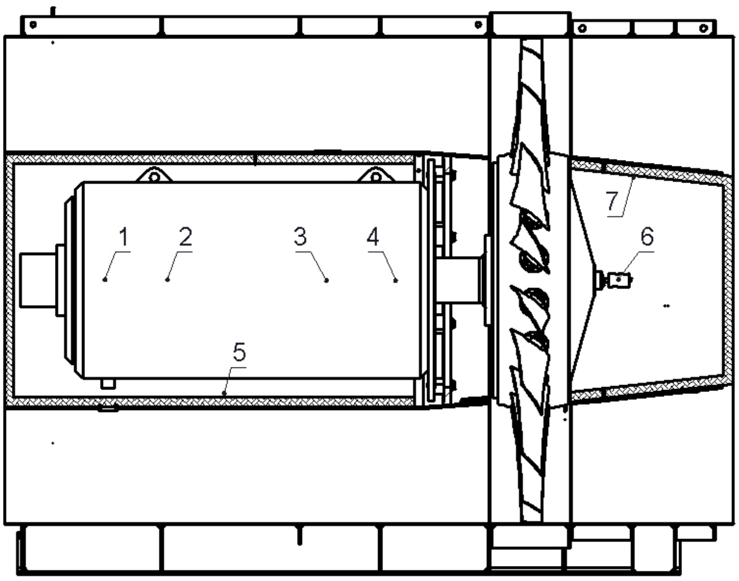


Figure 4: Thermocouples arrangement

1: Surface of the motor at the position of the non-driven end bearing
2: Surface of the motor
3: Surface of the motor
4: Surface of the motor at the position of the driven end bearing
5: Inner surface of the tube with the motor.
6: Surface of the rotating oil supply device.
7: Inner surface of the tube with hydraulic hoses and rotating oil supply device.

Test results

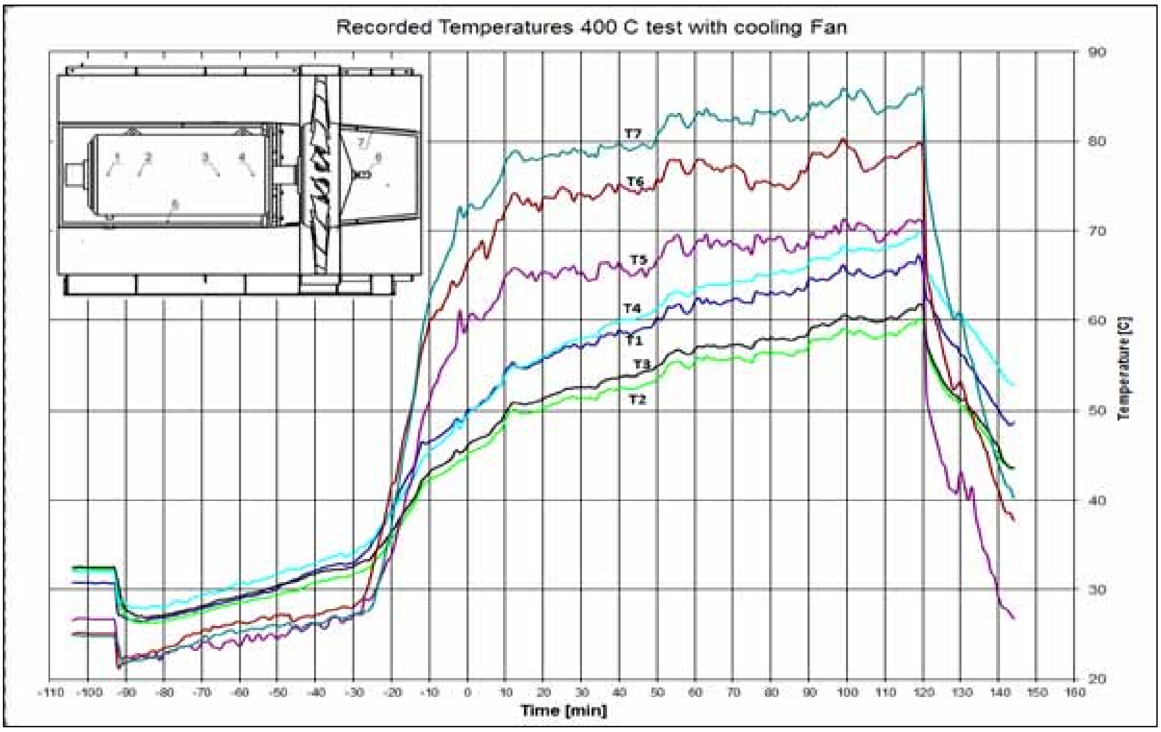


Figure 5: Recorded temperatures, test at 400 °C with cooling fan

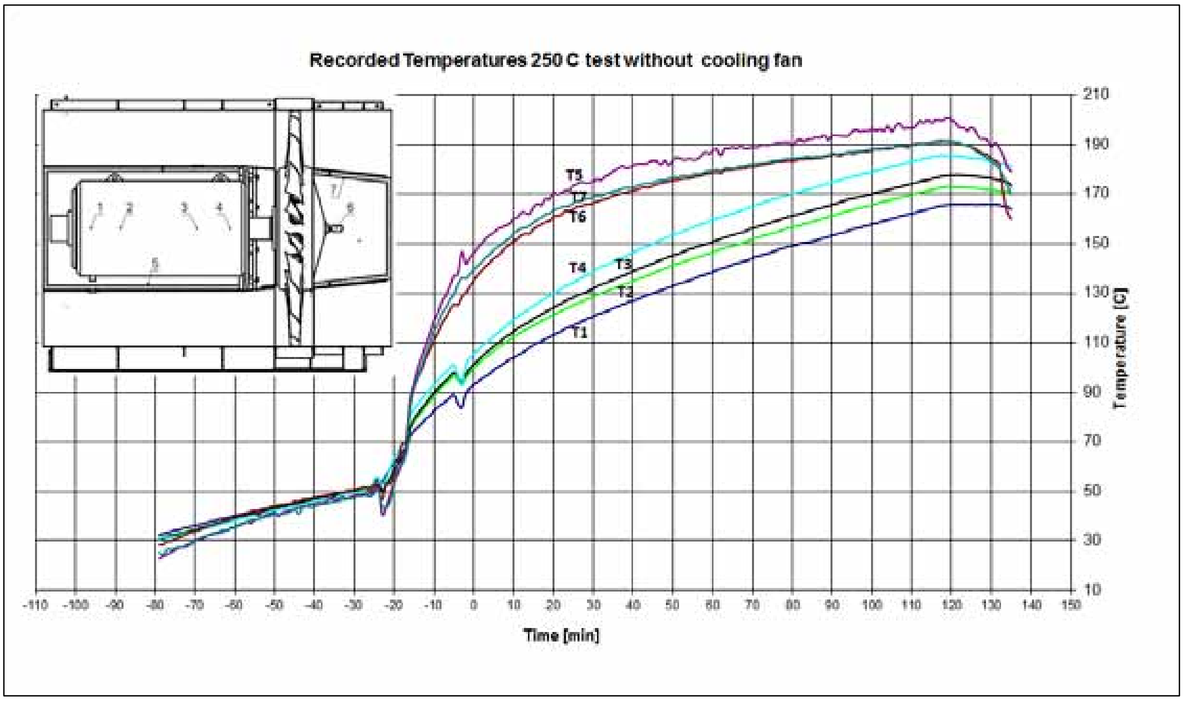


Figure 6: Recorded temperatures, test at 250 °C without cooling fan

The test shows that use of an auxiliary cooling system results in temperatures which are just above normal operating temperatures of the drive motor, even during a test at 400 °C.
Without cooling system the temperatures rise quickly to temperatures close to the test temperature.

After a fire incident the fan may have to be equipped with new blades.
With the availability of adequate spare blades this can be done in a short period of time.

As the temperatures during the emergency situation are not much higher than the operating temperature, the drive motor does not have to be replaced. The unavailability of the tunnel to the traffic can be reduced significantly.

For exhaust fans with auxiliary cooling a drive motor with a lower temperature certification could be considered, offering an opportunity for cost saving.
Furthermore, the use of an auxiliary cooling system reduces the risk of failure from the motor, the rotating oil supply device or hydraulic hoses considerably.

5. CONCLUSIONS

- High temperature certificates of large exhaust fans based on past testing have to be carefully evaluated on validity for new applications. Most likely a new high temperature test is required.
- Availability of certificates may drive fan selection and result in less efficient fans.
- Design reports can be considered as an alternative means of verification.
- The use of an external cooling system reduces the temperatures in the inner tubes considerably resulting in less down time of the tunnel after an incident and offering opportunities for cost savings.

EUROPEAN DIRECTIVE: GUIDELINES FOR TUNNEL SAFETY OFFICERS IN THE FRENCH CONTEXT

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ABSTRACT

European Directive: Guidelines for Tunnel Safety Officers in the French context:

The European directive 2004/54/EC on tunnel safety (and its transposition in member states) defines the activities, responsibilities of four entities: the administrative authority, the tunnel manager, the inspection entity, the tunnel safety officer, and their relations between them and with the emergency services.

The paper is an attempt from a tunnel safety officer working in the French context to show, from his standpoint, how to perform his duty. After giving a few statements derived from the Directive itself (in its French transposition) and from experience, the “tasks and functions” of the directive are reviewed and commented.

1. PREAMBLE

In the process of transposition of European directives within each member state laws and regulations, some (normally minor) discrepancies may appear. It is also in the Tunnel Safety Officer (TSO) attribution to speak his mind. Therefore, the content of this paper engages only its author and may anyway differ on some aspects, which will be duly mentioned when appropriate, from what it would be in other member states.

2. INTRODUCTION

Following the publication of the European directive 2004/54/EC on tunnel safety and its transposition in member states by 2006, people in charge of the newly position of Tunnel Safety Officer had to invent a new job, at least new in the area of road tunnel: New, but based on a list of 7 “tasks and functions” described in the directive, based on the description of the various “safety actors”, and based on the principle of independence of the TSO in his (her) statements.

Based on the experience gained in the meantime, it appeared interesting to somehow complete the base of the TSO activity above mentioned by a subjective view in the French context, as mentioned in the preamble, with the ambition of providing a base for some general guidelines to help TSO’s in the application of the directive.

This paper starts with a few “general statements” that will then be detailed within each of the 7 assignments.

3. STATEMENTS (BASED ON THE EUROPEAN DIRECTIVE)

3.1. Statement 1

The fundamental reason behind the creation of the position of Tunnel Safety Officer (TSO) is to create as much awareness as possible of all “safety actors”. The Tunnel Safety Officer makes sure, as much as his position permits, that all available information is reasonably used by responsible actors using their respective expertise and that, when deemed necessary, additional expertise is sought. This cannot be better exemplified than by quoting an expert in risk analysis in nuclear power plants (Ralf Mock, FHZ, Switzerland, during ITA-COSUF workshop Frankfurt 8th June 2010):

To achieve a high level of safety, the key is creating multiple, independent and redundant "layers of defense…"

The TSO should always make himself available for discussion with the "safety actors" especially with the tunnel manager, and take any occasion to state his availability. Output of these discussions should always be put in writing. The same actually goes, whatever the result, with his overall activity.

3.2. Statement 2

The tunnel manager is the decision-maker, under the supervision of the authorities. The tunnel manager is also the provider of information and as such, he is central in making sure, as mentioned in statement 1, that the experts, emergency services… and the TSO will perform well and will be able to give their feedback (to be shared with the authorities).

In case of information obtained from another source, clarification should be requested from the tunnel manager.

4. STATEMENTS (BASED ON EXPERIENCE)

4.1. Statement 3

The author's experience shows that, **once tunnels have been upgraded to reach European requirements as defined by Directive 2004/54/EC**, further improvements are mostly achieved with regards to **organisation, coordination, training and maintenance**. It might be worth mentioning to tunnel managers that this is often done with little financial consequences other than the time spent thinking, discussing and making decisions on these topics *(that would come as no surprise to companies or organisations having experienced more than once that, by improving the quality of their products or services, they had also, at the same time, reduced their costs).*

4.2. Statement 4

Generally, and more specifically on the 4 items mentioned just above, the importance of **lessons learnt from experience** must be stressed. In that regard, debriefs made collectively by the tunnel manager and emergency services, plus the TSO on "significant events" are of paramount importance (being informed, the authority could decide to participate, or at the very least, will be informed with the Safety documentation yearly update).

Beside the definition given by EU member states of what is a significant event, some events minor in their consequences could prove major by their significance and any opportunity to learn from them should also be taken. This lies mostly in the hands of the tunnel manager (and services involved if any).

Agreements on what went wrong and what should be done are generally not very difficult to obtain, though it is sometimes obtain at the cost of a somehow vague description. If otherwise, the TSO should nevertheless request his position to be mentioned, and, if not possible, give in writing his position to the tunnel manager.

These lessons might be of interest for other tunnels, operators, etc.

5. TASKS AND FUNCTIONS OF THE TSO

a) Ensure coordination with emergency services and take part in the preparation of operational schemes

The French transposition states that coordination is mostly done by taking part in the preparation of operational schemes. This was done, it seems, to be more coherent with the fact the TSO has no other credit than the possibility of independently giving his view on any safety related matter.

The bases for discussion with the tunnel manager, services and the authority are:

- The safety documentation;
- Emergency plans (plus operational schemes provided by the emergency services if not included);
- Regulations;
- Lessons learnt from experience (emergency operations, exercises, tunnel or equipment failures);
- Any information the tunnel manager transmitted to the Tunnel Safety Officer.

b) Take part in the planning, implementation and evaluation of emergency operations

Taking part in planning and implementation is mostly done through tasks: a, c and e. As for evaluation, it is suggested to debrief emergency operations just like exercises (see item g below).

(c) Take part in the definition of safety schemes and the specification of the structure, equipment and operation in respect of both new tunnels and modifications to existing tunnels

For new tunnels and modification to existing tunnels, in order to perform that task, the tunnel manager should involve the TSO in the process as early as possible (1 or 2 years for a new tunnel, several months for a modification).

The Safety Documentation describing the tunnel as being built, then as built, should provide most of the information necessary for the TSO. This may be complemented by seeking clarification from the experts who provided this documentation.

While highly recommended, the participation at project and construction stage does not imply the TSO agreement on decisions made (some possibly against his view) and the documentation, once finalized, will be independently reviewed before being submitted to the authorities.

(d) Verify that operational staff and emergency services are trained, and he/she shall take part in the organization of exercises held at regular intervals

French transposition: Verify the existence of training programs for operational staff and emergency services and their implementation.

The documents showing the reality of the training of the operational staff should be provided on a regular (yearly) basis by the tunnel manager. As for the emergency services, the verification can hardly include the very core of the job of a fireman or a policeman and should focus on training regarding the tunnel specificities. It is suggested that a training program for and with emergency services be built with the tunnel manager including a tunnel visit (tunnel itself, access, installations). The safety documentation should provide most of the necessary information. Training sessions should be organized by the tunnel manager at the emergency services request.

Exercises can be included in the training program for all staff. Active or passive (observer) participation should be encouraged.

Planning and evaluation of exercises provide two occasions for debate with the “safety actors”. For planning, the main focus is on choosing a theme that seems relevant and organizing it; as for evaluation, it is on the lessons drawn from the exercise.

Besides, these two meetings provide an opportunity to discuss on any matter pertaining to the other TSO tasks and functions, would it be difficult to organize specific gatherings. At the minimum, the need for such gatherings, for documents and one’s availability should be stated.

(e) Give advice on the commissioning of the structure, equipment and operation of tunnels

Under French regulations:

TSO advice is given to the tunnel manager;

The tunnel manager is in charge of transmitting the Safety Documentation to the administrative authority every 6th year (or less in case of substantial modification or at the administrative authority’s request) and a yearly update in between, ***together with the TSO advice regarding these documents****;*

The tunnel manager is in charge of transmitting to the administrative authority and emergency services ***all other pieces of advice given by the TSO****.*

Beside the one or two fields of expertise the TSO may have, he should not refrain from asking further analysis or expertise if deemed by him necessary.

States regulations would normally request mandatory structure and equipment commissioning, then regular inspections. These should provide enough information in their conclusions for the TSO whose main tasks in that respect would be to:

Make sure these regulations are applied (content, frequency);

Follow the implementation of conclusions made

Minimum operation parameters (when a given parameter is below the threshold mentioned in the Safety Documentation, the tunnel should be closed):

These parameters should be derived as much as possible from the risk analysis included in the safety documentation.

A typical example for a tunnel equipped with longitudinal ventilation is the number of fans out of order:

Acceptable before operating the tunnel in a degraded mode
Acceptable in a degraded mode before closing the tunnel

Some parameters would be based on a qualitative assessment.

All of them should anyway be adjusted based on experience.

(f) Verify that the tunnel structure and equipment are maintained and repaired

French transposition: Verify the existence of tunnel structure and equipment maintenance programs and their implementation

Due to the very large variety of equipment in tunnel, it seems reasonable to pick, on a yearly basis for example, and based on experience, a type of equipment to be thoroughly verified, such as:

Structure commissioning;

AID system rate of availability, performance;

Ventilation (sometime highly demanding) mechanical and electronic systems

Water supply

Etc.

For each item, the documentation provided should show that:

The maintenance program exists

The frequency of tests, cleaning, settings given in the program are followed

If a test failed, action is promptly engaged

(This is based on the assumption that the maintenance is reasonably well done, as should be the case on the TERN. Otherwise, a stronger action should have to be taken. For new or refurbished tunnels, how demanding are the minimum operation parameters can give a clue on how the tunnel manager is confident on the tunnel and its equipment).

Additionally, equipment (or structure) failure pushing the tunnel in a degraded mode or to be closed should be debriefed thoroughly.

(g) Take part in the evaluation of any significant incident or accident as referred to in Article 5(3) and (4)

Exercises should be treated more or less the same way as incident-accident in the evaluation process.

Lessons learnt from experience should normally be based on the following sequence:

Facts>Remedies>Implementation>Evaluation;

And back to remedies if not satisfactory (following the classical method of Quality Improvement).

A table of all pending or being processed remedies decided based on the evaluation should be established, updated and discussed on a regular basis during meetings between the tunnel manager and the TSO.

6. CONCLUS

7. IONS

While being always ready to discuss any tunnel safety matter, the author, as a tunnel safety officer himself, is unlikely to change his view regarding the four statements heading that paper, specially the two first on the European Directive understanding. This owes a lot on the discussions that took place within the ITA-COSUF working groups and more specifically on the first European TSO Forum that took place in Lyon in 2009.

If the rest of what is written above can help each TSO find his own way, following or not the tracks suggested, the objective of that paper will have been reached. That being said, I wish to close this paper with another quotation, from M. Arnold Dix, scientist and lawyer, during the already mentioned European Forum in 2009:

“Independence: Ability to write unpopular opinions without recrimination”

INCREASED TUNNEL AVAILABILITY THROUGH MODEL BASED DECISION SUPPORT

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ABSTRACT

Tunnel safety depends on several systems operating as designed at the required moment. Tunnel Technical Installations (TTI) may function as expected in new tunnels but their functionality will decrease with aging. Maintenance processes help keep the tunnel in good condition, but it is hard to determine the actual safety level. For example, it is difficult to determine if a TTI defect can wait a few days for repair or should be repaired immediately with the tunnel closed. This is where model-based decision support comes in. This article describes the Tunnel Safety Indicator, a model in use in the tunnels of the Dutch cargo train link between Rotterdam seaport and the German border which is now being built into all the other Dutch railway tunnels. Application of this model in road tunnels has just started with a first pilot project.

The top level of the model consists of the four Lines of Defense, i.e. prevention, mitigation, evacuation and rescue. These Lines of Defense must be available at a certain minimum level in order to consider a tunnel safe and available for traffic. Within the tunnel complex, these Lines are maintained by Safety Functions (2nd level). In the Dutch situation there are approximately 45 Safety Functions for a two-tube tunnel. These Safety Functions are fulfilled by the tunnel's technical systems (3rd level) and ultimately by the technical components (4th level) in a tunnel (Figure 1). This model enables the definition of business rules regarding the deterioration of installations and the ultimate effect of deterioration on the more abstractly defined level of tunnel safety. Using the output from the technical installations (SCADA) combined with the results of regular inspections, the Tunnel Safety Indicator provides an accurate and objective indicator of the tunnel safety required by or agreed upon with the authorities.

Keywords: tunnel safety, decision support system, lines of defense, functional safety/availability

1. INTRODUCTION

During the last few decades, road and railway tunnel disasters have led to an increased interest in tunnel safety. This interest not only focuses on the design and building stages of new tunnels but also on the exploitation of existing ones. Many existing tunnels have the following characteristics:

- increased complexity and a large number of installations and software
- an increased focus on availability (the traffic must not stop)
- deterioration over time that can be quite different per tunnel technical installation
- lack of an objective method to determine when and what systems need maintenance, renovation or replacement
- difficulty in determining whether and how long a safety measure can be compensated by other safety measures
- an operating system with technical troubles from time to time
- lack of an objective method to determine when an operating system has become so weak that safe exploitation is no longer justifiable.

The tunnel operator continuously has to make choices between availability, necessary maintenance and temporary compensatory or mitigating measures. As a consequence, a special tool has been developed for the five cargo railway tunnels in the Rotterdam-German border link (the so-called *Betuweroute*) in the Netherlands, in order to help the operator in this permanent weighing and balancing between availability and safety; this tool is called the Tunnel Safety Indicator. The tool was tested, tuned and evaluated for a year and has been in official use since 2009. Experiences with the Tunnel Safety Indicator have been so positive that it will be built into all Dutch railway tunnels. In addition, a pilot project is underway to apply the Tunnel Safety Indicator in road tunnels.

2. ANALYSIS

In general, tunnel safety is assessed by looking at the availability of safety functions (measures or provisions for safety) within the four Lines of Defense (LODs), i.e. prevention, mitigation, evacuation and rescue [1]. These LODs must be at a certain minimum level for a tunnel to be considered safe and available for traffic, and they are maintained by the Safety Functions within the tunnel complex. Safety Functions are fulfilled by the tunnel technical systems and ultimately by the technical components in a tunnel. A ventilator (component), for example, is part of the ventilation (system) that takes care of clean and fresh air (function) needed in three different lines of defense, namely safe passage (prevention), safe escape (evacuation) and safe help (rescue).

In the Tunnel Safety Indicator, installation components have been combined into systems offering functional safety in order to maintain the LODs necessary for a safe tunnel. This model makes it possible to define business rules regarding the deterioration of installations and the ultimate effect of this technical deterioration on the more abstractly defined level of tunnel safety that is required by or agreed upon with the authorities. Using the output from the technical installation components through the Supervisory Control and Data Acquisition (SCADA) system in combination with the results of regular inspections, this model provides an accurate and objective indicator of tunnel safety.

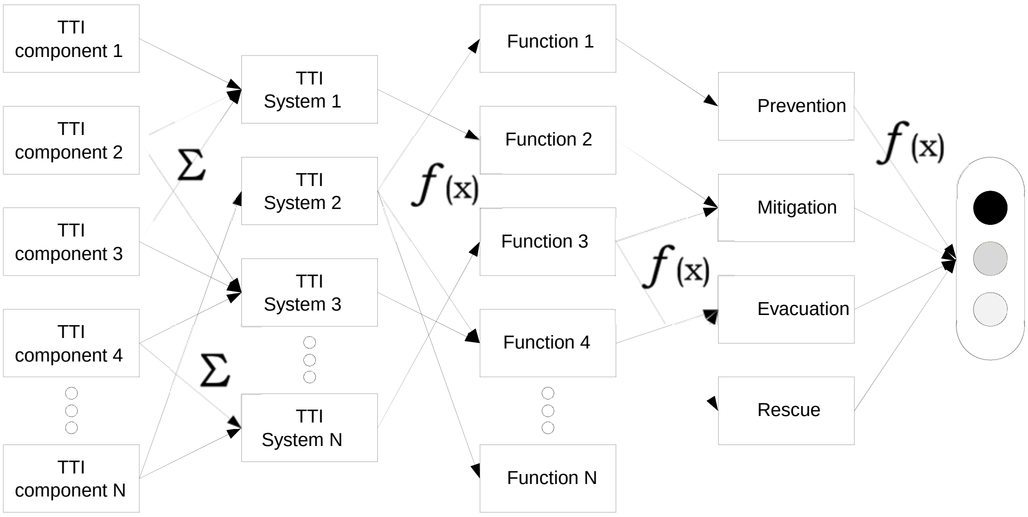

Figure 1: Model to determine safe tunnel availability

This model and the related systems have been developed with three aims in mind:

1. To arrive at an accepted indicator of the agreed safety level of a tunnel by which internal and external parties can be informed transparently and objectively.
2. To gain insight into the condition of a Line of Defense , by providing detailed information about the status of components throughout the systems and functions to the final status of the LOD; this information should be both objective and traceable.
3. To prioritize maintenance based on the expected and actual deterioration of tunnel safety.

3. THE MODEL

Figure 2: Model layers and their interrelationships

The first objective was to create a layered model that would make a link between an abstract definition of safety and concrete technical data. Using the TSI-SRT [1] Lines of Defense (prevention, mitigation, evacuation and rescue) as a starting point for the abstract definition of safety, the Safety Functions have been defined such that they support the Lines of Defense. It appears that these Safety Functions largely comprise the same functions for different road and railway tunnel projects. These Safety Functions serve as functional requirements, which is why they were used to compile a definition of

Logical Systems fulfilling these requirements. Lastly, these Systems were broken down into Components, which are the smallest technical units that produce status data. This approach has led to a four-layer model: Lines of Defense – Safety Functions – Logical Systems – Components. The model resembles a graph fanning out from the LODs to the Components. Between every layer there are business rules, which define how the status of a particular level influences the status of the level above it. This chain of reasoning propagates from the concrete Component layer up to the more abstract Lines of Defense and ultimately to the Tube.

3.1. Component layer behavior and business rules

The component layer contains the definition of all physical components in the Tunnel Technical Installation. The following business rules apply:

- A Component is always either Available (A) or Not Available (NA).
- The SCADA system indicates the status of Components.
- A Component always belongs to only one System, and each System contains one or more Components (one-to-many relationship).
- Each Component is given a weight, thus indicating its relative importance to the System to which it belongs.
- A Component may have a specific position (ordering) in a tunnel tube.
- The status of a Component is either reported by the SCADA system or manually determined as the result of an inspection.

Example:
In a sprinkler system, a section valve and main valve for two adjacent sections are examples of components belonging to the same system. The main valve has twice the weight of the section valve, as its importance to the system is similar to two adjacent section valves. Section valves are numbered sequentially in the tube, which indicates their ordered position.

3.2. System layer behavior and business rules

The system layer models the physical systems as closely as possible. Systems are collections of components. The availability of these components determines the total system availability. The following business rules apply:

- A System consists of one or more Components
- A System has a maximum availability, which is determined by adding up the weights of all the Components it contains:
  $$S_{\max} = \sum C \qquad (1)$$
- A System has an actual availability value, which is determined by adding up the weights of all the components with the status Available:
  $$S_{actual} = \sum C_{Avail} \qquad (2)$$
- Special rules for degradation may apply, in which case the system degrades further than the sum of the Non-Available components. An extra value R is subtracted from the system availability if such rules apply, acting as a penalty.
- Actual availability is never less than 0.
- A system can contribute to multiple Functions. The weight for each Function will be set such that it indicates the contribution of the specific system to that function.

Example (simplified):
A sprinkler system consists of 100 section valves with a weight of 1, so $S_{\max} = 100$.

There is a special Rule that says that no two consecutive section valves may have state NA. If this rule is breached, then an additional deduction of R = 5 applies. In the following numerical example two adjacent section valves have status NA: $S_{actual} = \sum C_A - R \Rightarrow 98 - 5 = 93$. Therefore the system has a current availability of 93 out of 100 (or 93%).

3.3. Function layer behavior and business rules

Safety Functions define abstract behavior of the Tunnel which can be realized by one or more systems, which may or may not be redundant. It is particularly important to make a distinction between Safety Functions, which define the functional behavior of an abstract system such as ‘ventilation’, and system functions, which describe the technical behavior of an installation such as a ventilator. The following business rules apply:

- A Function has either the state Available (A) or Not Available (NA).
- A Function is realized by one or more Systems (many-to-one relationship).
- Within a Function, systems may overlap, for example handrail, lighting and exit signs overlap within the Safety Function ‘offering an escape route’.
- For different combinations of Systems, the thresholds can be set per individual system. By using simple proposition logic (and/or combinations of Systems), the status of the Function can be determined.
- A Function can be assigned to one or more Lines of Defense (one-to-many relation).
- For every Function-LOD assignment, a Safety Class will be set, indicating the contribution (the weight) of the specific function to the specific LOD.

Example:
To realize the Function ‘cooling tunnel downwind’, the sprinkler system must be available at a 95% minimum (see the previous example). The longitudinal ventilation system, which has a maximum availability of 30 based on the added weight of its components (ventilators), has a minimum limit of 80% when running on mains power. If running on emergency power, the minimum limit on availability is adjusted downward to 40%. Maximum availability for mains and emergency power is 1 (assumptions are made for this example):

Overlap	System	Symbol for actual value	Smax	Slimit
	sprinkler system	Ssp	100	95 (95%)
1	longitudinal ventilation	Slv	30	24 (80%)
	mains power	Smains	1	1
2	longitudinal ventilation	Slv	30	12 (40%)
	emergency power	Semer	1	1

The availability (True: 1 or False:0) for this Safety Function can be presented in the following formula:

$$F = S_{sp} \geq 95 \wedge \left(\left[S_{lv} \geq 24 \wedge S_{mains} \geq 1 \right] \vee \left[S_{lv} \geq 12 \wedge S_{emer} \geq 1 \right] \right) \tag{3}$$

This means the Function is either Available, value 1, or Not Available, value 0.

3.4. Line of Defense layer behavior and business rules

Lines of Defense are maintained by Safety Functions. When one or more function is lost, the LODs deteriorate until they are breached. This mechanism is modeled by assigning Safety Class thresholds to the different states an LOD can have. The following business rules apply:

- For every Function-LOD assignment, a Safety Class will be set, indicating the contribution (the weight) of the function to the LOD.
- An LOD has the status Not Degraded, Degraded, Severely Degraded or Breached.
- An LOD is maintained by one or more Safety Functions (many-to-one relation).
- The LOD state is determined by calculating the Safety Classes (the total weight) of its underlying Safety Functions with the state Not Available, and evaluating that sum against a predefined threshold (for example: the threshold for Degraded is 1, the threshold for Breached is 6).

	Lost Safety Functions (count) per LOD		
	1	2	3
Safety Class 1	Degraded ∑ = 1	Degraded ∑ = 2	Severely Degraded ∑ = 3
Safety Class 2	Degraded ∑ = 2	Severely Degraded ∑ = 4	Breached ∑ = 6
Safety Class 3	Severely Degraded ∑ = 3	Breached ∑ = 6	Breached ∑ = 9

Figure 3: Total degradation for Safety Classes and count of lost Functions

Example:
In the table above all combinations of Safety Classes (3) and relevant number of Lost (= unavailable) Safety Functions are shown together with the resulting sum of degradation. The threshold for the status Degraded is set at 1. The next threshold, for the status Severely Degraded, is set at 3 and the final threshold for the status Breached is set at 6. So if two Functions with Safety Class 2 are unavailable, the total sum of degradation is 2x2=4. Because 4 > 3 (the threshold), the LOD in question is Severely Degraded. There is no need to show more than 3 unavailable functions, as that will always lead to a minimum sum of degradation of 4.

3.5. Tunnel Tube layer behavior and business rules

On the highest level in the model, safety per tunnel tube is determined based on the state of its four Lines of Defense. A Tube has an operating status, which can be Operation, Maintenance or Emergency. The safety status is assessed only during the state Operation; in the other two cases the safety status is Undetermined.

- A Tube can have the state Green (safe), Yellow (degraded safety) or Red (unsafe).
- The safety of a tube is assessed by means of four Lines of Defense: prevention, mitigation, evacuation and rescue.
- The status Severely Degraded in one LOD causes a status transition to Yellow.
- A tube can only have a Yellow status for a certain amount of time. If this time elapses without any transition back to Green, a status transition to Red will automatically occur.
- If the status of one or more LODs is Severely Degraded or Breached, this causes a transition to Red. If this transition occurs from the Yellow to Red status, the maximum time for Yellow continues to count down in the background.
- If during the status Red, LOD conditions for the status Yellow are met, transition to Yellow takes place. The remaining time for the status Yellow is not reset, but this time continues to count down.

4. TUNNEL SAFETY INDICATOR

The MUST™ suite of applications was used to create the Tunnel Safety Indicator. At present, this Tunnel Safety Indicator (TSI) tool is operational in the five cargo railway tunnels in the Rotterdam-German border link (the *Betuweroute*), and in the near future it will be implemented in all Dutch railway tunnels and several road tunnels. The tool has been certified by an accredited third party and is tamper-proof.

4.1. System architecture

The model described above can be configured for a specific tunnel using the MUST™ Engineering application. Simulations can be run using different configurations based on actual (logged) or simulated data from the SCADA systems. Simulation can also be used to test and certify (FAT) a new configuration before it goes into production.

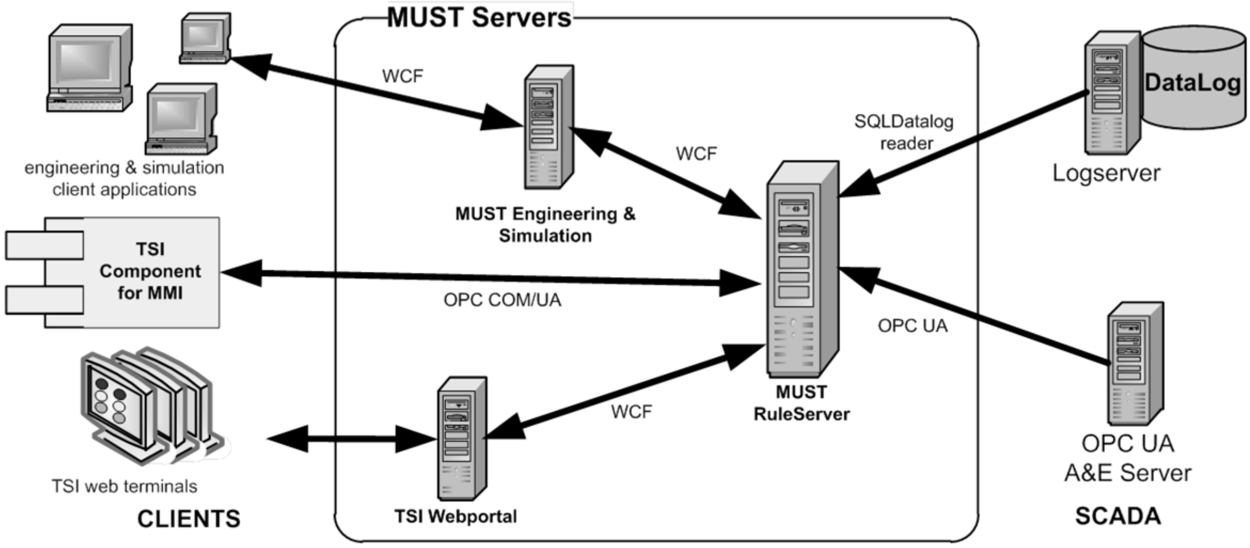

Figure 3: MUST™ suite of applications

Operational data is either retrieved by periodically reading out the SCADA data log, or real time through an OPC UA Alarm & Event server. The Tunnel Safety Indicator is implemented as a web application with regular browsers for clients. There is also an MMI component that acts as an OPC Client. This component can be embedded in existing SCADA MMI.

4.2. System functions

The main functions provided by the TSI system are the Safety Indicator, one traffic light per tube, and the underlying Safety Status overview, a tree-like overview of the model with detailed status information. These main functions are available through a standard web browser or SCADA MMI component.

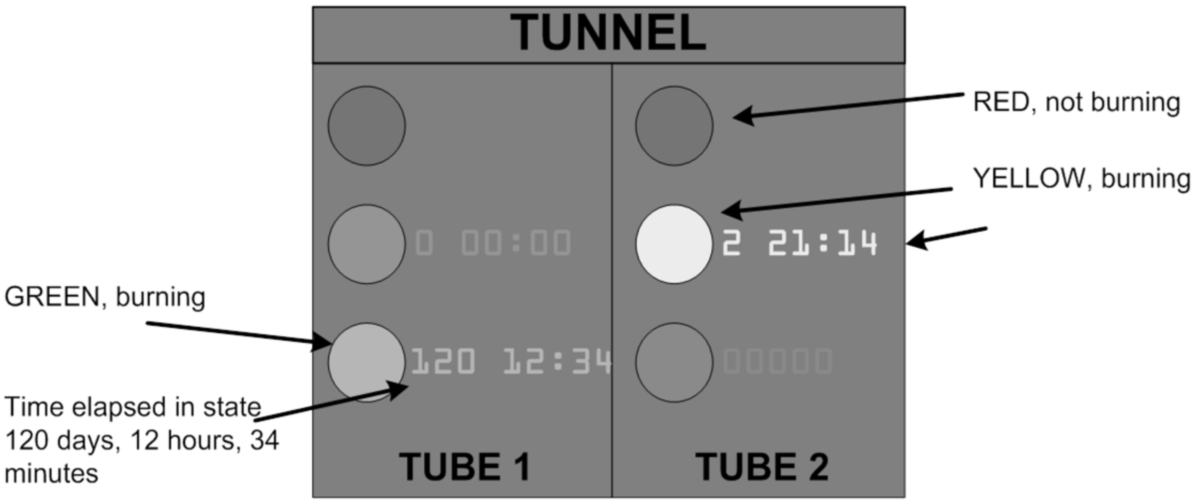

Figure 4: Tunnel Safety Indicator

Figure 4 shows the TSI for a tunnel with 2 tubes. Tube 1 is safe and has been in that state for more than 120 days, whereas Tube 2 has degraded safety. If this status is not resolved in less than 3 days, the tube will be declared unsafe, and this will result in the closing off of the tube.

The TSI makes it possible to drill down and obtain detailed information regarding the safety of the tunnel:

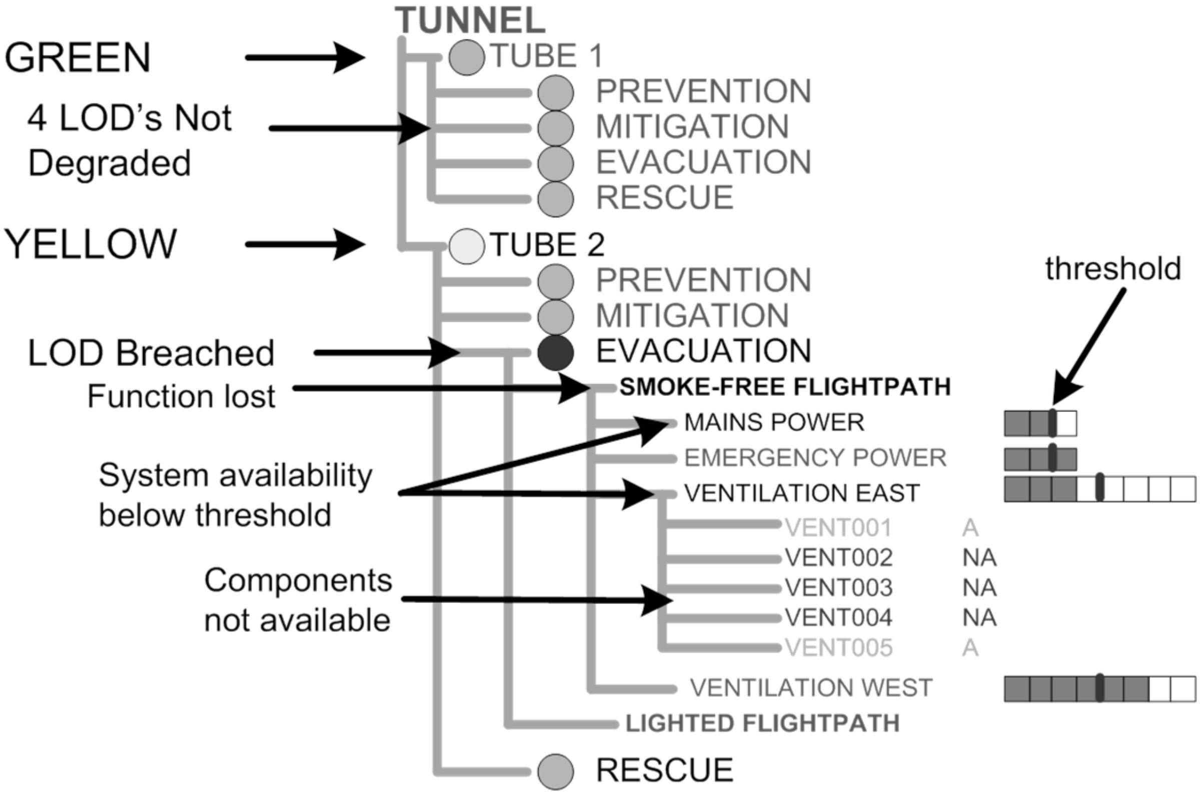

Figure 5: Safety Status overview

Figure 5 shows a drill down into the model underlying the Tunnel Safety Indicator. The drill down has a tree-like format and shows exactly how failed components affect the safety of the tunnel. Figure 5 visualizes the examples from Chapter 2. Three ventilators are Not Available. As a result, the System 'Ventilation East' loses 3/5 of its Availability and drops to 40%, which is below the threshold of 50% set by Function 'Smoke-free flight path'. This means the Function is lost. Apparently this function has a high Safety Class, because the loss of this single function is enough to breach the LOD Evacuation.

Secondary Tunnel Safety Indicator functions such as prioritized maintenance advice, temporary suppression of false events, entering inspection results and reporting, are supported through the TSI web portal and accessed through a standard web browser.

5. THE BENEFITS

The Tunnel Safety Indicator helps the tunnel operator deal with all the information on the safety status of the tunnel. The enormous load of the rail and road network has led to a situation in which every disturbance causes delays,, leading to negative economic consequences. With this tool the operator gains more insight into the continuous balancing between safety, maintenance and availability. The model:

- gives up-to-date information about the tunnel condition and the technical installations
- provides this information in terms of safety and availability
- continuously monitors the safety risks due to diminishing conditions and growing disturbances
- is based on decision rules that have been built in previously, without the pressure of an actual event and in cooperation with all the stakeholders that have power of decision
- continuously monitors the preset standards
- escalates when system warnings are ignored by operators or maintenance parties;
- gives insight into historical data
- provides operating staff with better judgment and less stress when they are confronted with failing components in the tunnel
- increases tunnel availability by avoiding unnecessary closure in case of events. Factual data show a possible 20% increase in tunnel availability.

In sum, the Tunnel Safety Indicator is an excellent tool that provides the tunnel operator with indispensable automatic support in his duties, decisions and responsibilities.

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RISK BASED MAINTENANCE IN SWISS ROAD TUNNELS

ANALYSIS, FINDINGS AND IMPLEMENTATIONS

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ABSTRACT

This study tries to establish that risk considerations should be taken into account to improve efficient maintenance of road tunnels. A survey of Swiss road tunnels shows that the combination of conventional condition assessments and qualitative risk considerations delivers a better basis for maintenance decisions. Based on average annual daily traffic and length, the tunnels were split into three maintenance types of rising order of importance (*I*, *II* and *III*) and put into relation with the respective ratings of periodically conducted condition assessments. The study concludes that maintenance focus should be prioritised according to maintenance type rating and, at the same time below average condition assessment. Regarding overall system tests it is recommended to test safety equipment of tunnels of higher maintenance type more often and more thoroughly than that of tunnels of lower maintenance type. In order to put the principles of risk based maintenance into practice, the Swiss Federal Roads Office has already implemented parts of the above findings in its maintenance concept. Hence, the combination of tunnel condition assessments and qualitative risk considerations provides a sound foundation for identifying suitable measures to preserve the substance as well as for efficient, transparent allocation of maintenance resources.

Keywords: Maintenance, safety equipment, qualitative risk considerations, condition assessment, system tests

1. INTRODUCTION

Overall safety of a road tunnel is strongly dependent on the condition of technical safety equipment such as ventilation, power supply and optical signals. In order to guarantee their functionality in incidents, the Swiss Federal Roads Office (FEDRO) inspects and tests the condition of safety equipment installed in road tunnels periodically. This large-scale assessment procedure conforms to European guidelines (EU, 2004, [1]) and results in object-related ratings. It also provides a practicable overview of the electro-technical condition, thus allowing planning, controlling and monitoring of road tunnel safety equipment (see FEDRO, 2013b, [6]).

Methodological enhancements applied to analyses of previously conducted condition assessments have shown that past procedures had only limited power to support a transparent allocation of maintenance means. Although objects in need of maintenance could be determined, the method did not take into account other aspects, e.g. the objects significance for traffic networks or its safety level. In short, it did not allow identifying maintenance-needs according to priority level. FEDRO's future maintenance management system implementing risk based approaches will eliminate these shortcomings. Once in place, financial maintenance resources can be allocated towards measures with the highest risk reduction potentials (FEDRO, 2012a, [3]). As already mentioned, this is currently not yet practicable.

With a view to public interests concerning the grounding or postponing of maintenance decisions on transparent criteria, we are facing several questions regarding the current maintenance concept for safety equipment in road tunnels:

- How can the significance of condition assessments be increased?
- How can maintenance resources be allocated appropriately and transparently with the currently available methods?
- Can certain future principles of risk based maintenance be included in actual methods already now?

With these questions the focus is deliberately placed upon working with already existing methods and not upon the development of entirely new ones. Hence, this study does not aim to realise the whole concept of risk based maintenance as defined in FEDRO (2012a, [3]), but works on the premise that established procedures shall be upgraded by inclusion of future principles. It is intended to allow operators to combine a reasonable degree of operational maintenance with the necessary enhancement of tunnel safety, fine tuning their maintenance decisions. It is aimed at providing additional decision support for improved, prioritised maintenance resource allocation for safety equipment in road tunnels.

2. METHOD

To address these questions, 38 unidirectional road tunnels operated and maintained by FEDRO were taken as a main unit. The tunnels were split into three maintenance types based on two factors that strongly influence a tunnel's risk: traffic intensity and tunnel length (see FSV, 2008, [7]). Once this qualitative and rather pragmatic sorting of the tunnels' risk related significance was completed, the consolidation with present condition assessment methods was undertaken. The tunnels' maintenance types were not only viewed in relation to their individual condition rates, they also defined the basic intervals between overall system tests. The following chapters illustrate these three methodical steps. First, the methodical procedure of condition assessments is briefly highlighted, before the overall system tests of safety equipment, as they are conducted by FEDRO, are explained. Followed by the typification process of road tunnels showing how risk based maintenance principles can be incorporated into existing maintenance methods on a qualitative basis.

2.1. Condition assessment

In order to guarantee an adequate condition of road tunnel safety equipment, FEDRO gathers specific data of every tunnel within predetermined time intervals and in accordance with standardised methods (FEDRO, 2012b, [4]; 2013b, [6]). The condition of electro-technical safety systems, e.g. power supply, ventilation or signalisation is described each with nine criteria, permitting a standardised assessment of the tunnels' condition (FEDRO, 2012a, [3]) (see **Table 1**).

Table 1: Condition criteria for safety systems

Criterion	Definition
Documentation	Completeness and actuality of system documentation
Adherence to safety rules	Compliance of system installations with actual safety rules
Availability of spare parts	Existence of spare parts in storage or through external suppliers
Life-cycle coefficient	Difference between time of use and planned lifetime of equipment
Mechanical condition	Visual and haptic observable corrosion or decomposition etc.
Safety coefficient	Number of malfunctions with direct consequences on tunnel safety
Software version	Actuality and function of used software version
Malfunction coefficient	Number of malfunctions without direct consequences on tunnel safety
Availability of support	Availability of support personal for maintenance or repair

Every condition criteria may be described with one of five evaluation classes ranging from 1 (*good*), via 3 (*sufficient*) to 5 (*alarming*). With this procedure, safety equipment that exceeds critical condition requirements can be separated from those that fall below (see **Table 2**). As a basic principle, only integer values can be used to characterise a system's condition in respect to the condition criteria. All nine criteria values of an assessed system are then averaged arithmetically, so that every safety equipment system gets an overall condition value. Relative weighting of criteria values 4 and 5 guarantees an adequate visualisation of conditions below critical requirements and ensures that systems which are in dire need of maintenance are not overlooked.

Table 2: Evaluation classes for condition assessments

	Evaluation class	**Integer values**	**Numerical range**
Above critical requirements	Good	1	1
	Acceptable	2	$1 < x \leq 2$
	Sufficient	3	$2 < x \leq 3$
Below critical requirements	Bad	4	4
	Alarming	5	5

In order to draw a general conclusion about a tunnel's safety equipment, the condition values of all systems are again averaged arithmetically and shown together to represent an overall view of the tunnel's safety equipment condition (see **Figure 1**).

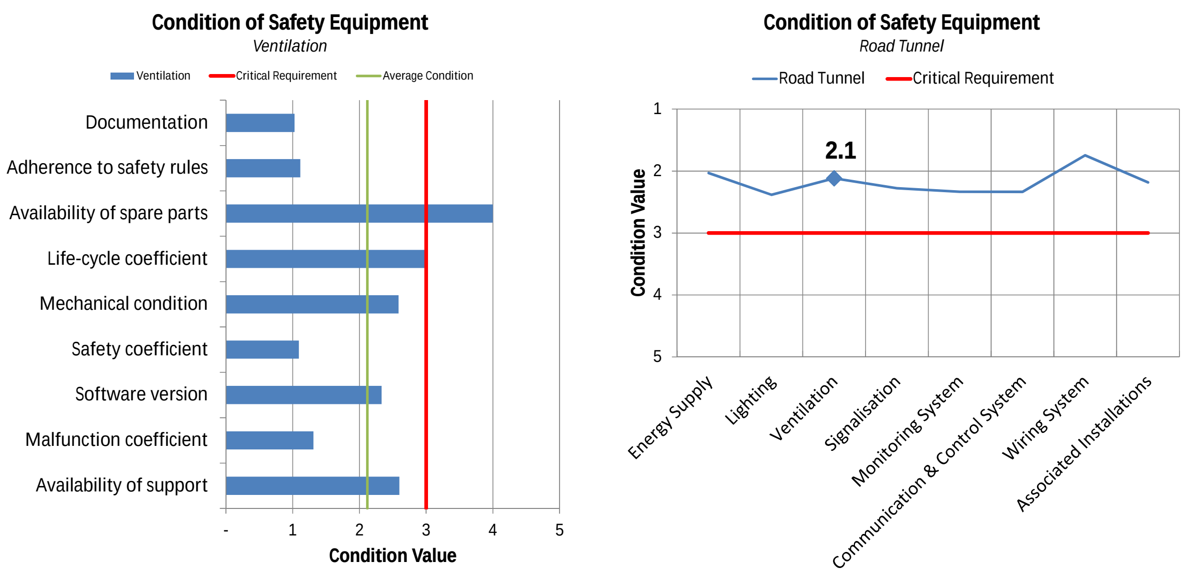

Figure 1: Specimen illustration of a ventilation system's condition assessment and its integration into the overall picture of a tunnel's safety equipment condition

2.2. Overall system tests

Besides inspecting the condition of safety equipment in road tunnels, FEDRO also tests their functioning periodically. The main goal of these overall system tests is, on the one hand, the checking of interdependencies between systems and validation of predefined reflexes and special functions of systems. On the other hand it influences the documentation of possible deficits as well as their consequent correction (FEDRO, 2009, [2]). By conducting *reflex tests, endurance tests* and *special tests*, measures to correct faulty system responses and other anomalies may be discovered and their implementation prioritised according to their urgency.

The assessment of identified anomalies follows a standardised method (see FEDRO, 2009, [2]) and concentrates on the description of divergences between the specified and actual system performance granting either *OK* or *Not OK*. Since taking over responsibility for operation and maintenance of the federal roads network, FEDRO has initiated annual overall system tests of road tunnels, i.e. each and every road tunnel must be tested integrally every year, irrespective of cost-benefit-considerations. This shortcoming will be ameliorated with future principles of risk based maintenance.

2.3. Qualitative typification of road tunnels

Every road tunnel features different characteristics; no tunnel is truly comparable to another. Variations in length, inclination, elevation, cross section, specific location and significance in road networks make each tunnel unique. Nevertheless, when it comes to allocating limited financial maintenance resources to various objects simultaneously, the need for typification of road tunnels arises. Once it is possible to categorise road tunnels according to a few distinctive features, similarities between road tunnels can be highlighted and used to split road tunnels into different types.

With respect to risk based maintenance of safety equipment in road tunnels, the distinction of relevance should ideally be built on a combination of system availability and the tunnels' risk profile (FEDRO, 2012a, [3]). The basic concept dictates that maintenance efforts should primarily be directed towards those tunnels, where a diminishment of system availability due to bad system condition leads to the highest risk increase. This implies that every system component of every road tunnel must be analysed in regards to its specific availability and the possible consequences of malperformance on particular tunnel risk. This very large data collection has so far not yet been done.

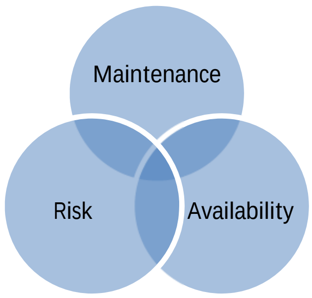

Figure 2: Interdependencies between maintenance of safety equipment, its availability and overall tunnel risk

Because the above mentioned relationship between maintenance, availability and risk (see **Figure 2**) is not yet analysed sufficiently and quantitatively for Swiss Road tunnels, it was decided to look for more practicable ways of typifying road tunnels. A possible solution was found by identifying two factors that have a strong influence on the overall tunnel risk in conventional risk models: Traffic density and tunnel length (see FSV, 2008, [7]). Based on the averages of their average annual daily traffic (AADT) and lengths, road tunnels can be split into three maintenance types that help to prioritise maintenance measures. Tunnels with both below average AADT and below average tunnel lengths fall into *Type I*. Tunnels with either above average AADT and below average lengths, or below average AADT and above average lengths are defined as *Type II*. Whereas tunnels that are above average for both AADT and length are referred to as *Type III* (see **Figure 3**).

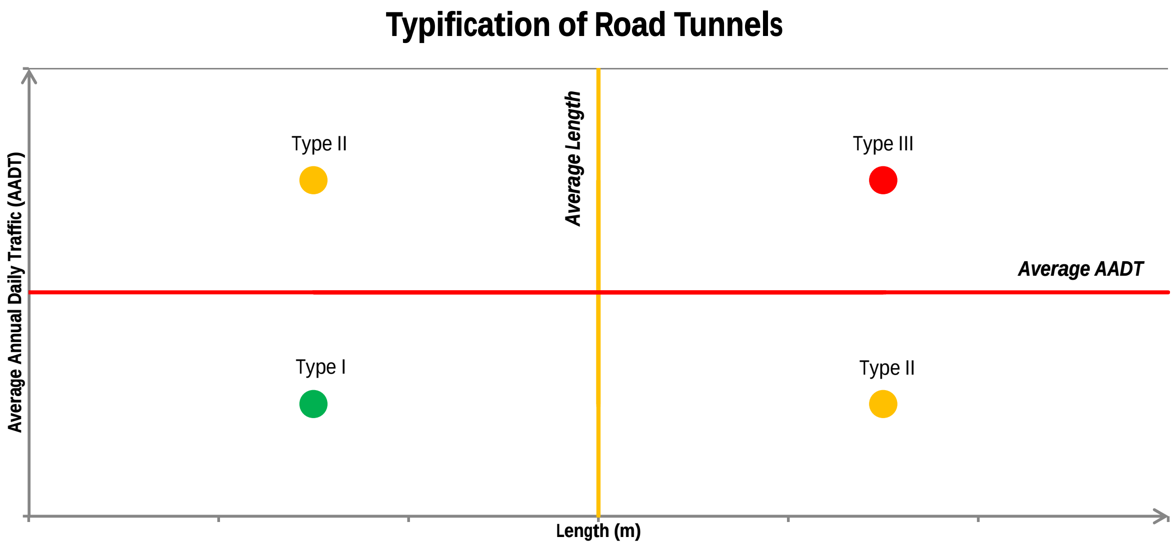

Figure 3: Concept for splitting road tunnels into different maintenance types

At first glance, the simplistic approach of taking averages to distinguish features may be challenged, of course. It may be argued that typification of road tunnels should be solely based on probabilistic risk considerations and past experience (see Mashimo, 2002, [8]). But, maintenance efforts and resources for road tunnels are usually allocated within predefined maintenance regions to specific tunnels. While one maintenance region contains many *Type 1* tunnels, another may have more *Type III* tunnels. Because the collective road tunnels' typical features of a region determine its demand for maintenance resources, average characteristics such as traffic density or tunnel length are well suited to describe a maintenance region's typicality. Although risk based maintenance of safety related equipment should ideally be based on quantitative, verifiable availability and risk calculations rather than qualitative typifications, this basic approach still allows a prioritisation of road tunnels where maintenance efforts should be undertaken primarily.

3. RESULTS AND IMPLEMENTATIONS

The analysis of 38 unidirectional road tunnels in the north-eastern part of Switzerland shows that 18% of all tunnels have both above average AADT and above average lengths (see **Table 3**), i.e. overall only a minority is defined as *Type III* (see also **Figure 4**).

Table 3: Analysis of unidirectional Swiss road tunnels

Type	Number	Percentage	Average AADT (vehicles/24h)	Average Length (m)	Average Condition
Type I	16	42%	23'292	430	1.9
Type II	15	39%	57'665	1'022	1.9
Type III	7	18%	71'049	2'871	1.8
Total	*38*	*100%*	*45'658*	*1'114*	*1.9*

This of course implies that safety equipment of the few *Type III* tunnels should be maintained with top priority when financial and human resources need to be distributed between several maintenance projects including other lower tunnel types.

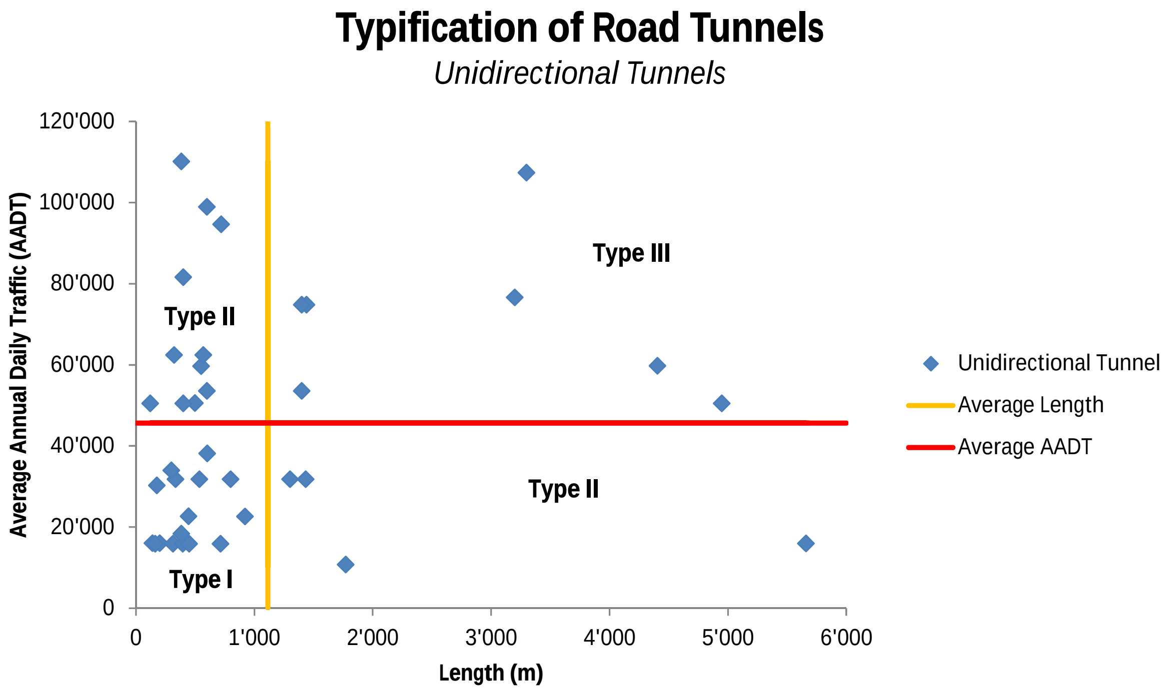

Figure 4: Typification of unidirectional road tunnels

Previous research has shown that equally distributing maintenance resources between tunnels without questioning their effectiveness leads to suboptimal solutions regarding risk based maintenance of safety equipment in road tunnels (see FEDRO, 2012a, [3]). **Figure 4** illustrates that typifying road tunnels according to their AADT and their lengths supports risk based maintenance concepts for safety equipment.

All tunnels in **Figure 4** defined as *Type III* are located at sensitive spots within high density road networks and therefore must have high safety system availability levels. Hence, condition related unavailabilities of safety equipment in *Type III* tunnels have a large impact on tunnel risk. On the contrary, *Type I* tunnels generally are situated in peripheral regions that feature low traffic densities and thus smaller risk consequences if the availability of safety equipment happens to be below certain levels. Consequently, and as the concept of risk based maintenance prescribes, the allocation of financial and human resources must concentrate on projects with large potential for risk minimisation.

3.1. Maintenance type and condition of safety installations

Once the concerned road tunnels are typified, the condition of their safety equipment can, in a next step be put into relation. **Figure 5** shows that the condition of the safety equipment of all analysed road tunnels averages at 1.9 and may be classified as *acceptable* (see **Table 2**). It may be stated that none of the analysed tunnels is in danger of falling below the critical condition value of 3.

If the focus is directed towards the different types, it becomes clear that only certain *Type I* and *Type II* tunnels contain safety equipment of below average condition. By comparison, safety equipment of all *Type III* tunnels are all above average condition. These discrepancies, although of miniscule significance still emphasize a central fact of the actual strategy of FEDRO: Tunnel types of higher importance have to be maintained with greater concentration than tunnels of lower importance because they have less risk tolerance for bad conditions of their technical installations.

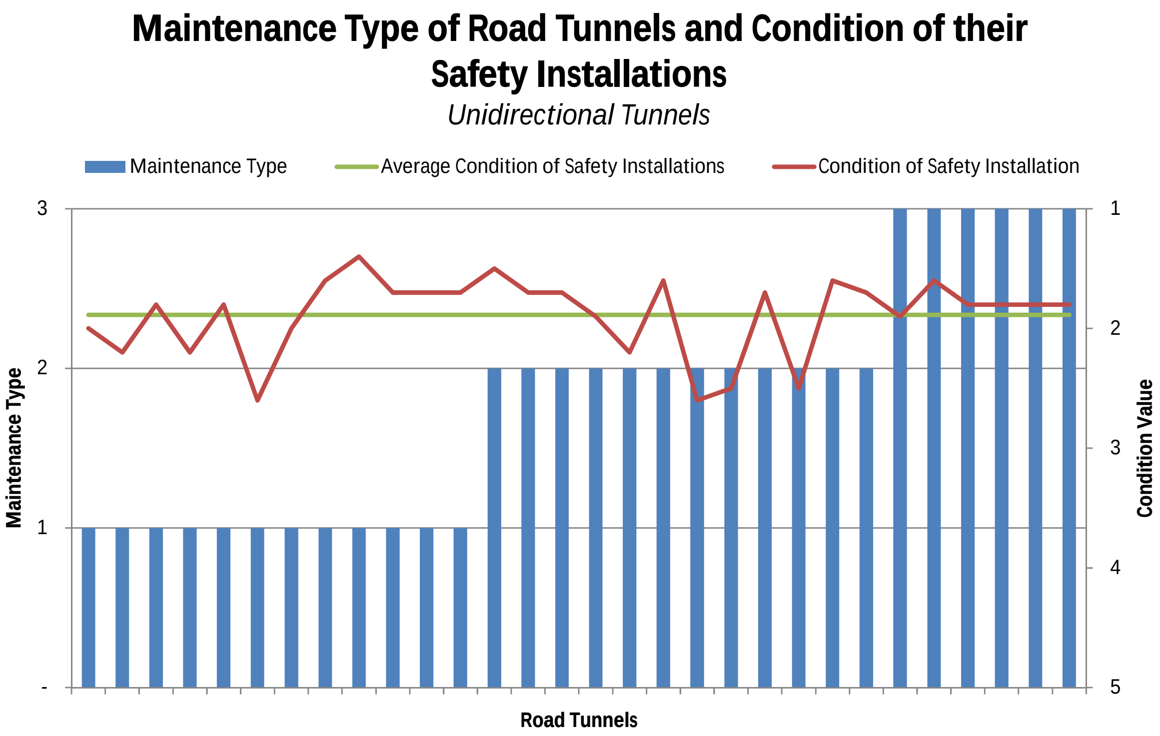

Figure 5: Maintenance type and condition of safety installations in road tunnels

This methodical procedure allows operators to combine a reasonable degree of operational maintenance with the necessary enhancement of tunnel safety, fine tuning their maintenance decisions. Additional decision support for improved, prioritised maintenance resource allocation for safety equipment in road tunnels is provided.

3.2. Periodicity of overall system tests

In the past, as a general requirement, the technical installations of every tunnel had to be tested every year. Previous studies have highlighted that these methods needed to be optimised because they disregarded cost-benefit considerations (see FEDRO, 2013a, [5]). Splitting the examined unidirectional tunnels into different types opens the possibility to differentiate about periodicity of overall system tests.

Based on the above findings it was decided that yearly recurring overall system tests can only be justified economically with *Type III* tunnels. Consequently, test intervals may be lengthened for tunnels of lower typification. This in turn reduces the number of simultaneous tests to be undertaken annually and therefore inevitably leads to a reduction as well as a redistribution of maintenance resources. When periodicities of overall system test are based on the typification of road tunnels, which in turn is derived from two factors that influence tunnel risk strongly, then maintenance management may be organised more transparently and congruously with future principles of risk based maintenance. Hence, efficient allocation of maintenance resources as defined in concepts of FEDRO is enhanced.

Table 4: Periodicity of overall system tests for unidirectional Swiss road tunnels

Type	**Periodicity of overall system tests in years**
Type I	2
Type II	2
Type III	1

3.3. Outlook

After having shown that the combination of tunnel conditions assessments and rather qualitative risk considerations may support an efficient management of maintenance measures, FEDRO has started to implement the findings in its actual concept. It is thus clearly demonstrated that already existing tools and methods do not have to be overthrown in order to implement risk based maintenance principles.

But still, this rather pragmatic approach presents only the beginning of risk based maintenance and raises some new questions for the future. It is still not clear whether time and effort for determining specific availabilities of system components as well as their particular influence on tunnel risk are really creating the added value. The complex and furthermore changing interdependencies between maintenance, risk and availability (see **Figure 2**) can only be made concrete when regular large scale data collection and periodic updates, guarantee reliable models. It may be challenged whether detailed models have the potential to stimulate manageable risk based maintenance measures, when existing methods already provide a practicable decision support for adequately allocating maintenance resources.

Safety equipment in road tunnels needs to be maintained with adequate, transparent but also reasonable and economically justifiable effort. Incorporating qualitative risk considerations into methods for condition assessments and thus real prioritisation seems to be the right way forward.

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ON THE FOUR ELEMENTS OF TUNNEL SAFETY: FIRE, AIR, WATER AND EARTH

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ABSTRACT

Based on an assessment of the tunnel safety in terms of the four elements: fire, air water and earth, some principal aspect regarding tunnel safety have been established.

With respect to tunnel equipment, it appears that rapid fire detection and the subsequent swift tunnel closure for incoming traffic is a main element.

In case of fire, it should be expected that active information of tunnel users is required and for this purpose the loudspeakers of the type SLASS are to be considered.

The emergency exists need to be attractive to use and should distinguish themselves from the service doors.

In case of unidirectional traffic that is never congested, longitudinal ventilation is appropriate for smoke management. Otherwise, smoke extraction is more favourable.

Fixed fire fighting systems can be installed to reduce the impact of tunnel fires on the tunnel structure and in order to increase the level of safety for the tunnel users.

Keywords: tunnel safety, self rescue, tunnel fire, fixed fire fighting systems FFFS

1. INTRODUCTION

Tunnel safety is the subject of numerous papers and the idea behind the concept of the present one is to view this from the perspective of the four elements: fire, air, water and earth. A new organization could lead to other conclusions than in the past.

In certain areas, tunnel safety is little different from conventional safety. However, this paper focuses on aspect where the nature of the tunnel environment becomes important i.e. when there is limited to time to conduct egress. In such circumstances, self rescue by the tunnel users has to be assumed and the typical incident is a tunnel fire.

2. FIRE

2.1. Introduction

Other accidents than tunnel fires result in many more annual casualties, see e.g. PIARC (2012) [1]. Although rare, tunnel fires may lead to exceptional dimensions of the impact and are therefore given particular attention when assessing the tunnel safety.

2.2. Tunnel design fires for tunnel safety

For the design of the integrity of the tunnel structure in case of fire, time-temperature curves are normally used. However, for the assessment of the user safety, the design fire is normally described in terms of its heat-release rate (HRR). As shown in **Table 1**, there is a wide range of HRR for road vehicles.

Table 1: Typical peak heat-release rates (HRR) from different road vehicles from PIARC 2011 [2] according to Ingason [3].
* Depending on the quantity and nature of the load.

Vehicle type	**Peak HRR [MW]**
Passenger car	5 – 10
Light Duty Vehicle (LDV)	15
Coach, bus	20
Lorry, heavy-goods vehicle (HGV) up to 25 tonnes*	30 – 50
heavy-goods vehicle (HGV) 25 - 50 tonnes	70 – 150
Petrol tanker	200 - 300

The decision which design fire to assume is implicitly a cost-benefit consideration. In case of longitudinal ventilation systems, the additional costs when deciding on a higher HRR is much lower than in case of smoke extraction. As a rough estimate, the size of the smoke extraction duct is proportional to the HRR of the design fire.

It is important to note that a tunnel ventilation system also is of benefit, when it is used for fires larger than the design fire.

Moreover, it is not evident that a tunnel with a smoke extraction designed for a 30 MW provides a lower level of safety than a tunnel with longitudinal ventilation that is designed for a 200 MW fire.

2.3. Fire mitigation methods

The best mitigation method is the prevention of the fire. Firstly, this is done by having a tunnel that is not prone to the occurrence of accidents. Secondly, the prevention of overheated vehicles from entering the tunnel is a valued method. This is done for the Mont-Blanc, Fréjus and the Gotthard tunnel by thermo scanning of the trucks approaching the tunnel. It is being said that up to 30% of the brakes of the trucks due not comply with the requirements.

From a perspective of the structural design of a tunnel, a passive fire protection seems the evident choice. However, thermal isolation of the tunnel walls reduces the heat transfer through the walls and results in higher temperatures in the traffic space, which again worsens the tenability i.e. deteriorates the conditions for self rescue.

Whereas the growth rate of a fire is by and large proportional to the longitudinal flow in the tunnel, the maximum heat-release rate does not seem to be influenced by the flow rate in the tunnel [8]. Higher flow rates, however, can increase the risk of fire spread.

3. AIR

3.1. Ambient conditions

The external ambient conditions are particularly important for the design of the tunnel-ventilation system, which also became evident in the Mont-Blanc fire. The requirements from different countries vary. In Switzerland [6], it is specified to dimension the ventilation system according to the annual average of the winds in the disadvantageous direction with respect to the orientation of the tunnel portals. In Austria [4], the requirements are more onerous, as it is based on the statistic of the half-hourly mean values and the tunnel ventilation has to cater for the 95 % percentile of the winds. In case of the highest risk category IV, even dimensioning for 98 % of the winds is required.

When a tunnel goes through a mountain, the difference in barometric pressure between the tunnel portals can be much higher than the wind pressure. The French guideline on the design of tunnel ventilation systems [7] provides a method to estimate this barometric pressure difference that though to our experience appear to lead to rather high values.

3.2. Control of the longitudinal flow

In order to have an efficient smoke management, the tunnel-ventilation system needs to cater for the ambient condition.

In case of smoke extraction, the simplest and most robust method is to specify the smoke-extraction rate so that the required conditions are inherently satisfied irrespectively of the ambient conditions. Similarly, in case of longitudinal ventilation and if there are no persons downstream of the fire, the adequate applied thrust need to be engaged in case of fire. In both cases, it is considered that the high flow velocities that occur may be judged to be permissible.

In other circumstances, an active control of the longitudinal flow is inevitable. PIARC 2011b [10] gives advice on the operation strategies for emergency ventilation in road tunnel and also provides a description of various tunnel-ventilation systems.

With respect to the ventilation control routine, Altenburger et al. (2013) [9] concluded that a PI-regulator with the parameters according to the Ziegler/Nichols criteria and incorporating anti-windup is the best applicable scheme.

The main difficulty in the control of the longitudinal flow during a fire is that the desired flow velocities, which depending on the application are between 1 and 3 m/s, are close to the accuracy of the flow measurements in the tunnel. In a laboratory, an anemometer may have an accuracy of ±0.1 m/s but in a tunnel application, it is difficult to envisage accuracies better than ±0.3 m/s. Erroneous measurements inevitably lead to a wrong control of the longitudinal flow which can have fatal consequences. Therefore plausibility tests based on several independent measurements are required ([4], [6], [10]). In order to do this, at least three measurements need to be available. Considering that the average flow velocity is of importance, anemometers that measures the flow across the tunnel cross section e.g. based on the ultra-sonic technique are favoured.

In particular in long tunnels, an additional difficulty controlling the longitudinal flow based on velocity measurements is that the flow can initially be driven by the moving traffic. One solution is to base the control of the longitudinal flow on to measurements of the barometric pressures at the portals, as it is done in the Fréjus tunnel [11]. The difficulty is that the barometric pressures are of the magnitude of 100 000 Pa which should be compared to typical wind pressures of 20 Pa. Based on three measurements at each portals of 13 km long Fréjus tunnel that experiences barometric pressure differences between the two portals of up to 600 Pa, it is therefore possible to conduct a first response to the atmospheric conditions immediately subsequent to the fire detection.

3.3. Smoke management with tunnel ventilation

3.3.1. Longitudinal ventilation

With longitudinal ventilation, the smoke is blown towards one tunnel portal and the tunnel user upstream of the fire are then in a safe haven. In case of fluent unidirectional traffic, this is the simplest smoke management. As long as it can be ensured that nobody is downstream of the fire, there is no obvious maximum length for a tunnel using this ventilation concept. Moreover, the view could be adopted that there is no need to control the velocity of the longitudinal flow as long as the velocity is adequately high to prevent backlayering of smoke i.e. avoiding that smoke flows against the direction of the main flow. Therefore, longitudinal ventilation is envisaged for the 18 km Fehmarnbelt tunnel that is to establish the fixed link between Denmark and Germany. This is characterised by low traffic figures, an emergency lane and the fact that the connecting road work is not expected to cause traffic congestion in the tunnel.

The connecting road work has an influence on the traffic flow in the tunnel and it is therefore often not to be expected that traffic congestion can be prevented at all times for tunnels in urban areas. In case of traffic at standstill, Ilg et al [12] concluded that the best ventilation strategy in case of longitudinal ventilation is to maintain the flow direction at a flow velocity of 1.0 to 1.5 m/s. At this velocity, there is a certain chance that smoke stratification occurs so that the tunnel users can escape below the smoke layer at normal walking speed. In case that there is no smoke stratification, it could be the better strategy to blow the flow at higher speeds e.g. 3m/s, which would keep on side of the fire smoke free and dilute the toxic gasses on the downstream side of the fire [13]. However, at such flow velocities, the visibility on the downstream side is bound to be very poor and therefore the walking speed reduced to a fraction of a meter per second (down to 0.2 m/s).

The use of longitudinal ventilation in a tunnel with bi-directional traffic is problematic and similar to the situation with unidirectional traffic at standstill. As an alternative to controlling the flow velocity, it is often decided not to engage the tunnel ventilation system at all and to hope that this results in smoke stratification i.e. provides the best tenable conditions.

3.3.2. Smoke extraction

A smoke extraction limits the smoke spread to the extraction zone. Tunnel users outside this are in a safe haven. This is therefore the favoured ventilation system in case of bidirectional traffic and for congested unidirectional traffic.

Considering that the smoke-extraction rate is similar to the smoke-production rate, it is important to have an active control of the longitudinal flow so that the smoke does not flow beyond the extraction zone.

3.3.3. Response time

Irrespectively of tunnel ventilation system, it is of paramount importance that it is activated quickly and that the tunnel portals are closed to incoming traffic [13]. The base line in [13] was to assume fire detection within 60 s when it had reached 5 MW, which corresponds to the criteria in RABT (2006) [5], and that the tunnel ventilation as well as the tunnel closure was initiated merely 20 s subsequent to the fire detection. If the fire detection took 600 s, the benefit of the tunnel ventilation was little different from assuming an infinitive fire-detection time.

4. WATER

4.1. FFFS – fixed fire fighting systems

There are two main types of water based FFFS installed in road tunnels today. These are water-spray systems and water-mist systems. The main mechanisms of fire suppression using these two types of systems are different. A water-spray system predominantly controls a fire mainly by fuel surface cooling, as well as taking heat out of the system by cooling surfaces directly adjacent to the fire site, whereas a water-mist system predominantly operates by gas cooling.

The benefit of the water spray systems is their simplicity. On the other hand, the water-mist systems require much less water. Moreover, it is advocated that water mist is better in dealing with pool fires (see discussion in section 4.2).

In contrast to earlier concerns, PIARC 2008 [15] concluded that FFFS under certain circumstances could be beneficial for the safety in a road tunnel. In spite of some concerns about the tenability, where in particular the potential negative influence of FFFS on the visibility is being argued, the predominant current thinking is that using FFFS has a positive net effect on the tunnel safety.

In the two large tunnel project in Stockholm (Norra länken and Förbifart Stockholm), FFFS is being introduced as a remedy against traffic congestion. As a consequence in Förbifart Stockholm, the design fire for the dimensioning of the tunnel-ventilation system was reduced from 100 MW to 50 MW.

4.2. Drainage and pool fires

The necessity to have an efficient drainage system has been recognised for decades. Longitudinal slots are more efficient than drainage at individual points.

Experiments in Törnskogtunneln [16] demonstrated that the drainage system was capable of removing the water by the FFFS envisaged for the Norra länken tunnel. Another spillage experiment examined the consequence of an immediate release of 2 m^3 of water. If the spillage had been gasoline, the HRR of a fire could be up to 150 MW. However, the fluid layer was so thin that it was concluded that the fire at this size would be of very short duration. Consequently, it appears that in a road tunnel, a pool fire will have limited duration unlike the ones in experiments that use pans to contain the liquid.

5. EARTH

5.1. Distance between emergency exits

In the Nordic research project on egress from tunnel fires in road tunnels [13], it was concluded that the potential number of fatalities was proportional to the distance between egress routes, which were at distances of 50 m, 150 m and 250 m. This is in line with the model by Vrouwenvelder [14] for such distances. In [14], however, it is predicted that the degree of deterioration of the chances for successful egress becomes much smaller when the distances between escape routes exceeds about 200 m.

5.2. Use of emergency exits

The prime question with respect to egress routes is, “will they be used”? Based on expert judgement [13], it was estimated that under normal circumstances, it should not be expected that in average more than about a third of the users would commence egress and use the egress routes. The reason for this behaviour is that people do what they are used to do. In case of traffic congestion or an accident, it is normal to stay in the car and normally nobody have experiences with tunnel fires.

This probability of egress could be increased to about 100 %, if a person of authority demands the tunnel user to leave their vehicles and to use the emergency exits. This is a good argument for having rapid response teams.

In any respect, the tunnel user need to be informed that they have to egress and the effect is larger when using multiple means of information. Conventionally, radio broadcast and information on variable message sings has been applied.

Due to reflections by the tunnel walls, messages from conventional loudspeaker systems are difficult to understand. However, with the new synchronised longitudinal announcement speaker systems (SLASS, see Figure 1), this is not the case. From personal experience driving through a tunnel in a vehicle with closed windows, the announcements were clear and easily understandable. When having such systems, it could even be considered no longer to use the broadcast system.

The likelihood that emergency exits are being used is increased if they clearly distinguish themselves from service doors. This can be done by colouring them green as the exit signs and have particular lights to attract them, see example Figure 2. The attractiveness of the egress door is increased , if it has a window and there is light on the other side. Moreover, the opening of the door should be intuitive. With this respect, some believe that panic bars are required. However, other mechanism work just as well and may lead the users to open even sliding doors. Sliding doors are mandatory in Switzerland, as the pressure differences in a road tunnel in most cases inhibits opening conventional swing doors applying the maximal permissible required force of 100 N

Figure 1: Illustration from [13] of SLASS loudspeaker system in the Elbe tunnel.

Figure 2: Illustration from [13] of emergency exit the Elbe tunnel.

6. CONCLUDING DISCUSSION

Rapid fire detection and closure of the tunnel for incoming traffic is the main feature in minimising the consequences of a tunnel fire. It is proposed to adopt the criteria in RABT (2006) that a tunnel fire of 5 MW in a tunnel at an air flow at 6 m/s shall be detected within 60 s. Shortly after this fire detection, the tunnel has to be closed to incoming traffic. Nevertheless, recognising that most fires are detected by the tunnel users and reported prior to the detection of a system, full coverage for the use of mobile telephones should be ensured. In Switzerland, smoke detectors are compulsory. Experiments in Sweden demonstrated that they are much faster in detecting the fire than conventional linear heat detectors.

The tunnel user need to be actively informed that they need to egress in case of fire. Several methods should be applied and a good system is the SLASS loudspeaker system.

Emergency doors should be easy to open i.e. by applying a force of no more than 100 N and attractive for egress: green with light around and having a windows showing with light in the space on the other side.

Longitudinal ventilation is a good system for smoke management of tunnels with unidirectional traffic as long as traffic congestion is avoided at all times. In other cases, smoke extraction is more favourable.

Fixed fire fighting systems can be installed to reduce the impact of tunnel fires on the tunnel structure and in order to increase the level of safety for the tunnel users.

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TRANSITION OF JAPANESE ROAD TUNNELS VENTILATION AND SMOKE EXHAUST IN TUNNEL FIRES

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ABSTRACT

In 1958, the first ventilation facilities were installed in a road tunnel in Japan: the Kanmon tunnel which is an undersea tunnel 3,461 m in length. Since then, ventilation facilities have been developed adapted to conditions on inter-city expressways, urban expressways and ordinary roads. Today, there are many ventilated tunnels (more than 1,000) in Japan. The present study summarizes changes of ventilation systems, volume flow rates of ventilation, operation strategy of smoke exhaust, etc., since 1958. The first ventilation systems adopted were the transverse ventilation system based on the European method, and air supply semi-transverse ventilation systems were adopted in many inter-city expressways. The first longitudinal ventilation system using a jet fan was installed in the short (630m) Okuda tunnel, and the system has been studied since then. In 1979, the longitudinal ventilation system using electrostatic precipitators was introduced for use in long tunnels (over 3,000 m), establishing longitudinal ventilation as the main ventilation system in Japan. Task clarification of future ventilation systems based on these changes and their backgrounds, this research for example, will contribute to the development of effective and economic systems.

Keywords: ventilation system, ordinary ventilation, smoke control

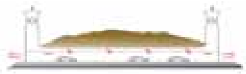
1. INTRODUCTION

The first ventilation system in a road tunnel in Japan was installed in 1958. A number of tunnels were constructed as the road network grew because about 70 % of the national land in Japan is mountainous. Tunnel ventilation systems play important roles in the control of smoke in the event of a fire as well as ensuring driving safety and a good maintenance work environment by providing regular ventilation. The ventilation systems and operation methods have been improved for economic reasons as the number of tunnels increased, the rising demand for environmental protection created a need to reduce the environmental load around tunnel portals, regulations on car exhaust emissions were tightened, and a record setting fire disaster occurred. In this study, we clarified future ventilation system planning based on our study of past changes, and recommended measures to overcome these problems.

2. OUTLINE OF TUNNEL VENTILATION SYSTEMS IN JAPAN

As of 2014, over 9,000 tunnels exist in Japan, and about 1,100 of these tunnels have ventilation systems. Ventilation systems are classified broadly into seven kinds as shown in Table 1.

Table 1: Types of ventilation system and numbers of each type (In 2014)

Ventilation system		Number	Schematic view
Transverse ventilation type	Transverse	13	
	Air supply semi-transverse	59	
Longitudinal ventilation type	Ventilation tower	87	
	Electrostatic precipitator	31	
	Ventilation shaft (supply and exhaust)	11	
	Ventilation shaft with electrostatic precipitator	11	
	Jet fan	923	
Total		1,135	

3. CHANGES OF VENTILATION SYSTEMS IN JAPAN

Tunnel ventilation systems on inter-city expressways, urban expressways and ordinary roads have developed separately considering the characteristics of each region and traffic characteristics such as traffic volume and vehicle speed plus tunnel length.

3.1. The first installation

The Kanmon Tunnel with length of 3,461 m is the first tunnel equipped with a ventilation system, which was installed in 1958. It is an undersea tunnel across the Kanmon straits. At that time, a large flow rate of 780 m^3/s was necessary to maintain the concentration of gas emissions below the acceptable level (CO < 400 ppm was standard at that time). The transverse ventilation system originally devised in Europe in the 1920s was adopted in the tunnel to assure its ventilation effect, because of the large required flow rate and long distance [1], [2], [3]. Figure 1 shows a schematic view of the overall ventilation system in the Kanmon tunnel [4]. Each supply system and exhaust system has four ventilation shafts and eight ducts as shown in the figure.

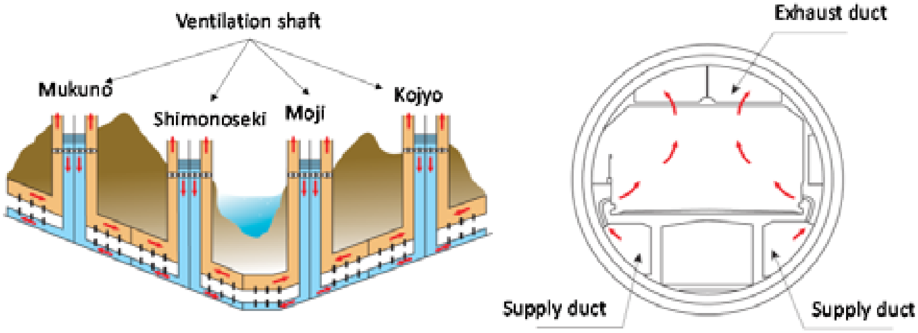


Figure 1: Schematic view of the ventilation system in the Kanmon Tunnel

3.2. Inter-city expressway tunnels

The ventilation systems used on the Tomei-Meishin expressway that connects Tokyo to Osaka through Nagoya were planned between 1960 and 1970. This route connecting two large cities is characterized by heavy traffic (approx. 3,100 vehicle per hour in the Tomei expressway) although the tunnels are as long as 2000 m. The air supply semi-transverse ventilation system which was a more economic system than the transverse ventilation system was introduced because the acceptable level of gas emissions in a one-way traffic tunnel which was not very long could be satisfied by dilution by supplying of fresh air from the ducts [5], [6]. The system had been applied to tunnels over 500 m long. This system can exhaust smoke in the event of a fire by reversing its axial fan.

Figure 2 shows annual change of the number and cumulative length of tunnels on inter-city expressways in Japan, and Table 2 shows the initial ventilation systems of capital inter-city tunnels when they were opened to traffic. Until the late 1970s, the number of tunnels increased, with most of these new tunnels air supply semi-transverse ventilation systems. However, the transverse ventilation system was applied in the Sasago tunnel and Enasan tunnel, which are both longer than 4,000 m because the outflow velocity from the portal exceeded 12 m/s.

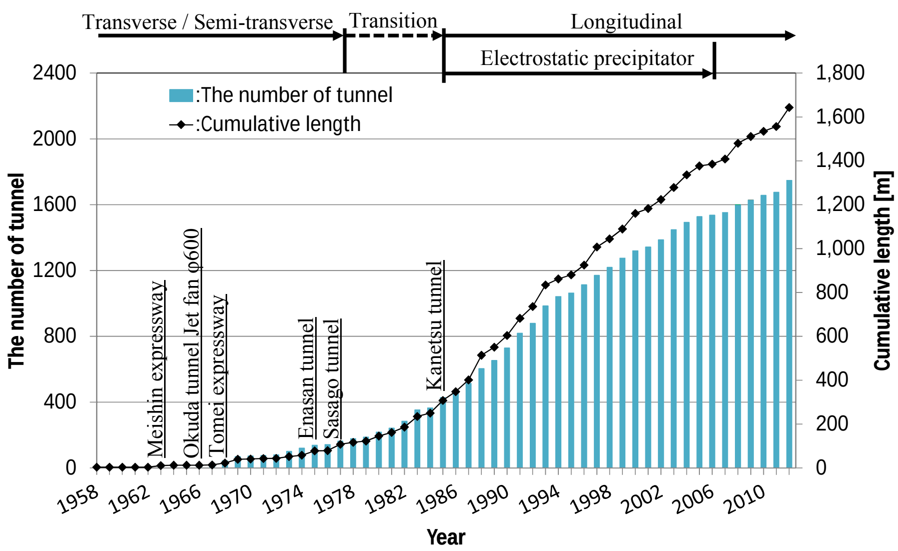


Figure 2: Annual change of the number and the cumulative length of tunnels on inter-city expressways in Japan

From the late 1970s, the longitudinal ventilation system which can reduce the initial cost of construction and running cost below those of the transverse system began to be introduced to provide more economical ventilation systems as the number of tunnels rapidly increased. The longitudinal ventilation system using a jet fan began to be studied after the installation of jet fans in 1966 in a short tunnel of only 634 m, which needed ventilation as its traffic volume grew. The longitudinal ventilation system became available for long distance tunnels by the late 1970s because the applicability of the system was verified based on knowledge gained from experiments on ventilation shafts, resistance coefficients of cars, and long field surveys of traffic volume etc., the rate of each car class and the concentration data in short tunnels with longitudinal ventilation. Since then, the longitudinal ventilation system has become the main stream of ventilation systems in Japan.

Table 2: Initial ventilation systems in capital inter-city tunnels

Tunnel	Route	Length [m]	Open	Ventilation system	Traffic
Kanmon	Ordinry road	3,461	1958	Transverse	Two-way
Tennouzan	Meishin expy	1,454/1,390	1963	Semi-Transverse(Air supply)	One-way
Nihonzaka	Tomei expy	2,005/2,045	1968	Semi-Transverse(Air supply)	One-way
Imajyo	Hokuriku expy	2,755/2,756	1977	Semi-Transverse(Air supply)	One-way
Sasago	Chuo expy	4,417/4,415	1977	Transverse	One-way
Enasan	Chuo expy	8,456	1975	Transverse	Two-way*
Komeyama	Chugoku expy	3,260	1983	Ventilation shaft (supply and exhaust)	Two-way
Okuda	Ordinry road	634	1966	Jet fan	Two-way
Sekido	Sanyou expy	3,325	1987	Electrostatic precipitator	One-way
Kanetsu	Kanetsu expy	10,920	1985	Ventilation shaft with electrostatic precipitator	Two-way*
Takedayama	Sanyou expy	1,842/1,778	1988	Ventilation tower	One-way

*: It is one-way traffic now.

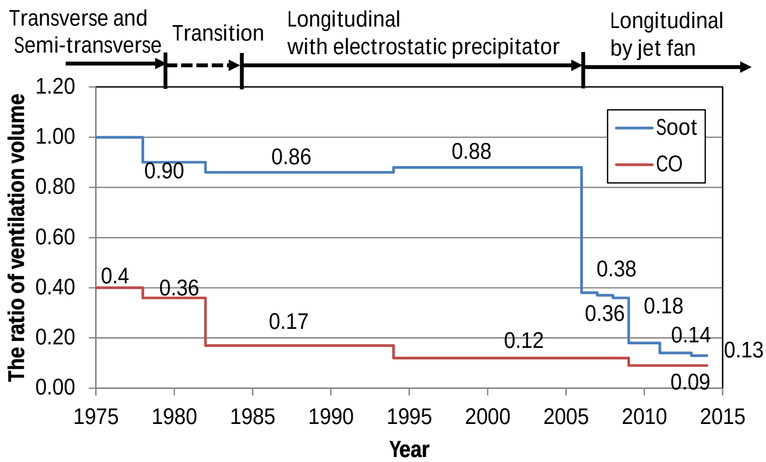


Figure 3: Annual change of the rate of ventilation air volume between CO and soot

The longitudinal ventilation of a long tunnel requires a ventilation shaft located at the midpoint of the tunnel. However, the constricted site and huge cost of such a shaft present difficulties. The factor requiring this ventilation shaft was, as shown in Figure 3, not the required ventilation air volume of carbon monoxide (CO) but that of soot. So, a ventilation system which removes soot using an electrostatic precipitator installed in the bypass tube instead of the ventilation shaft was developed, and the system was introduced into the Kanetsu tunnel for the first time in 1985 [7], [8]. Between that time and 2004, the electrostatic precipitator was introduced into 41 long tunnels. However, the ventilation air volume required to deal with soot became less necessary as a result of the remarkable effectiveness of vehicle emissions control after 2006. Therefore, systems with electrostatic precipitators were not necessary to ventilate long distance tunnels: only a jet fan was needed to enable longitudinal ventilation.

Planning of tunnels in residential zones began with the growth of the road network about 1990, requiring measures to reduce environmental loads around the tunnel portals. So, longitudinal ventilation systems with a ventilation tower which releases the exhaust from the tunnel directly into the atmosphere or after disposal of collected dust were introduced.

3.3. Urban expressway tunnels

There are about 60 urban expressway tunnels in the urban areas of the Tokyo metropolitan region and the Hanshin region. The ventilation of urban tunnels differs from that of inter-city tunnels because of their heavy traffic, existence of junctions in tunnels and the need to reduce the environmental load around the tunnel.

The first ventilation planned for a capital urban expressway tunnel was that for the loop line in the Tokyo metropolitan area, and at about the same time, the ventilation system of the Tomei-Meishin expressway with its typical inter-city tunnels was planned. So the transverse ventilation system or air supply semi-transverse system was introduced into urban tunnels over 1km long as it was in inter-city tunnels from 1960 to 1970. And after the 1970s, the system was changed to the longitudinal ventilation system as a result of further development of ventilation technology. However, the longitudinal ventilation system using localized exhaust vents was adopted in short tunnels about 300 m length beginning in the 1960s because the traffic volume became very large. This system was developed by combining jet fans or the Sacald method to suppress air leakage from the portal.

Traditionally, it has been difficult to clarify the traffic volume and volume flow rate of each ramp tunnel and main tunnel in detail, so the transverse ventilation system had been introduced into tunnels with junctions to assure ventilation effects. Recently, technological developments such as the real-time feedback of measurements to ventilation control has enabled the introduction of longitudinal ventilation systems in tunnels with junctions. For the above reason, the change-over to the longitudinal ventilation system in long urban expressway tunnels occurred over 30 years later than it did in the long inter-city tunnels in the 1970s. This system was introduced into the 3,321 m long Shorenjigawa tunnel in 2013. Six tunnels with the same ventilation system are now under construction: the Shinagawa-line in the central loop route of the Metropolitan expressway, the North-line in the Yokohama loop route of the Metropolitan expressway, the Yamatogawa-line of the Hanshin expressway, and so on.

A recent trend in the ventilation of urban tunnels, namely introducing an electrostatic precipitator and NOx removal equipment to reduce environmental load around the tunnel began with the opening of the Yamate tunnel in 2007.

3.4. Ordinary road tunnels

There are far more ordinary road tunnels managed by the national and local governments than there are expressway tunnels. These tunnels are generally two-way traffic with low design speed. So, from the mid-1960s to the 1980s, tunnels over 1,500 m long were equipped with air supply semi-transverse ventilation systems, and tunnels below that length were equipped with longitudinal ventilation systems using jet fans or ventilation shafts located at their midpoints. Later, as shown in Figure 4, the pronounced effect of vehicle emissions control enabled the application of the longitudinal ventilation system using jet fans up to 6 km.

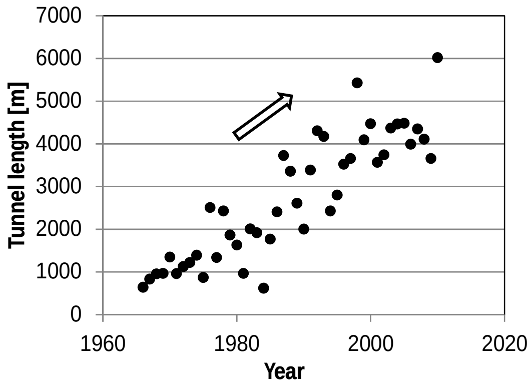


Figure 4: Change of maximum application length of longitudinal ventilation systems using jet fans in two-way traffic tunnels

3.5. Task of ventilation in the future

As mentioned above, recent ventilation systems in Japan tend to be longitudinal type even when the length is very long. And the size of ventilation equipment is shrinking because of the decrease of the required flow rate. Therefore, the following tasks concerning ventilation of long tunnels will arise in the future.

- The direction of jet fan operation in two-way traffic tunnels will vary according to the ratio of traffic in the inbound and outbound lines. So, the change of the direction of airflow will take a long time if the number of jet fan units is low.
- In urban areas, longitudinal ventilation systems with large exhaust vents will be necessary to reduce the environmental load around tunnels even if the concentration of gas emissions is lowered below acceptable levels by natural ventilation. Economical operation of this system will be achieved by reducing the flow rate of the axial fan by suppressing the inflow from the portal by reverse operation of the jet fan. But there is concern that running vehicles in the tunnel may permit the leakage of gas emissions if the capacity of the axial fan falls too low. Therefore, ventilation schemes would be much better on a cost-benefit basis.

4. CHANGE OF SMOKE CONTROL BY VENTILATION SYSTEMS

4.1. Change of operation

Traditionally, smoke produced by a fire was controlled by the ventilation system operating in the ordinary ventilation capacity range. The transverse and semi-transverse ventilation systems played important roles in smoke control by operating ventilation ducts to maintain the stratified flow of smoke and to suppress the longitudinal extension of smoke as shown in Figure 5. However, stationary vehicles behind the fire point were burnt by a spreading fire during the Nihonzaka tunnel fire in 1979. This accident resulted in smoke control in one-way traffic tunnels being operated to sweep the smoke away in a direction parallel with the traffic: the smoke was controlled to avoid backlayering. Additionally, since the 1980s, the introduction of evacuation tunnels along main tunnels has been considered for two-way traffic tunnels over 3 km in length on inter-city expressways, if the longitudinal ventilation system is applied. In 2006, operators of two-way traffic tunnels were obligated to expand control to include a low-velocity airstream that can maintain a stratified flow. Figure 6 shows the schematic of the operation of a longitudinal ventilation system under fire conditions.

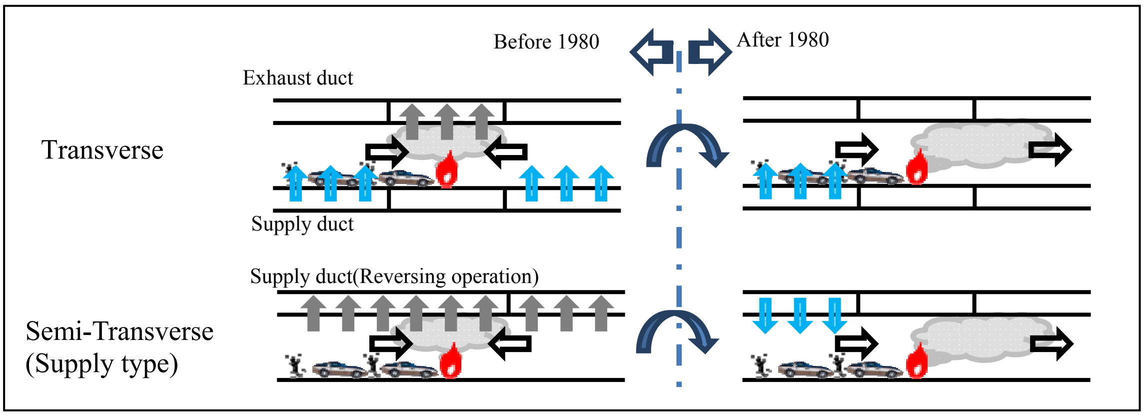


Figure 5: Change of smoke control of the transverse and the semi-transverse ventilation systems

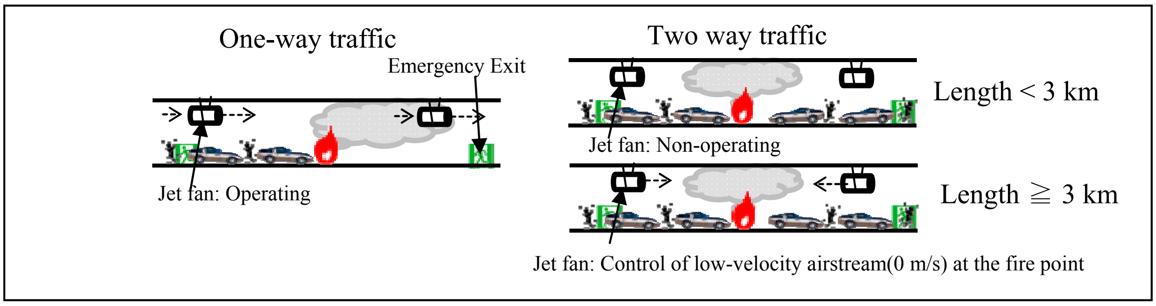


Figure 6: Principle of smoke control of longitudinal ventilation systems (Inter-city tunnel)

Recently, the design of fire-escapes in long urban tunnels, such as the capacity of ventilation systems in a fire, operation strategy, distance between emergency exits and walking space under the stratified flow have been determined with reference to the results of 3-dimensional simulations also considering the change of velocity caused by traffic and ventilation control. The performance of a transverse ventilation system with an exhaust flue, which was introduced into the Yamate tunnel, was confirmed from the analysis such as; the ventilation performance for smoke or the ability to control low-velocity airstream (0 m/s) at the fire point. The current principle of smoke control in Japan is shown in Table 3.

Table 3: Current principle of smoke control in Japan

	Transverse	Semi-transverse	Longitudinal
One-way traffic tunnel	Suppression of backlayering	Suppression of backlayering	Suppression of backlayering*1
Two-way traffic tunnel	Exhaust: At fire point Supply: Both neighbor ducts	Exhaust At fire point Supply: Both neighbor ducts or not	Non-operating*2 (Low-velocity control)
Note	*1: There are some tunnels which control to 0 m/s if the tunnel holds the potential for a traffic jam in the urban tunnel. *2: It is for over 3,000 m and 4,000 vehicles per day The smoke control system has to be equipped to the tunnel over 1,500 m		

4.2. Task of smoke control in the future

Traditionally, ventilation capacity under ordinary conditions was sufficient for smoke control. However, equipment as large as that used for ventilation is not required very much as mentioned in chapter 3. So, the ventilator has to be equipped not for ventilation but only for smoke control. Therefore, tasks related to smoke control shown below will arise in the future.

- The ventilation design will have to be determined considering the smoke control capacity.
- Do we need huge investments to deal with infrequent events like tunnel fires? Namely, maintenance and operation costs over a number of years must be incurred, whether or not it is used.

To secure safety by comprehensive planning not only of smoke control by ventilation systems would be a reasonable and cost-effective solution to deal with the tasks; locational planning of evacuation passages, improvement and expansion of evacuation guidance, and so on.

5. CONCLUSION

Over 30 projects to construct tunnels over 3km long, including one as long as of 20 km will be implemented in the future in Japan. The ventilation systems of these tunnels must be planned considering rationality and cost-effectiveness based on comprehensive planning including safety under fire conditions, energy saving operation of the ventilation system, environment protection, and so on.

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INFLUENCE OF FIRES ON - AIR VELOCITY MEASUREMENTS AT DOWNSTREAM MEASUREMENT LOCATIONS

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ABSTRACT

Ventilation control in case of a fire is a very important issue in tunnel safety. In general an automatic system is employed in order to control smoke movement inside the tunnel. The major control parameter is the air velocity upstream the fire location. Depending on the ventilation philosophy critical or low air velocity philosophy might be applied. In both cases a proper measurement of the air speed is required. The control itself is performed by a PID or PID like controller, which triggers fan operations and uses the measured value of the air or smoke speed as feedback value.

The best solution would be having a measurement of the upstream situation, i.e. far away from any influence of the fire. However, there exist always locations inside the tunnel, for which this ideal conditions are not possible.

This paper deals with situations, where velocity information has to be taken from monitoring locations downstream the fire. Numerical simulations for wind distributions in a cross section for different heat release rates are performed and compared to measurements. The numerical simulations are performed with the FDS code.

Keywords: ventilation control system, fire in tunnels, sensor location in tunnels, air velocity

1. INTRODUCTION

Any incident with a fire inside the tunnel bears a quite big risk to tunnel users. In order to enhance rescue in such cases a controlled ventilation of the smoke is imperative in order to reduce human and capital losses.

There are multiple philosophies how to vent a tunnel during fire cases. Mainly a ventilation procedure for ‘critical velocity’ or ‘low velocity’ is applied. Both methods have their pros and cons [1]. In order to enable controlled incident/fire ventilation closed loop control systems are nowadays employed. The feedback information for such systems is the air/smoke velocity, measured by appropriate sensors at appropriate locations. This measurement shall represent the average air flow over the tunnel cross section.

Best practice is to measure the air velocity upstream of the fire. At such locations any influence from heat releases due to the fire can be avoided – as long as any backlayer of smoke does not reach the measurement location. However, as an incident can happen everywhere inside the tunnel, there might be the possibility that upstream air velocity sensors do not exist or are out of order. In such cases information of sensors downstream the fire have to be used. Of course in such situation each designer of a control system would promote the usage of a location as far as possible downstream, in order to have already a uniform flow situation.

Here the problem arises as any heat release in a vertical temperature gradient and hence in different velocities at different heights. Due to buoyancy forces generated by the fire the nearfield of the fire is highly turbulent with high temperatures at ceiling and low temperatures at ground level. Dependent on the heat release rate (HRR) the air flow at low levels could even be from both sides of the fire. The situation downstream of the fire is strongly influenced by the heat transfer to the walls (cooling down) and by turbulent mixing of air masses with different temperatures over the cross-section. The more turbulence is present, the more uniform the vertical temperature distribution will be. In tunnels with active jet fans downstream the fire the temperature profile will be much more uniform compared to natural flows.

This means that any point- or line measurement at a certain height downstream the fire gives only information about the velocity at that location. The interpretation of such a value for ventilation control purposes – where the upstream information is needed – is quite questionable.

2. EXPERIMENTAL DATA

According to the Austrian standard for ventilation design [3] a fire test has to be part of the commissioning test of a tunnel. During this test the performance of the ventilation system has to be checked by having two pool fires with a HRR of roughly 3 MW as source. According to the RVS 09.02.31 [3] a low velocity philosophy for ventilation in incident cases has to be applied.

During the course of the commissioning tests of the Niklasdorf tunnel in winter 2013/14 various tests were performed. During one test air velocity was recorded at different locations inside the tunnel. Fig. **1** depicts the air velocity values at different locations along the length of the tunnel, but all of them at the ‘usual’ installation height of some 4.8 m. The two horizontal lines represent the boundaries of the acceptable air velocity range upstream the fire. This velocity band is according to [3] for unidirectional traffic 1.5 to 2.0 m/s. The majority of the lines (blue and red) are measurements at upstream locations. The air velocity stays more or less within the accepted velocity band. The yellow (orange lines depict the accepted accuracy of the measurement equipment. The test shows, that the required ventilation response is given. But there is one line showing a quite different behaviour – the green one. Shortly after fire ignition (‘Brandauslösung’ in Fig. **1**) the air velocity rises strongly. This is a measurement location some 300 m downstream of the fire. If such a value would be used for ventilation control the upstream velocity would be much too small and a big backlayering cone would be one of the results.

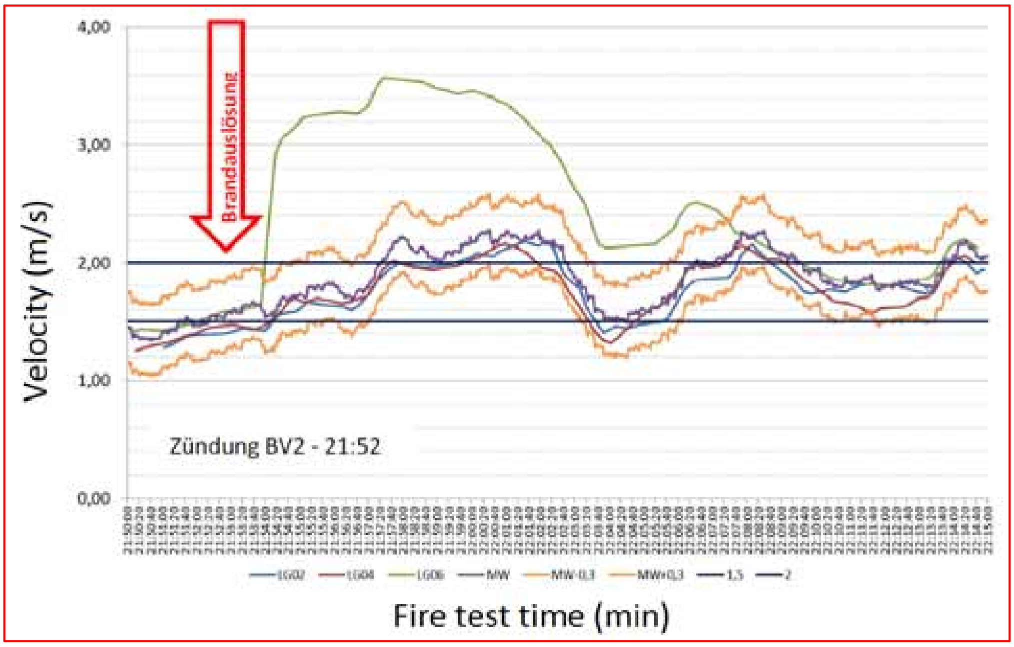


Fig. 1: Air velocity inside the tunnel at different locations during a fire test; courtesy of Lechner& Partner [2]

These results show clearly, that measurements performed downstream the fire can be strongly misleading. Any simple temperature correction would not be of help as the vertical profile and hence the volume flow is not known. Between fire and downstream measurement location no fans were active; hence an almost naturally driven layering could be established.

3. NUMERICAL SIMULATION

In order to get a better understanding of the length of the zone which might be impacted by thermal layers due to a fire, CFD calculations were performed. FDS version 6 was used for this task. In order to validate the CFD application, the test described in section 2 was used.

3.1. Tunnel geometry and FDS modelling

The simulation was based on the actual dimensions of the tunnel. The tunnel has a length of 1,300 m, a cross section of 52 m² and a circumference of 27.7 m. The tunnel tube considered for the simulation has a positive road gradient of 2%. Fig**. 2** shows the cross section and Fig**. 3** the plan view of the tunnel. Fig. **3** contains in addition the monitoring locations (point 1 to point 6 downstream as well as point 11 und 22 upstream of the fire location used for displaying the CFD results. Position 1 is equivalent to the position of the air velocity measurement location shown in Fig. **1** (green line, downstream location).

The tunnel has a horse shoe profile, which can't be resolved from the FDS due to the rectangular grid structure.

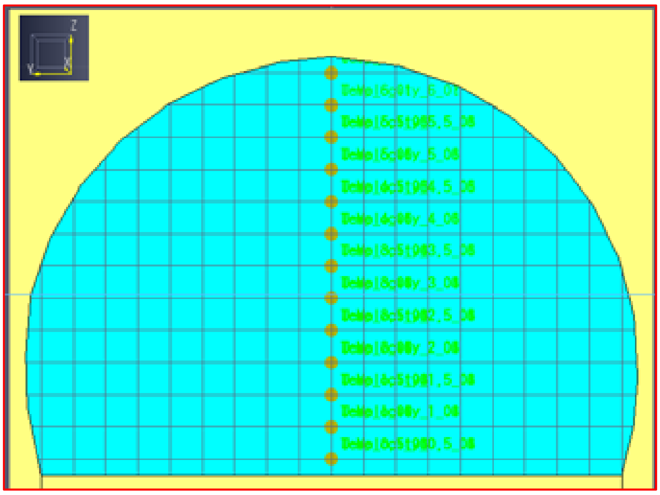


Fig. 2: Used cross section form for simulation modeling by FDS

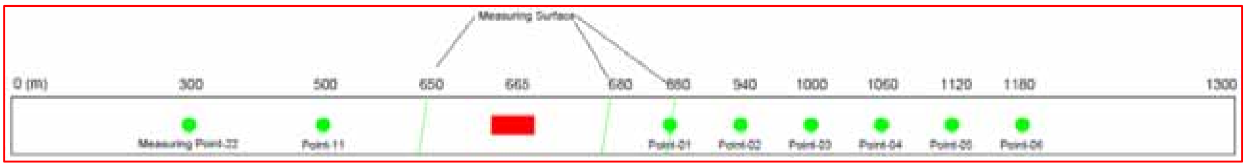


Fig. 3: Tunnel plan view, fire location (red square) and FDS monitoring cross-sections (green points)

3.2. Fire source and HRR

The fire is located 665 m after the entrance portal and has a central position. The first calculation concerned the validation of the model using the test as described in section 2 for this purpose. According to the RVS 09.02.31 [3] the fire source consists of two pool fires with an area of 1 m² filled with 20 l diesel and 5 l gasoline each. The HRR rate is assumed to 3 MW with a burning time of roughly 20 minutes. The second calculation used a HRR of 30 MW, while in a third one the influence of active fans on the temperature and U-velocity profile was investigated.

In order to allow for a uniform air flow development in the tunnel the heat release started 600 s after the start of the calculation.

As these calculations shall show only the principles of the development of the air flow, the fire source was simply be represented by a volume source with a specific HRR, combustion processes were not considered. Fig. **4** shows the HRR boundary condition for the 30 MW case. The maximum HRR was achieved within 180 s and remained constant for the rest of the simulation time.

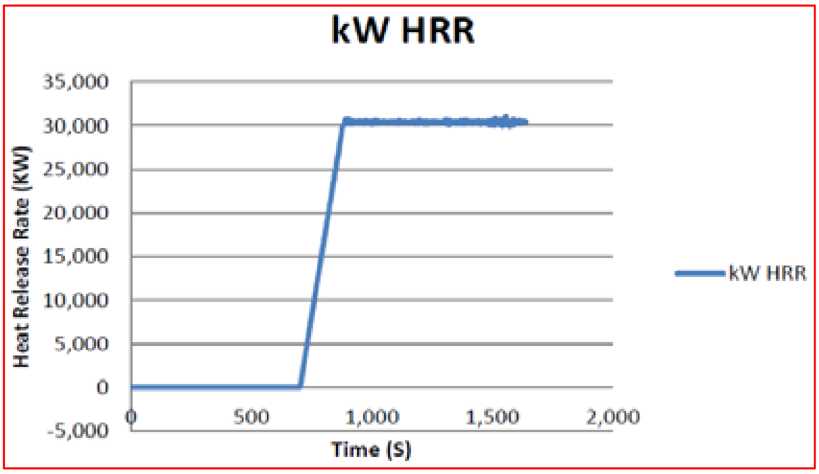


Fig. 4: Boundary condition for the HRR, simulation case 30 MW

3.3. Inlet and exit boundary condition

In order to allow for a quick consolidation of the airflow inside the tunnel before the fire starts a mass flow boundary condition was set at the entrance portal. After achieving a constant flow within the tunnel, the boundary condition was changed from fixed mass flow to 'open' in order to allow the flow to develop according to the evolution of the fire. Exit portal boundary condition was again 'open'. The incoming air has a temperature of 6°C, wall temperature is assumed to be also at 6°C.

3.4. Simulation results

Simulations were performed for the 3 MW case for model validation and for the 30 MW case in order to show how the air flow will be disturbed in case of a bigger fire. For both cases almost natural flow behaviour was simulated as it was observed during the validation experiment. An additional test case was performed in order to demonstrate the influence of active jet fans downstream the fire location but upstream the air velocity measurement location.

3.4.1. 3MW fire simulation

This case was used for validation the FDS application. The validation case is the 3 MW fire according to the RVS certification procedure [3]. The test results performed in the Niklasdorf tunnel is described in section 2. The calculation results will be shown for the locations 01 and 04 at a distance of 215 m (880 m from west portal) and 395m (1060 from west portal) downstream the fire (see Fig. **3**).

Fig**. 5** depicts the evolution of the U-velocity at cross section 01 at various heights between simulation start and 2,500 s. Before fire starts (at 600s), the air velocity distribution is quite uniform, between 1 and 1.5 m/s dependent on height, temperature is kept to 6°C. After the start of the fire there is a strong transient behaviour at the beginning. However, after some time an almost steady state situation is achieved. Wind speed varies between quite small values at the bottom and 2.7-2.9m/s close to the ceiling (note that slip condition which is applied in FDS as boundary condition for the wall influences the result negatively). Temperature varies between 10°C close to the bottom and 27°C close to the ceiling.

Fig**. 5** depicts the profile for U – velocity and temperature at the centre line of cross section 01. The measurement of the velocity during the experiment was taken at a height of 4.8m above ground. According to Fig. **1** the U-velocity value peaks at around 3.0 to 3.5 m/s (±0.1), temperature at that location was recorded around 25°C(±4). This fits quite well to the simulations.

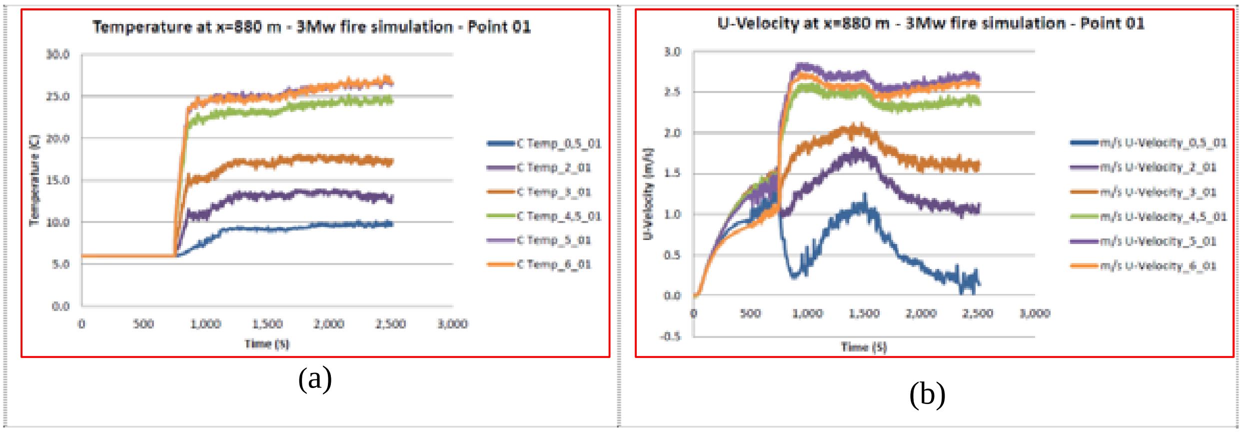


Fig. 5: Temperature (a), U-velocity (b) at tunnel cross section 01, 3MW case

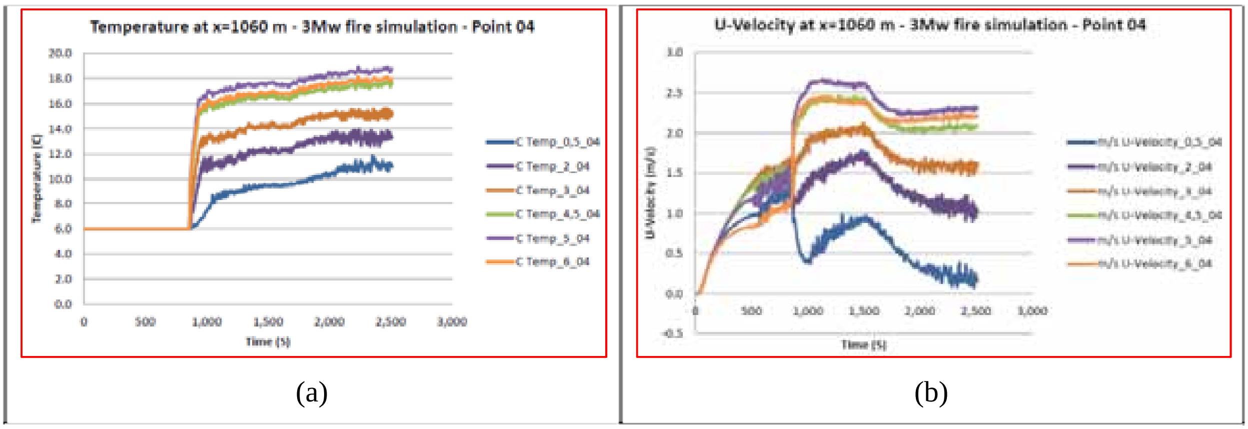


Fig. 6: Temperature (a), U-velocity (b) at tunnel cross section 04, 3MW case

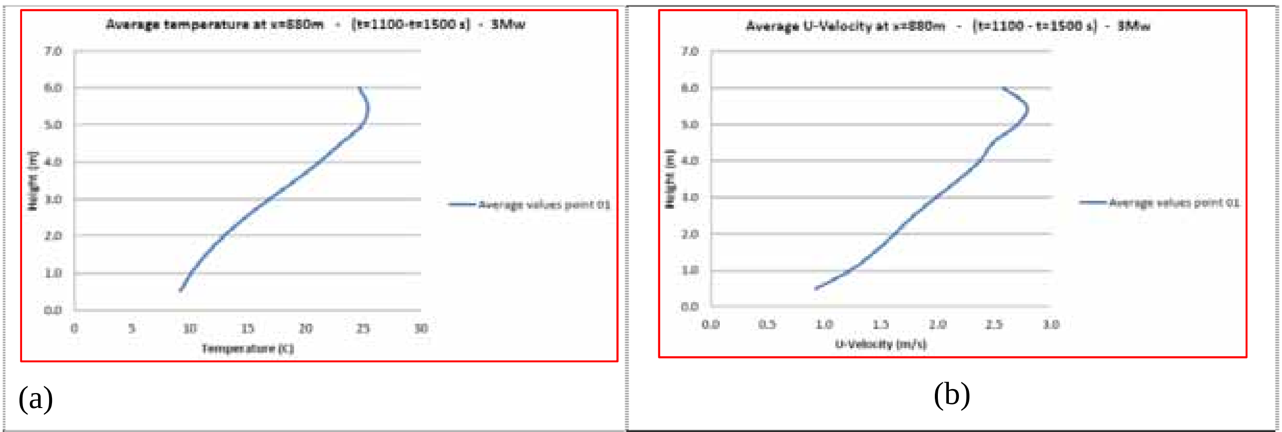
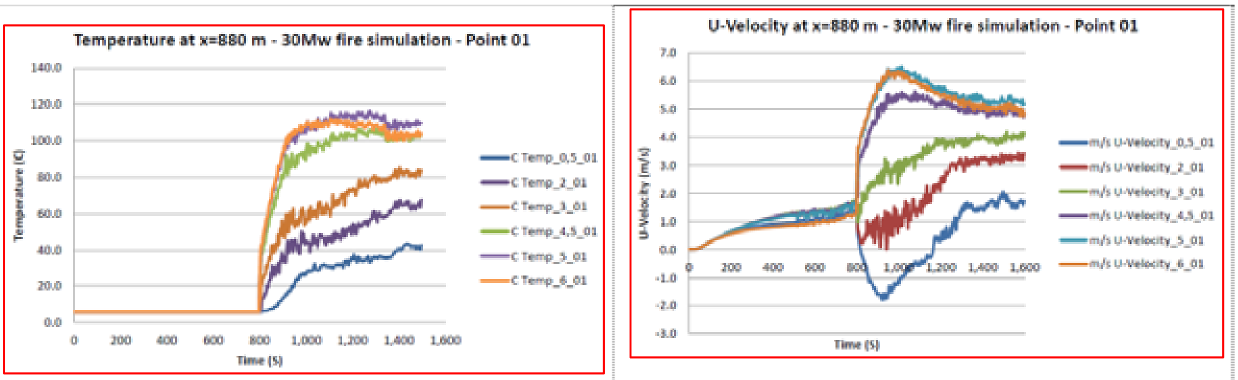


Fig. 7: Average values for Temperature (a), U-velocity (b), at tunnel cross section 01, 3MW case

3.4.2. 30MW fire simulation

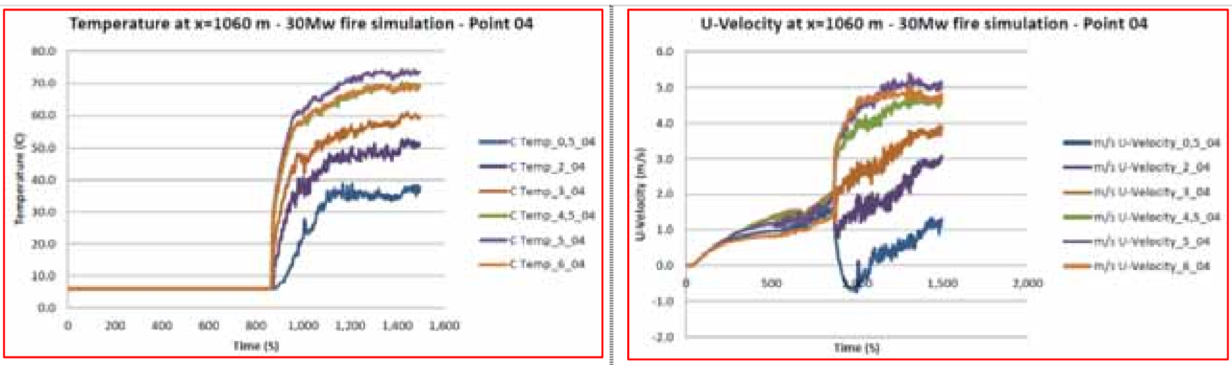
The standard design fire size for road tunnels in Austria is a 30 MW HRR representing a truck fire. Taking the same boundary conditions (except the HRR) as described above the following results were simulated.

Fig. **8** depicts air velocity and temperature at cross section 01 (+215 m, downstream). Air velocity rises from some 2 m/s at ground level to more than 5.3 m/s in 5.5m, temperature rises from 45 to 110°C for the steady state case. A quite similar situation appears also at the more remote location cross section 04 (Fig. **9**).



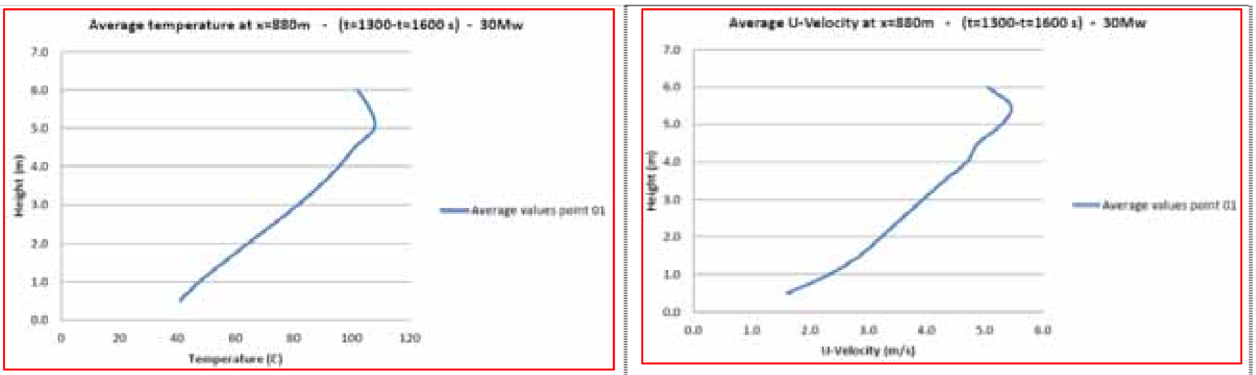
(a) (b)

Fig. 8: Temperature (a) and U-velocity (b) at cross section 01, 30MW case



(a) (b)

Fig. 9: Temperature (a) and U-velocity (b) at cross section 04, 30MW case



(a) (b)

Fig. 10: Average values for Temperature (a), U-velocity (b),
at tunnel cross section 01, 30MW

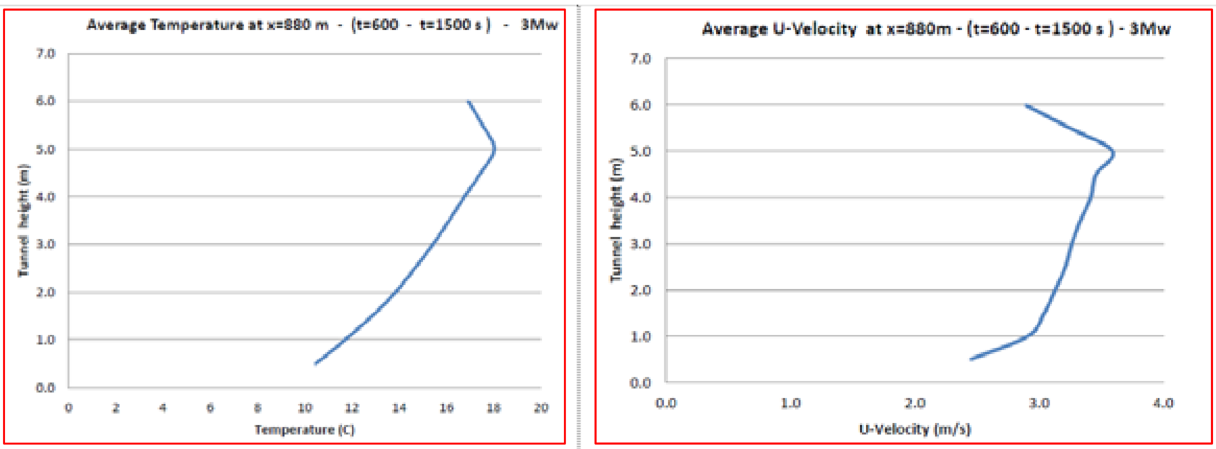
Fig. **10** depicts the profile for U – velocity and temperature at the centre line of cross section 01. There is a quite strong gradient with height. If now a measurement for ventilation control must be taken from such a location downstream the fire the value is much too high. Instead of displaying the required 1.5 to 2 m/s upstream the fire almost 5 m/s are recorded. Even when taking the temperature reading (~100°C) into account, a temperature corrected value would still be around 4 m/s. Hence any control system based on this information would reduce the velocity of the incoming air, resulting in a big backlayering zone upstream the fire.

While this wrong behaviour of the ventilation control system would result in an unwanted backlayering in longitudinal ventilated tunnels, the negative effects in transverse ventilated tunnels could be much worse. It could lead to a strongly reduced extraction of smoke in favour of clean air from the other side of the extraction openings (dampers). Such malfunctions could be fatal.

3.4.3. 30W fire simulation with active fans downstream the fire and measurement location

The following scenario should show the effect of active fans downstream the fire and measurement location. The scenario is based on a 3 MW fire, an air velocity monitoring location downstream the fire at position 01 in Fig. **1** and a pair of active jet fans some ~ 350 inside the tunnel at downstream location (around 1000 in Fig. **1**). Such a scenario would be applicable in tunnels with unidirectional traffic (assuming no vehicles are between incident and exit portals) but should be avoided in tunnels with bi-directional traffic do to down-mixing of smoke in areas where traffic is stopped.

Fig. **11** depicts the profile for U – velocity and temperature at the centre line of cross section 01. Contrary to the cases discussed above, the active fans increase the turbulence downstream the fire and hence a much more uniform distribution of temperature and U-velocity over the height. When correcting the locally measured velocity with the temperature the resulting air velocity for smoke control is much closer to the control value needed upstream of the incident.



(a) (b)

Fig. 11: Average values for Temperature (a), U-velocity (b), at tunnel cross section 01, 3MW case with active fans downstream

4. CONCLUSION AND RESULTS

Active (closed loop) ventilation control relies on correct measured values of the air velocity upstream an incident with a fire. Regardless which ventilation philosophy is applied, it is always the air velocity value, which is the input parameter for the control system. In standard tunnels such sensors are installed at multiple locations, hoping that one set of sensors is out of the zone which might be influenced by the fire. Any location fare enough upstream the fire would fulfil this requirement. However, due to unfavourable location of the incident or sensors with malfunctions or simply sensors being out of order, a second choice sensor on less appropriate locations has to be taken for redundancy purposed. However, if such a redundancy sensor lies within a smoke layer (downstream the fire) the reading will be strongly influenced by the absolutely non-uniform velocity and temperature profile at such a location. In cases with an almost natural flow between fire and monitoring location (no active fans in between), the values recorder will be much too high and a it is almost impossible to use them for ventilation control purposes. The simulation showed that is such cases increased turbulence due to active fans will reduce this problem. That means that for ventilation control purposes it might be necessary not only to switch sensors in case of malfunction of the main sensor, but also to change the priority tables for fan activations, in order to achieve a more or less acceptable ventilation control.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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