SMOKE DETECTION IN ROAD TUNNELS LEADING TO AUTOMATIC INCIDENT RESPONSE

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ABSTRACT

The numerous tunnels with two-way traffic in the Canton of Grisons, Switzerland, are all monitored from one common control centre. In an emergency, automatic responses control the safety systems. The operator is not expected to intervene manually during the initial phase. Therefore, fire and smoke need to be detected automatically and the ventilation system has to respond with a high degree of reliability. In long and steep two-way tunnels with a smoke extraction system, rapid and precise detection is especially crucial. Under these conditions, the automatic differentiation between a moving and a stationary smoke source is particularly challenging.

The Swiss directive [2] released in 2007 aims at a rapid detection. According to this directive new and refurbished road tunnels in Switzerland are required to be equipped with a smoke detection system in addition to the thermal linear sensor. The first of the two systems to trigger the alarm, initiates all necessary reactions of the safety system.

This paper focusses on smoke detection and the triggering of the appropriate ventilation response. The evaluation routine was optimized using a simulation model and numerous data sets obtained from smoke tests. However, in the case of an initially moving smoke source, a trade-off between a quick reaction and a precise detection has to be accepted.

The article covers the following subjects:

- Presentation of the refurbishment of the Crapteig Tunnel
- Requirements and functional description of the automatic smoke detection in case of a fire incident
- Results of smoke tests with stationary and moving smoke sources
- Limitations of smoke detection for automatic ventilation control
- Proposals regarding further measures for the improvement of the reliability of smoke detection and standardised test procedures

Keywords: Tunnel safety, smoke detection, ventilation control, test procedures

1. INTRODUCTION

The Crapteig Tunnel is part of the A13 route, an alternative to the Gotthard route. The tunnel opened to traffic in 1996. It is 2.2 km long, has a slope of 6.5% with 2 lanes uphill and 1 lane downhill. From 2015 to 2017 the electromechanical equipment of the tunnel was refurbished and upgraded in night shifts.

The emphasis of the original transversal ventilation system design was on maintaining sufficient air quality during normal operation.

The tunnel was equipped with a distributed air exhaust and supply system, which was divided into two sections (Figure 1). This system design managed normal operation satisfactorily.

However, fire tests conducted in 1998 already showed that due to the lack of controllable dampers and without jet fans, the ventilation system could not satisfactorily control the smoke propagation. The distributed air exhaust system with extraction slots every 10 m needed to be triggered by temperatures exceeding 100°C in order to enable a more concentrated air extraction over the fire location. These temperatures were not achieved in the fire tests despite a test fire of 5 MW. Furthermore, the control of the bulk air velocity in the tunnel using the fresh air inlets was not sufficient.

To eliminate the safety deficit, two projects were launched. The aim of the first project was to upgrade the electromechanical equipment and refurbish the ventilation system to the current standards of the Swiss Federal Road Office FEDRO [1], [2]. These measures were carried out during the years 2015 to 2017. The second project consists of building a new parallel safety gallery, according to the requirements of [4] and [3]. The emergency exits are expected to be operational by 2022.

2. REFURBISHMENT OF THE CRAPTEIG TUNNEL

Major changes to the original ventilation system were necessary in order to fulfil the requirements of the current FEDRO standards, whilst not lowering the previous safety level during the execution phase.

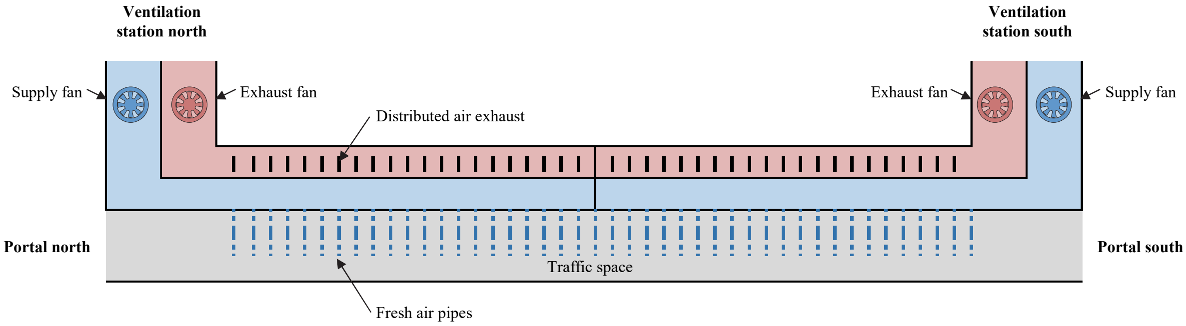


Figure 1: Ventilation system before the refurbishment

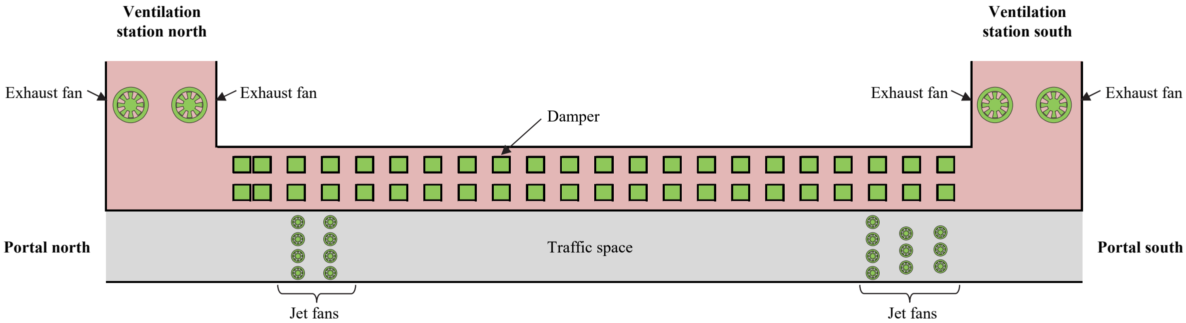


Figure 2: Ventilation system after the refurbishment

The following modifications were undertaken:

Ventilation stations:

- Replacement of the axial fans (2 supply and 2 exhaust fans) by 4 axial exhaust fans. The fans are equipped with variable pitch in motion to be able to cover varying pressure differentials. Additionally the limitations of the available power supply required the use of variable speed drives in order to limit the starting current.
- Since distributed fresh air is no longer required for the fresh air demand, all axial fans are redirected to the existing exhaust stacks.

Ventilation ducts:

- All fresh air orifices were sealed. Following this step, smoke exhaust dampers were installed every 90 m along the former fresh air duct.
- The former supply and extraction ducts were aerodynamically connected.
- After completion of the new exhaust system, 5 over-head niches for jet fans were built. This step required temporary partitioning of the new exhaust duct. The jet fans were installed and commissioned according to the progress of work.

Traffic space:

- In addition to the existing thermal linear sensor 2 groups of 3 velocity sensors, 25 smoke detectors and 4 opacity sensors were newly installed. The passively ventilated smoke detectors are mounted under the intermediate ceiling along the centreline of the tunnel.

3. INCIDENT PROCEDURE

According to the FEDRO standards [6] the first main alarm of the thermal detection or the designated smoke sensors triggers all safety systems. The systems then switch to the operation mode predetermined by the control system. Subsequent alarms do not overrule the active alarm.

The opacity monitors only control the ventilation during normal operation.

Due to the limitation of available manpower at the operations centre, a manual intervention by the operator into the automated procedure is considered unpractical. The main focus of the operator is to support the rescue forces.

The fire detection systems in the traffic space consist of smoke detectors every 90 m and the thermal linear sensor along the whole tunnel length. While the smoke detector and the thermal linear sensor affect the ventilation system and the other equipment directly, the video system provides a possibility for the operator to get additional visual information.

Figure 3 shows an extract of the reflex matrix giving information on the correlation between detection and reaction.

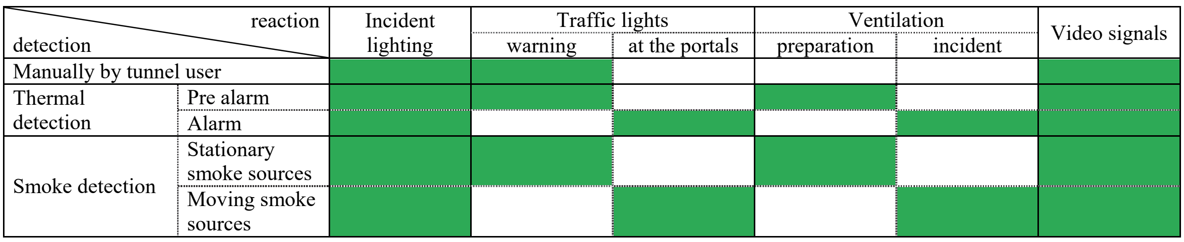


Figure 3: Extract of the reflex matrix for the Crapteig Tunnel

The detection of a localised fire or smoke source automatically starts the smoke extraction system: opening 2 pairs of dampers, starting up the 4 extraction fans and initiating the control process for the longitudinal air flow. In general the latter consists of a symmetrical air flow in the tunnel cross section, from both portals to the extraction point. If the incident is close to a portal the system reaction depends on the direction of the airflow at the moment when the main alarm is set off. With air flowing into the tunnel the smoke is extracted through the dampers whereas with airflow out of the tunnel the smoke is pushed out of the portals using jet fans.

4. REQUIREMENTS FOR THE SMOKE DETECTION

[2] requires a smoke sensor at every tunnel cross section where dampers are located. The technical manual [5] states the following key requirements for smoke detection:

- Use of two smoke concentration threshold values (GW1 = 10 1/km, GW2 = 30 1/km). Exceeding the threshold value GW1 starts the smoke evaluation routine and computes the smoke propagation velocity. GW2 triggers the alarm stationary smoke source.
- Distinguish between mobile and stationary smoke sources, starting with the assumption of a mobile source.
- Take into account the smoke propagation velocity and the bulk air velocity in the tunnel.

Whereas requirements exist for thermal linear detectors and their testing [2], [8], no specifications are given for the testing of the smoke evaluation routine.

In the design process, the ventilation engineer has to define a detailed functional description based on the above-mentioned requirements. Further assumptions are necessary, e.g. sample rates, averaging or the storage of the status of each smoke detector. It is inevitable that all persons involved in the process need to meet high technical and communicative demands.

5. FUNCTION OF THE SMOKE DETECTION

The smoke evaluation routine analyses the sequence of the data of the smoke detectors. The smoke source is either a vehicle that has already stopped or a moving vehicle. For the safety of the tunnel users it is essential to determine the correct position of the stationary incident. As long as the smoke source is still moving or the location of the stationary source is not identified, the air extraction must not be activated since an air extraction at the wrong location would endanger the tunnel users by moving smoke from the incident location through the tunnel to the distant extraction point.

In the Crapteig tunnel and 10 other tunnels in the Canton of Grisons, the same smoke evaluation routine is implemented. The main features of the routine are:

- Estimate of the smoke propagation velocity using the sequence of the smoke detector signals
- Use of a limited spatial evaluation zone for the smoke detectors considered in the smoke evaluation routine

The correct implementation of the smoke evaluation routine is verified before conducting a smoke test. The state of the art is to simulate values for single smoke detectors in a specific sequence and to check the reaction of the smoke evaluation routine. The values are mimicked using the manual-simulation mode on the user interface. The ventilation engineer specifies the test sequence for each project individually.

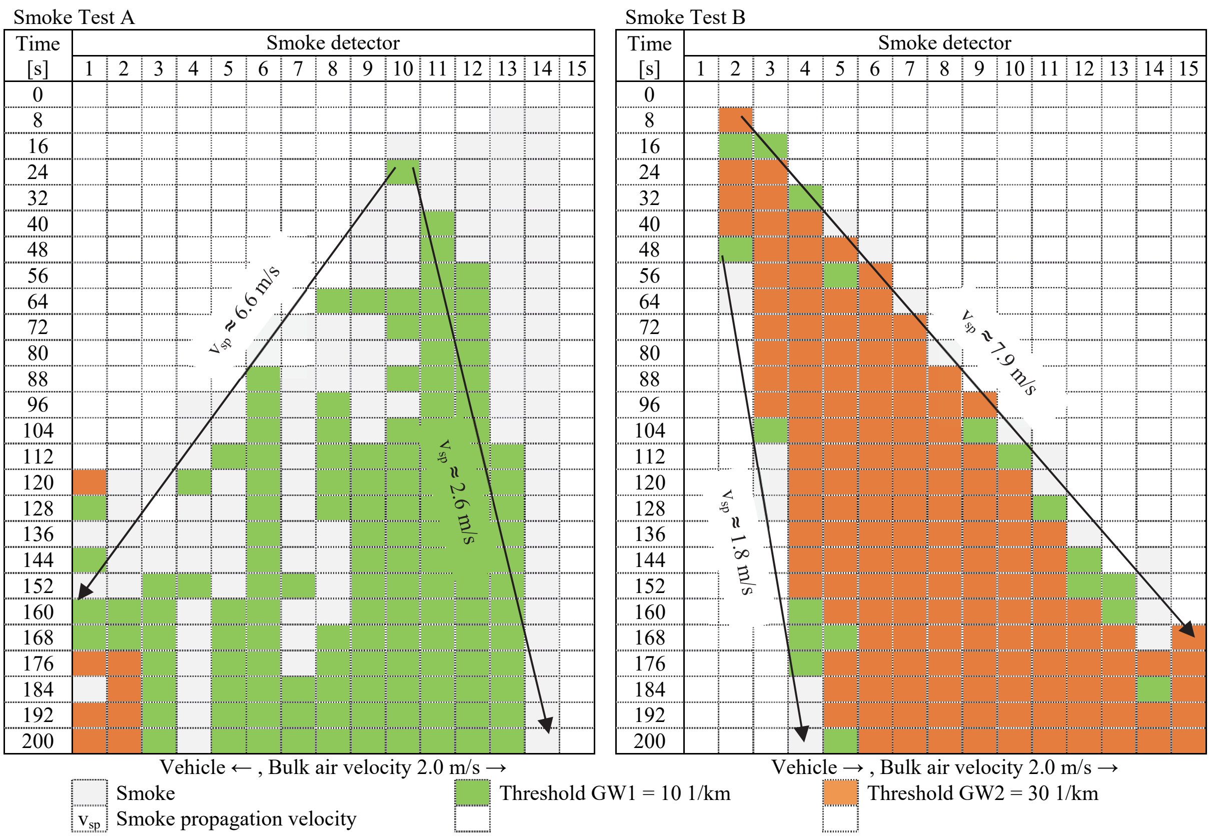
6. RESULTS OF SMOKE TESTS WITH STATIONARY AND MOVING SMOKE SOURCES

During real fires as well as in tests it is very unlikely that smoke detectors are triggered in a linear sequence. Thermal effects and the turbulent bulk air velocity influence the movement of smoke. The distribution of smoke in the traffic space is irregular and the smoke concentration varies, as shown in Table 1.

In the Crapteig Tunnel tests, the smoke consisted of a dense white aerosol as seen in Figure 4. This procedure does not require protection measures of the tunnel lining since the heat development is small but still buoyant enough to make it rise to the ceiling. The tests included stationary as well as moving smoke sources.

Figure 4: Moving smoke source in the Crapteig tunnel

Table 1: Smoke distribution with moving smoke source. In test A, the vehicle is moving against the direction of the bulk air flow; in test B, both directions are the same. The smoke source and the absolute value of the vehicle speed and the bulk air velocity are comparable in tests A and B.



Observations from the Crapteig smoke tests are:

- Stationary smoke sources are detected with great reliability.

- The evaluation of the stopping point of moving smoke sources (approx. 20 m^3/s smoke generation, driving speed 40 km/h) has shown to be reliable as long as the direction of the bulk air velocity and the moving smoke source are equal.
- If the direction of the bulk air velocity is opposite to the direction of travel of the moving smoke source, it is likely that the calculated location will have an offset with respect to the true location of the vehicle. In the Crapteig Tunnel, the longest offset with the current *Grisons routine* under unfavourable circumstances was up to 800 m.
- As shown in Table 1, the detected opacity is strongly reduced if the direction of the bulk air velocity is opposite to that of the moving smoke source. Reasons for this are the higher dilution by the approaching fresh air and the more intensive turbulence. In combination with the implemented spatial evaluation zone in the Grisons routine these effects can lead to a disregard of smoke detectors outside the zone.

The tests with moving smoke sources in the Crapteig Tunnel confirmed results from tests in other tunnels where, under certain circumstances, the correct position of a moving vehicle could not be evaluated.

7. OPTIMISING THE SMOKE EVALUATION ROUTINE

Taking into account experiences from several tunnel projects a new evaluation routine was developed and optimised by using the existing 35 data sets from smoke tests. In January 2018 an additional test series with moving smoke sources expanded the data set. Smoke generation with low smoke concentrations, simulating a starting fire was of special interest. An entire data set of 55 tests was pre-processed and then used in the optimised smoke evaluation routine HBISD^{plus}. This routine allowed performing a parameter study. The following parameters were examined:

- Increase of the spatial evaluation zone. This zone specifies the spatial expansion of smoke detectors used in the smoke detection routine.
- Influence of the threshold values for GW1 and GW2.

Table **2** shows the comparison of the currently implemented *Grisons routine* to the routine HBISD^{plus} with 16 different parameter sets.

Table 2: Results of the parameter study for moving smoke sources for the current state Grisons routine and the optimised HBISD^{plus} routine

	Grisons routine	HBISD^{plus} GW1 = 10 1/km, GW2 = 30 1/km				HBISD^{plus} GW1 = 30 1/km, GW2 = 30 1/km			
		evaluation zone ±3 SD	evaluation zone ±5 SD	evaluation zone ±8 SD	no evaluation zone	evaluation zone ±3 SD	evaluation zone ±5 SD	evaluation zone ±8 SD	no evaluation zone
Not detected	5.5%	3.6%	1.8%	1.8%	1.8%	1.8%	0.0%	0.0%	0.0%
Out of range	18.2%	5.5%	7.3%	7.3%	5.5%	14.5%	16.4%	14.5%	12.7%
+/- 3 to 4 SD	9.1%	9.1%	7.3%	7.3%	7.3%	3.6%	3.6%	3.6%	3.6%
+/- 1 to 2 SD	32.7%	36.4%	38.2%	38.2%	38.2%	34.5%	38.2%	38.2%	36.4%
Exact	34.5%	45.5%	45.5%	45.5%	47.3%	45.5%	41.8%	43.6%	47.3%
Not acceptable	32.7%	18.2%	16.4%	16.4%	14.5%	20.0%	20.0%	18.2%	16.4%
Acceptable	67.3%	81.8%	83.6%	83.6%	85.5%	80.0%	80.0%	81.8%	83.6%

	HBISD^{plus} GW1 = 30 1/km, GW2 = 75 1/km				HBISD^{plus} GW1 = 75 1/km, GW2 = 75 1/km			
	evaluation zone ±3 SD	evaluation zone ±5 SD	evaluation zone ±8 SD	no evaluation zone	evaluation zone ±3 SD	evaluation zone ±5 SD	evaluation zone ±8 SD	no evaluation zone
Not detected	20.0%	20.0%	21.8%	21.8%	9.1%	3.6%	7.3%	9.1%
Out of range	9.1%	9.1%	7.3%	7.3%	12.7%	10.9%	10.9%	10.9%
+/- 3 to 4 SD	3.6%	3.6%	3.6%	3.6%	9.1%	7.3%	7.3%	7.3%
+/- 1 to 2 SD	27.3%	25.5%	23.6%	25.5%	30.9%	36.4%	32.7%	32.7%
Exact	40.0%	41.8%	43.6%	41.8%	38.2%	41.8%	41.8%	40.0%
Not acceptable	32.7%	32.7%	32.7%	32.7%	30.9%	21.8%	25.5%	27.3%
Acceptable	67.3%	67.3%	67.3%	67.3%	69.1%	78.2%	74.5%	72.7%

The results of the parameter study are:

- For tests with a stationary smoke source, the location was determined with a high degree of temporal and spatial accuracy. The verification of a stationary source takes approximately 50 secs.
- The currently implemented *Grison routine* leads to acceptable results in 67% of the cases. Acceptable is defined here as an aberration of max. 2 smoke sensors or 180 m.
- The routine with the best performing parameter set leads to an acceptable smoke detection in 86% of the tests.
- The best parameter set contains unchanged threshold values GW1=10 1/km and GW2=30 1/km but with abatement of any spatial evaluation zone.

Videos of real incidents prove that it remains impossible for an automatized routine to detect moving smoke sources with absolute reliability. Smoke might not impinge the detectors and the smoke detectors are not necessarily triggered in a regular sequence. With respect to these facts, a detection rate of 86% is high.

8. EXPERIENCE WITH SMOKE DETECTION FOR AUTOMATIC VENTILATION CONTROL

Since 2007 smoke detectors are part of the standard equipment in Swiss road tunnels. The experience gathered from the use of smoke detectors in road tunnels is presented below:

- The threshold values GW1=10 1/km and GW2=30 1/km are adequate for smoke detection.
- Incidents with little heat development are detected significantly faster with smoke detection than with thermal detection.
- Using a transgression of the threshold GW1 to trigger reactions such as stop lights at the tunnel portals is considered inappropriate due to the high number of false alarms when referring only to GW1.
- Bulk air direction and velocity have an important effect on the dilution of smoke from a slowly moving source and therefore on smoke detection.

9. IMPROVEMENTS FOR SMOKE DETECTION AND TEST PROCEDURES

The proposed improvements are:

- Standardisation of the smoke evaluation routine.
- Standardisation of the virtual smoke detection tests with defined sample data (FAT of control system). A set of virtual data shall be predefined to set the minimal standard of what the executed smoke routine must handle successfully.
- Standardisation of on-site tests especially for moving smoke sources.
    - Factors to be standardised are smoke quality and quantity, heat development of the source, speed of the moving source and bulk air conditions.
    - These tests shall be carried out in form of a general test for detection and ventilation.
- Standard tests with moving smoke sources combined with additional heat sources are desirable, however technically challenging and at the time, not state of the art.

10. SUMMARY AND CONCLUSIONS

The refurbishment of the Crapteig Tunnel including a state of the art ventilation system and up to date detection methods was fulfilled successfully within the given time and cost frames. Whereas the ventilation system functions very reliably there is still room for improvement of the detection of incidents. The major challenge here, is detecting any type of moving smoke source and assigning its stopping location to the correct fire zone within the tunnel.

The current smoke evaluation routine functions reliably, but it is known to occasionally determine the wrong position of a stopped vehicle if the smoke detectors are not triggered in a constant sequence. Hence efforts were made to improve the situation. The key step was to develop an optimised smoke evaluation routine. For the optimization of the smoke evaluation routine, 55 data sets of smoke tests were used. This process led to the optimised smoke evaluation routine HBISD^{plus} with an increase in the detection reliability of incidents from 67% to 86%. In spring 2018 this optimised routine has not been implemented in any tunnel yet. Approval is expected for Tunnel Crapteig until summer 2018.

Potential for further improvement of reliable smoke detection remains. This is due to the circumstance that the FEDRO guidelines are not specific enough in this area and allow room for interpretation, starting with the design of the system and ending with the testing of the software. This will allow for a more efficient use of the already installed hardware and achieving a higher safety standard at moderate costs.

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The current FEDRO standard uses thermal and smoke monitoring to detect incidents. In the first phase of an incident, the concept relies on automatic processes, without requiring the operator to intervene or adjust the ventilation system control. The smoke detection concept is confirmed by the high success rates, when correctly implementing a well-engineered smoke detection routine. Further, the standardization of the smoke detection routine design and its testing must be a future goal.

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