# Proceedings from the Ninth International Symposium on Tunnel Safety and Security, Munich, Germany
March 11-13, 2020

Edited by Anders Lönnermark and Haukur Ingason

RISE Safety Research
RISE Report 2020:09

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# ABSTRACT

This report includes the Proceedings of the 9th International Symposium on Tunnel Safety and Security (ISTSS) held in Münich, Germany, 11-13th of March, 2020. The Proceedings include 42 papers given by session speakers and 13 extended abstracts presenting posters exhibited at the Symposium. The papers were presented in 12 different sessions. Among them are Keynote sessions, Tunnel Safety Concepts, Fire Dynamics, Risk Analysis 1&2, Tunnel Safety Design Concepts, Poster Corner, Explosion Hazards, Active Protection 1&2, Emergency Management, Ventilation, Passive Protection and Evacuation.

Each day was opened by invited Keynote Speakers (in total six) addressing broad topics of pressing interest. The Keynote Speakers, selected as leaders in their field, consisted of Anne Lehan, German Highway Research Institute, Germany, Marc Tesson, Centre for Tunnel Studies (CETU), France, Trond H. Hansen, Oslo Fire and Rescue Service, Norway, Mia Kumm, RISE, Sweden, Roland Leucker, Research Association for Tunnels and Transportation Facilities (STUVA), Germany and Rune Brandt, HI Haerter, Switzerland. We are grateful that the keynote speakers were able to share their knowledge and expertise with the participants of the symposium.

RISE Research Institutes of Sweden AB
RISE Rapport 2020:09
ISBN 978-91-89049-89-5
Borås

# PREFACE

These proceedings include papers presented at the 9th International Symposium on Tunnel Safety and Security (ISTSS) held in Münich, 11-13th of March 2020. The symposium is well established in the tunnel fire community and the success of ISTSS is a tribute to the pressing need for continued international research and dialogue on these issues. These proceedings provide aa state-of-the-art knowledge in the field of fire safety and security in undergrounds structures.

This ISTSS regularly attracts over 150 delegates from all parts of the world and represents an arena for researchers to discuss safety and security issues associated with complex underground transportation systems. We see that new energy carriers (vehicles with new type of propellant) protection has become a major field of interest. The explosion of the CNG bus in Stockholm 2019 and the car park fire in Stavanger 2020 are examples of the challenges of the future. Inside an underground construction these incidents would have much higher potential for damage. The new energy carriages will in near future become one of the most important research fields. Furthermore, risk and engineering analysis continues to be an area that attracts many papers. This year there is also a specific focus on best practice engineering and research. Numerous renowned researchers and engineers have contributed to these and other topics at this symposium for which we are very thankful. The enormous costs for underground structures forces engineers to design alternative solutions. The sessions that have greatest focus on mitigation of fire development include those dealing with the effects of ventilation systems, active and passive fire protection, firefighting and human behaviour.

We received nearly 70 extended abstracts in response to our Call for Papers (not including our six invited Keynote Speakers) and believe that the quality of the accepted papers is a testament to the calibre of research that is on-going around the world. Of these, 49 abstracts were selected, based on their high scientific quality, for paper presentations. The poster session contains 13 posters to canvas interesting emerging research. During the symposium there is also an exhibit where businesses present their work.

The selection process was carried out by the 15 members of the Scientific Committee. The Scientific Committee consists of many of the most well-known researchers in this field (a list can be found on the Symposium website, www.istss.se). We are grateful for their contribution to make this symposium as the leading one on fire and safety science in tunnels. Ten of the 2018 symposium papers were selected to candidate as full journal papers in Fire Safety Journal. A special issue has been published related to the ISTSS 2018 which finally included eight accepted papers. These papers were peer reviewed and selected by members of the scientific committee together with the editors of Fire Safety Journal. It is our hope that this process will continue in the future in order to raise the level of the scientific part of the symposium.

Finally, we would like to thank the other members of our organisation committee: Jonatan Gehandler, who is program co-ordinator, Kaisa Kaukoranta, symposium co-ordinator, Dr Ying Zhen Li, scientific co-ordinator and Linnéa Hemmarö, marketing co-ordinator. We also would like to thank our sponsors who contributed with their support and engagement.

| | |
|---|---|
| Haukur Ingason | Anders Lönnermark |
| Chair of Organisation Committee | Chair of Scientific Committee |

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# Proposed best practice for the engineering of smoke-management systems in tunnels and other underground facilities

Rune Brandt
HBI Haerter, Bahnhaldenstrasse 7, 8052 Zürich, Switzerland, www.hbi.ch

## ABSTRACT

The paper proposes a new best practise for smoke management as part of safety engineering in tunnels and underground facilities. Particular requirements on passive measures such as platform-screen doors and anti-recirculation walls are also described. The main focus is on active smoke management using ventilation systems. The paper proposes that the dimensioning is to be carried out according to six main cases, applying a main and a minor design criterion. When only considering the smoke-management system and no other mitigation measures, this dimensioning corresponds to the minimum operation requirement. Closed-loop control of the longitudinal flow is a challenge, in particular due to the difficulty of obtaining adequately accurate measurements of the flow. The review of fire detection systems results in a proposal of properly specified linear heat detectors. In addition, smoke detectors using a novel data analysis technique can be beneficial. It is advocated that smoke-management systems shall be operated fully automatic. However, manual operator intervention shall be possible.

**KEYWORD:** smoke management, tunnel ventilation, active control, RAMS, automatic operation

## INTRODUCTION

The focus of this paper is to convey a personal view on smoke management as a mitigation measure in safety engineering. In simple terms, the objective is to keep smoke and the associated toxic gasses of a fire away from the users so that they may egress safely.

As the occurrence and development of a fire is unknown, the fire detection and the reaction by the smoke-management system needs to be fast i.e. enabling an adequately safe environment within few minutes after the onset of the fire.

## ON CERTAIN PASSIVE MEASURES FOR SMOKE MANAGEMENT

### Introduction

Due to their reliability, passive measures are obviously favoured. The smoke propagation is limited to certain zones i.e. by establishing fire zones separated e.g. by self-closing fire doors.

### Platform –screen doors (PSD)

Platform-screen doors or platform-edge doors need to establish a complete separation between the track and the platform, in order to be deemed efficient from a smoke-management point of view. Consequently, the openings of the PSD need to be aligned with the train doors. Due to this, the rail system therefore has be operated with purpose-built rolling stock.

### Anti-recirculation walls at tunnel portals

In many safety concepts, a parallel tunnel tube is intended to function as safe haven. Logically, this escape tunnel then has to be kept smoke free, in case of fire in the adjacent incident tube. The egress routes between the two tubes are kept smoke free by establishing an air lock i.e. having two doors.

Smoke can, however, exit through the portal of the incident tunnel and re-enter the non-incident tunnel through its portal, see *Figure 1*.

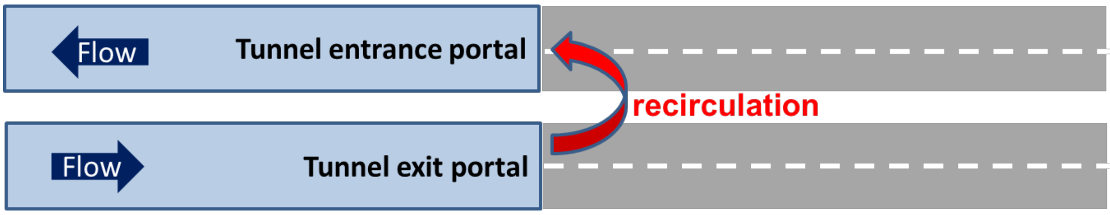
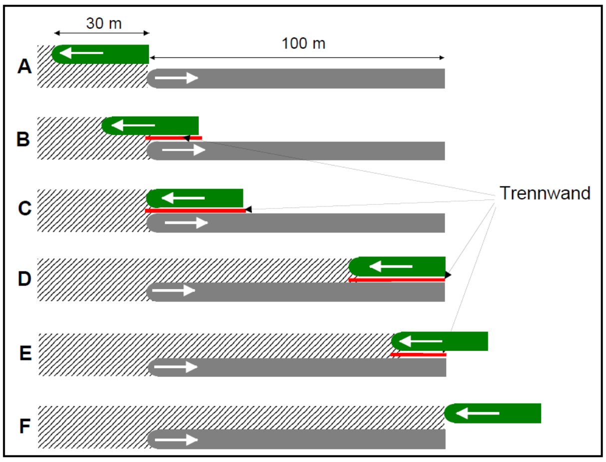


*Figure 1 Principle of recirculation from exit portal (outflow) to entrance portal (inflow)*

Such smoke recirculation can be adequately hindered by having an anti-recirculation wall between the two tunnel tubes. Based on [2] to [6], the Swiss guideline regarding road-tunnel ventilation [1] concluded that on of the following measures against recirculation are to be foreseen, depending on the location of the entrance and exit portals in relation to one another, see *Figure 2*.



A. Entrance is 30 m behind exit

B. Between situation A and C

C. A 30 m long wall separates the two portals zones

D. Between situation C and F

E. Between situation C and F

F. Exit is 100 m prior to entrance

*Figure 2 “Trennwand” = separation wall. Measures to minimise smoke recirculation at portals of road tunnels according to FEDRO/ASTRA [1]. Figure from [1].*

The deduced requirements to the separation wall between the tunnel tubes are valid when:
- the two tunnel tubes are close to each other,
- the tunnels are not in a trough and
- there is not an elevation behind the tunnel portal

A more refined empirical model that incorporates the requirements above, through influence factors, has been developed by Brandt [7].

## VENTILATION PRINCIPLES FOR SMOKE MANAGEMENT

### Ventilation principles

Two distinct principles are applied for smoke-management:

1) Longitudinal ventilation, which can be subdivided depending on the ventilation objectives (see *Figure 3*):
    a) Zero-velocity at the positions of the fire with the aim to benefit from adequately slow smoke propagation velocity in all directions so that the people can egress under the developing layer
    b) Some back-layering of smoke upstream controlled by the so-called confinement velocity ($u_{conf}$) and faster smoke propagation downstream
    c) Smoke propagation only downstream by ensuring at least the critical velocity ($u_{crit}$) just upstream the fire i.e. blowing the smoke away from the intended egress area to give tenable conditions on one side of the fire and allow smoke only on the other

2) Smoke extraction i.e. removing the smoke to provide tenable conditions in the space of interest. In order to ensure an efficient smoke-extraction, it can be argued that the flow velocities towards the extraction point should as a minimum be equal to the confinement velocity.

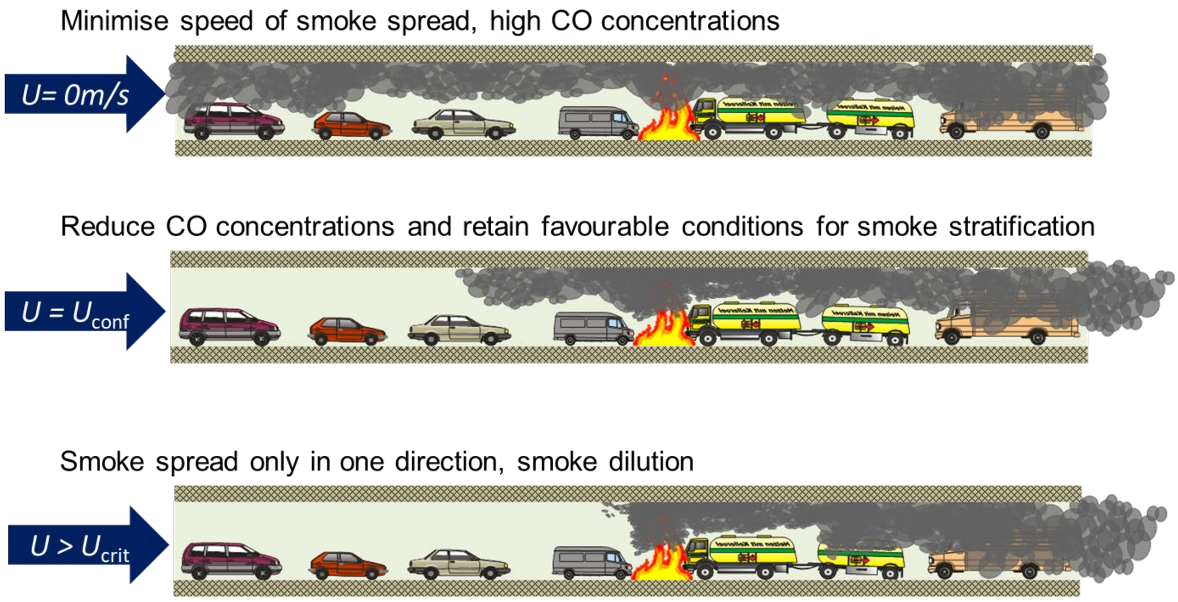


*Figure 3* *Longitudinal ventilation objectives*

### Typical design values

In practise, it appears that a minimum velocity ($u_{min}$) of 0.5 m/s is required in order to move even cold smoke. The value of the critical velocity has been subject of several studies, and one of the most recent proposals to calculate this can be found in NFPA502 [19]. For a 30 MW fire in a road tunnel, a typical value of $u_{crit}$ is 2.4 m/s. The value of $u_{conf}$ is somewhat more difficult to determine, but a typical value is 1.2 m/s.

The design velocities have to include a margin for ventilation control and therefore need to be higher than the theoretical ones derived for steady state. Without such margin, the flow is unlikely to achieve the design value. Consequently, it is proposed to increase the design velocity by 25%.

Early designs required the smoke-extraction rate to be 150% of the smoke–production rate i.e. about 120 $m^3/s$ for a 30 MW fire. From a smoke-management perspective, the smoke-extraction rate also needs to be at least $u_{conf}$ multiplied with the cross section areas on each side of the smoke-extraction point. Assuming that the cross sections on each side of the extraction point are equal, this results in the following volume flow calculation: $V = 2 \times u_{conf} \times$ (tunnel cross section area). The highest of the two values, smoke-management vs. smoke-extraction, has to be used in the design.

## Design philosophy

It is proposed to adopt two design criteria:

- *Main design criteria* covering all *typical worst cases* but not extreme scenarios
- *Minor design criteria* also for the typical worst case but having *one extreme design parameter*

## Ambient conditions and further external forces

Forces arising from ambient conditions (external winds and temperatures) have to be considered in the design. The 95%-percentile of long-time hourly mean values of ambient conditions should be assumed for the *main design criteria*, whereas the 99.9%-percentile should be applied as *extreme design parameters* when using the *minor design criteria*.

Other system forces that might occur e.g. due to operation of other equipment should in addition be considered in the design.

## Design fires

In order to determine the design fire, typically a credible worst-case scenario is assumed. In several countries, national guidelines prescribe the maximum heat-release rate to use for dimensioning, i.e one mega-watt number. However, particularly in rail applications, a fire scenario is used, in which the fire develops over time (mega-watt curve) to reach the maximum heat-release rate.

In addition to the credible worst-case scenario, an extreme design fire shall be determined. For the design criteria, this then corresponds to *one extreme design parameter.*

## Fixed fire-fighting system (FFFS)

Fixed fire-fighting systems (FFFS) efficiently reduce the development of a fire. However, rapid activation is crucial for a FFFS to provide any benefit in safety engineering. Assuming that the FFFS is adequately designed and activated within, say, 2 minutes of the onset of the fire, the question remains to assess its impact on the fire in terms of e.g. resulting heat-release rate. The FFFS would be expected to almost extinguish open fires but will have limited impact on concealed fires. Reviewing the fire experiments conducted with FFFS, it seems a good design assumption that the FFFS will reduce the potential maximum heat-release rate to half. This means that a design fire of e.g. 100 MW without FFFS can be reduced to 50 MW with FFFS.

### Applied fire-scenarios for the design

The design needs to cater for situations during which associated key systems fails that have direct impact on the functionality and/or the efficiency of the smoke-management system. One such system is the FFFS.

It is proposed to dimension the smoke-management system according to following design fires:

- Maximum heat-release rate of the Design Fire with FFFS
- Maximum heat-release rate of the Design Fire without FFFS
- Cold fire with the same smoke-production rate as the hot Design Fire

## CONTROL OF THE LONGITUDINAL FLOW

### Introduction

In many cases, the smoke-management system envisages to control the longitudinal flow so that its velocity is contained within a certain range.

For longitudinal ventilation systems, the objective of the control is to obtain and keep the velocity within a certain range. One objective can be to keep the velocity adequately low to enable egress by foot on both sides of the fire. Also, if the objective is to prevent backlayering and ensuring at least the critical velocity, it can be desirable to restrain the air flow and hence the fire development.

Regarding smoke-extraction systems, the objective is to limit the smoke spread to the extraction zone. However, external forces and/or the chimney effect by the fire can cause the flow to spread beyond the extraction zone, as was the case during the Mont-Blanc fire in 1999. At high smoke-extraction rates, the requirement for control of the longitudinal flow is reduced.

In a research project for the Swiss road authorities, all principles for influencing the longitudinal flow in road tunnels were investigated [9, 10].

### Passive measures

The passive measures aim at reducing the required air flow capacity.

A typical passive measure is to block the airway e.g. by closing purpose-built doors. This measure is used in rail and metro systems, where blocking the underground facility do not impede the egress and the intervention by the emergency services.

In road tunnels, however, egress and intervention normally require keeping the tunnel open to traffic. In the Roppener tunnel (Austria), a curtain is lowered in case of fire to reduce the longitudinal flow. This is designed in such a manner that vehicles can drive through it, see *Figure 4*. References [13] and [14] report on fluid-dynamic investigations of similar curtains.

Installing a large balloon that fills with air in case of fire and incorporates an airlock to enable passing through it, has also been proposed as an innovative measure to block the air flow.

*Figure 4 Flexible curtain that is lowered in case of fire in the Roppener tunnel, Austria*

Air curtains appear to be the viable alternative to genuine curtains. The principle is to inject flow at a high velocity and at a large angle (almost perpendicular) from one side so that it impinges on the opposite side, see *Figure 5*. However, it should be noted that it can only resist a certain pressure, above which it completely ceases to resist the longitudinal flow. Another issue is that it by design can only oppose a pressure difference in one direction. Although often used in HVAC systems, air curtains are therefore less common for tunnel applications.

*Figure 5 Air curtain without (left) and with (right) recirculating flow*

## Active Measures

In metro systems, the classical push-pull principle involves flow injection at one position and/or extraction at another to create a longitudinal flow. This method has also been used in road tunnels e.g. Seelisberg (Switzerland) and Saukopf-tunnel (Germany) [8].

In 1898, Saccardo patented the principle of injecting flow at a low, almost horizontal, angle to cause a longitudinal flow [11]. In the following year, this design principle was used for the Gotthard rail tunnel [12]. The drawback of the Saccardo nozzle is that it only functions in one direction at a fixed injection angle.

A refined utilisation of the Saccardo principle is to use fresh-air impulse dampers. Here, the injection angle can be varied so that injection is possible in both directions [15], see *Figure 6*. This is an often-seen solution for refurbishment of road tunnels with fresh-air ducts.

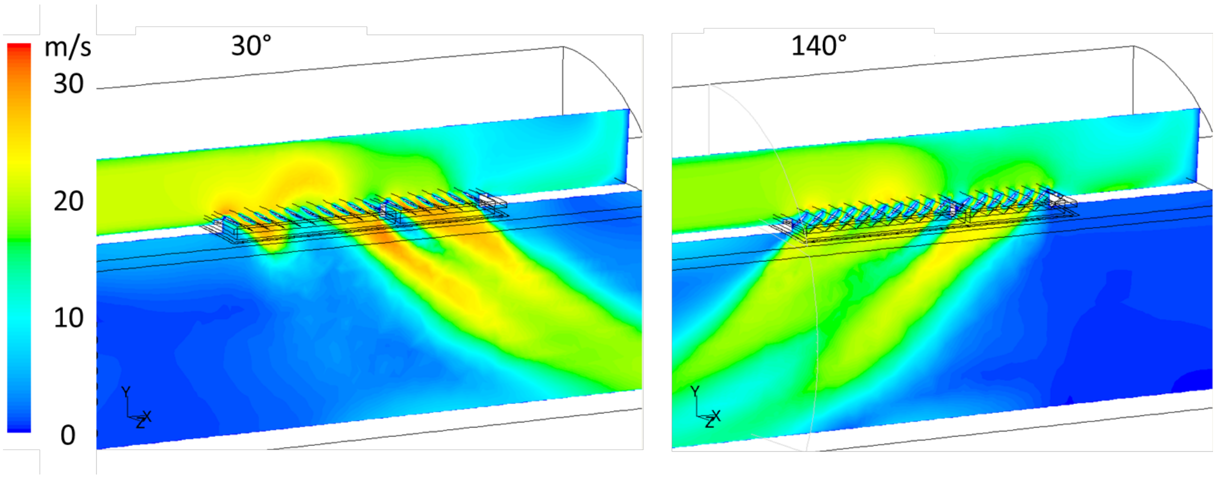


*Figure 6 CFD computation of a fresh-air impulse damper for two utilisations*

The most common method, however, for influencing the longitudinal flow in road tunnels is the utilisation of jet fans. The advantage of jet fans is that they maintain having an impact on the longitudinal flow irrespectively of the direction of the flow to control.

## Closed-loop control of the longitudinal flow

The principle of the closed-loop control is to measure the longitudinal flow and to adjust the ventilation capacity until the desired velocity is reached.

In order to ensure that the smoke was extracted entirely within the extraction zone, the bi-directional road tunnel Vue-des-Alpes [16] was the first tunnel to use closed-loop control of the longitudinal flow in case of fire. Based on these experiences, a closed loop control was applied to the refurbishment of the Mont Blanc tunnel [17].

The reason why active closed loop control has not been attempted earlier, is the realization that it is a challenge to obtain adequately accurate measurements of the volume flow in the tunnel. Vane anemometers and pitot tubes can merely measure velocities in a single point, but for this purpose the average velocity in the entire tunnel cross section is required. Considering that the tunnel can only have measurements devices situated near its wall, to not obstruct traffic, one viable measurement principle that gives adequately reliable values is based on measuring across the traffic space, using the ultra-sonic principle, see *Figure 7*.

Regarding the assessment of various measurements methods of the air flow in tunnels, the conclusions from the research project [18] on the matter is misleading, as it was based on measurements in tunnels operated with traffic. The piston effect of the driving vehicles mixes the flow field to such an extent that the entire flow field in a cross section has similar velocities. For the purpose of active control during a fire, the situation is different, as there should be no operating traffic and the flow field in a cross section is therefore very different and with large variations in velocities.

Even with the best possible anemometer for the measurements of the average velocities in a cross section, it has to be ensured that the measurements are plausible. Attempting to control the longitudinal flow based on inaccurate measurements can have devastating consequences. Consequently, a plausibility test of the measurements has to be carried out. The typical configuration for this purpose is to place three anemometers close to each other and to compare the three measurements using logical rules.

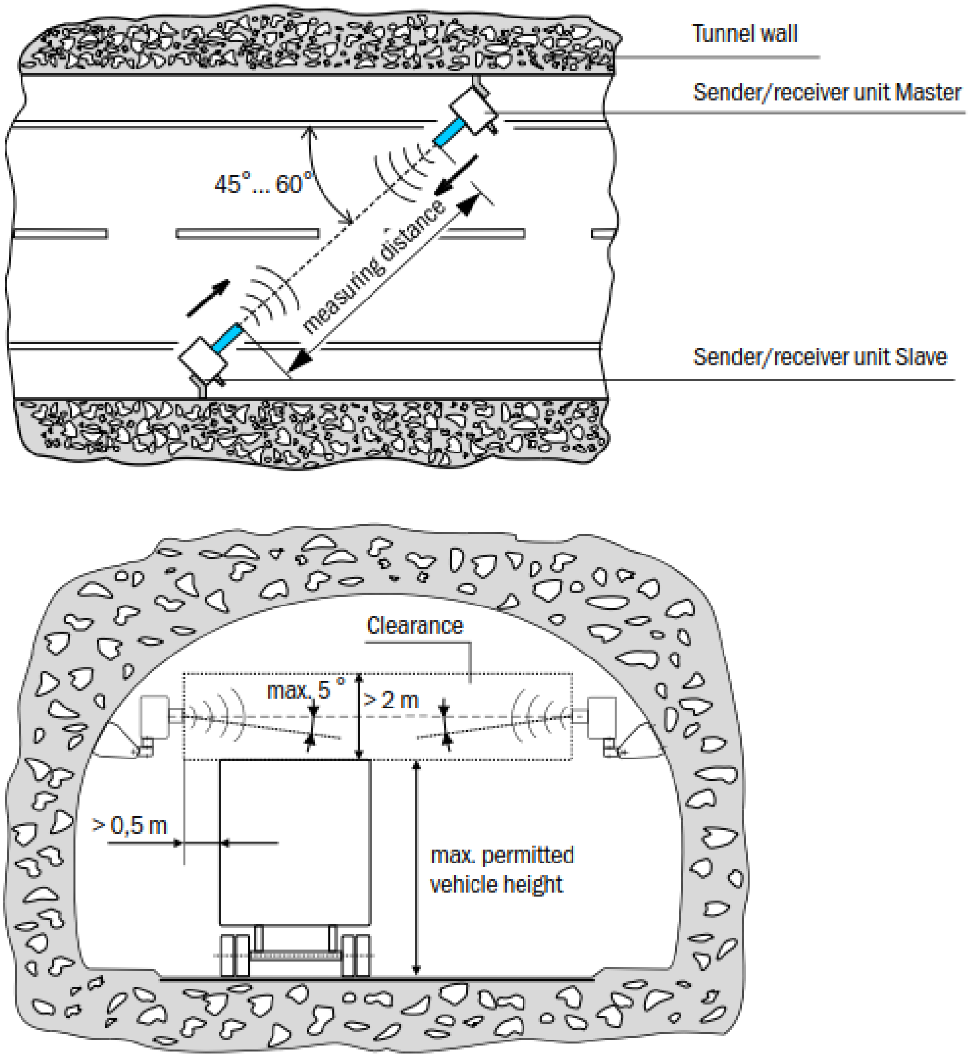


*Figure 7 Principle of ultra-sonic flow measurements by measuring across the tunnel section. Illustration from FLOWSIC200 operation instructions, release 2016-17*

Whereas the control routine for the Vue-des-Alpes was directly based on the equations describing the physics of the flow field, most routines nowadays are based on using standard PID libraries. This is in line with the conclusions of the in-depth research of various feed-back control principles that was carried out for the Swiss Federal Roads Office [22]. The practical use of PID and the determination of the control parameters is described in [21]. Active feed-back control is also prescribed for the E4 Bypass Stockholm, which is one of the largest and most complex road tunnel-networks under construction [20].

## DIMENSIONING

Two dimensioning of the smoke-management system have to be carried out:

- *Main Dimensioning* applying the *Main Design Criteria* and covering all *Typical Worst Cases* but not extreme scenarios
- *Minor Dimensioning* applying the *Minor Design Criteria* for the *Typical Worst Case* design situation and *One Extreme Design Parameter*

Moreover, the dimensioning needs to be carried for cases that key systems, which have a direct influence on the dimensioning, do not function. One such system is the fixed fire-fighting system, as failure leads to larger design fires than expected. If the likelihood of such system failures is as low as for the occurrence of one of the *Extreme Design Parameters*, it is proposed to conduct the dimensioning applying the *Minor Design Criteria* but applying the design fire without application of the FFFS.

The resulting dimensioning corresponds to the maximum of these six cases, see Table 1. It should be noted that there are several sub-cases of 3 and 4, as the result for each of the *Extreme Parameters* has to be evaluated.

*Table 1 Cases for the dimensioning of the smoke-management system*

| Case | Dimensioning | Criteria | Scenario | Design Fire |
|---|---|---|---|---|
| 1 | Main | Main Design Criteria | Typical Worst Case | Maximum heat-release rate with FFFS |
| 2 | | | | Cold fire |
| 3 | Minor | Minor Design Criteria | Typical Worst Case and One Extreme Parameter | Maximum heat-release rate with FFFS |
| 4 | | | | Cold fire |
| 5 | | | Typical Worst Case | Maximum heat-release rate without FFFS |
| 6 | | | | Cold fire |

Typical results of the dimensioning are the required:

- thrust for systems to control the longitudinal flow
- extraction rates
- distances over which the extraction takes places

The detailed selection of equipment is conducted when other requirements to the design aspects have been clarified.

## DESIGN

### RAMS and Minimum operation requirements

In order to establish the required mitigation measures in case the smoke-management system (and all other safety relevant systems) does not perform according to the design criteria e.g. due to equipment failures, a RAMS analysis of the entire safety system should be carried out (RAMS = reliability, availability, maintainability and safety). The key question is to determine the required availability of the smoke-management system. For how long time may the smoke-management system have partial or complete failure?

If, however, it is assumed that the only viable mitigation measure is to close the underground facility, the minimum operation requirements of the smoke-management system need to be defined. In this case, the capacity of smoke-maximum system needs to correspond to its dimensioning at all times.

### Equipment Selection and Design

Assuming that there are no viable mitigation measures available, equipment needs to be selected such that the underground facility is considered safe when part of the equipment is not operational. One aspect is to be able to conduct service on equipment without having to close the facility. Other reasons for adding equipment is to enable continuing the operation of the facility in case of equipment failure. Moreover, it has to be considered that a part of the equipment can be destroyed by the fire.

In case of a longitudinal smoke-management system, the procedure is firstly to establish the maximum possible locations for jet fans and anemometers.

At least two groups of anemometers per ventilation section need to be installed and they should be as far apart as possible. Each group has three single anemometers, and they have to be situated so that they are in fully developed flow that is not perturbed by the flow from jet fans, turbulence caused by signs etc.

A typical design philosophy is to assume that the group of jet fans near the fire will not be operated and might even be destroyed by the heat. Moreover, it is common practise to have an additional group of jet fans per ventilation sections. In this manner, it is permissible that one group of jet fans do not function or is in service.

Due to the delivery times of typically 3 months for jet fans and up to 9 months for axial fans, it should be considered to have spares on stock. However, in order to grease the bearings, the impeller of fans on stock need to be rotated several times per year.

For smoke-extraction systems, the design capacity has to be obtained even if one axial fan is not in operation.

If the smoke extraction is through opening of one or few remote-controlled dampers close to the fire, the consequences of incomplete opening of at least one damper has to be considered in the design.

## FIRE DETECTION

The Austrian highway administrations (ASFiNAG) requested a comparative assessment of various detection methods for road-tunnel operation [23]. Following criteria were examined:

- Detection possibilities
- Reliability
- Fast response
- Maintainability
- Cost effectiveness

The highest value (4) was awarded for excellent performance.

Figure 8 shows the evaluation for following detection principles:

- Linear heat detector
- Smoke detector
- CO-detector for fire detection (see [24])
- Multiple gas detector
- Flame detector
- Video for automatic fire/smoke detection

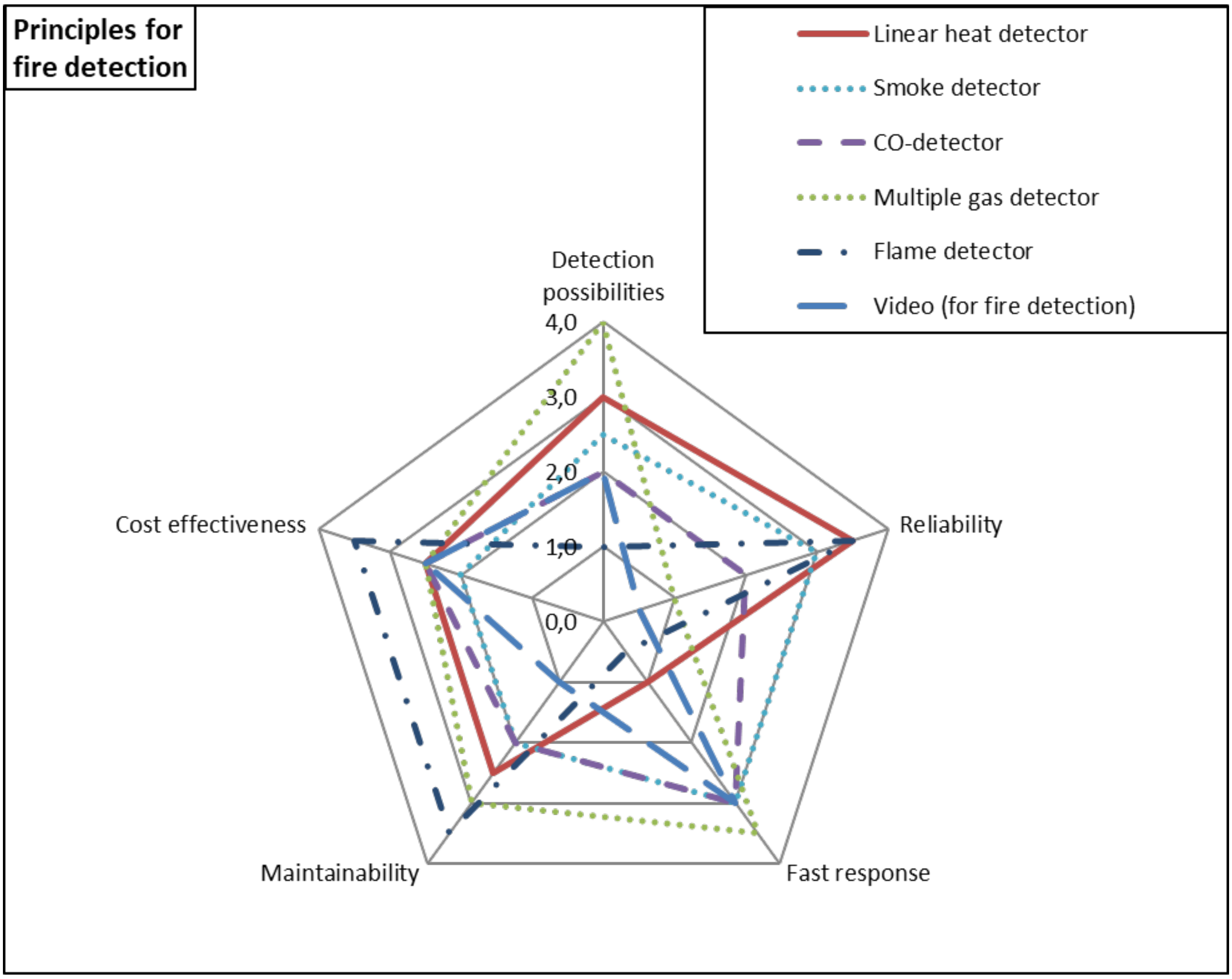


*Figure 8 Comparison of various principles for fire detection [23]*

Only the linear heat detector demonstrates a high reliability and the ability to detect many different types of fires, which is of paramount importance for fully automatic control systems. However, the response time is not very short. In order to obtain an adequately short response time, it is important to specify this in the procurement documents. The German recommendations for the configure ation and operation of road tunnels EABT-80/100 [25] specifies that the linear heat detector has to detect a 5 MW fire within 1 minute at an air flow of 6 m/s (unidirectional tunnel). The detection accuracy has to be 50 m.

In order to have faster fire detection, Switzerland requires installation of smoke detectors. In Germany, it is required that the visibility sensors also are used for smoke detection. Newly developed routines for the analysis of the signals from smoke detectors have resulted in an increase in liability to such an extent that they can be used for automatic incident response [26].

Video detection of smoke is normally very fast but prone to false alarms. Therefore, they should not be used for automatic incidence response.

## OPERATION OF SMOKE-MANAGEMENT SYSTEMS

Smoke-management systems shall preferably operate fully automatic without any need of operator intervention. Nevertheless, manual intervention by the operator has to be envisaged. It shall be possible manually to activate the smoke-management system and even to change fire zone for which it is activated. Moreover, the operator or the emergency services have to have the possibility to change the ventilation settings during intervention.

The principal aspects of the envisaged operation of the smoke-management system has to be known during the design stage.

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RISE Research Institutes of Sweden AB
P O Box 857, SE-501 15 BORÅS, Sweden
Telephone: +46 10 516 50 00
E-mail: info@ri.se, Internet: www.ri.se

RISE Safety Research
RISE Report 2020:09
ISBN 978-91-89049-89-5