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

<table>
<thead>
<tr>
<th></th>
<th>only fire detection</th>
<th>fire location detection</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lighting</strong></td>
<td>●</td>
<td></td>
</tr>
<tr>
<td><strong>Tunnel Ventilation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Longitudinal ventilation</td>
<td>●</td>
<td>○</td>
</tr>
<tr>
<td>Smoke exhaust ventilation</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td><strong>Escape gallery ventilation</strong></td>
<td>●</td>
<td></td>
</tr>
<tr>
<td><strong>Traffic control / Signalling</strong></td>
<td>●</td>
<td>○</td>
</tr>
<tr>
<td><strong>CCTV</strong></td>
<td>●</td>
<td>○</td>
</tr>
<tr>
<td>Others (HVAC, control centre, …)</td>
<td>●</td>
<td></td>
</tr>
</tbody>
</table>

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.

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.
4.1. Algorithm

The described algorithm requires the following data for the evaluation:

- 3 discrete values of the smoke concentration: $SV_0 < 10\text{mE/m} < SV_1 < 30\text{mE/m} < SV_2$
- 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 $SV_2$ for $> 60s$ and
2) All other SDs with $SV_0$

⇒ Fire location = location of the activated SD with $SV_2$

**B**
1) At least two activated SD, at least 1 SD with $SV_2$ 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 $SV_2$ and
2) Last activated$^{(1)}$ SD longer than 60s ($SV_1$ or $SV_2$)

⇒ Fire location = location of the last-activated$^{(1)}$ SD

$^{(1)}$ considering 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 ($SV_1$ or $SV_2$) 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

<table>
<thead>
<tr>
<th>Time</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>t0</td>
<td>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.</td>
</tr>
<tr>
<td>t0 + 30s</td>
<td>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).</td>
</tr>
<tr>
<td>t0 + 40s</td>
<td>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.</td>
</tr>
<tr>
<td>t0 + 120s</td>
<td>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.</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>1) Variable exhaust location</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>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</td>
<td></td>
</tr>
<tr>
<td>+ Simple algorithm, because no moving / stationary fire evaluation is required</td>
<td></td>
</tr>
<tr>
<td>+ Immediate ventilation reaction and smoke extraction.</td>
<td></td>
</tr>
<tr>
<td>- Danger that dampers do not correctly close: reduced efficiency or even hazardous situation</td>
<td></td>
</tr>
<tr>
<td>- Uncontrolled smoke propagation can be the result</td>
<td></td>
</tr>
<tr>
<td>- Negative reaction on exhaust ventilators and longitudinal air control</td>
<td></td>
</tr>
<tr>
<td>- Steady communication between SD- and ventilation system required</td>
<td></td>
</tr>
</tbody>
</table>

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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](image)

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.

9. REFERENCES