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ISAVFT Ltd.
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Foreword

On behalf of the organisers and the dedicated Technical Advisory Committee, I'm honoured to welcome you to the 20th International Symposium on Aerodynamics, Ventilation, and Fire in Tunnels, now in Scandinavia for the first time. Since 1973, this symposium has been the key event for idea exchange and learning in the field. This year, we received a record number of paper submissions, leading the committee to carefully review and select the best, which have been organized into the following sessions:

- CFD/1-D Modelling
- Design Methods Using Artificial Intelligence and/or Machine Learning
- Digitalisation
- Equipment
- High Speed Rail Tunnels & Hyperloop Systems
- Innovations in Ventilation Design and Control
- New Energy Carriers
- Platform Screen Doors
- Railway Case Studies
- Road Tunnel Case Studies
- Road Tunnel Refurbishments
- Smoke Control and Critical Velocity
- Smoke Management and Egress (Tenability)
- Sustainability in Underground Design and Construction
- Testing and Commissioning

Sincere thanks to the authors, the key-note speakers, the delegates, the exhibitors, the technical advisory committee, and the organisers. As a result of the contributions, work and passion for aerodynamics, ventilation, and fire in tunnels, this symposium offers an excellent opportunity to experience and to discuss, so that we collectively can raise the bar, for the very state of the art.

Dr Rune Brandt
Chairman of the Technical Advisory Committee

Smoke detection in branching tunnels

M. Ehrensperger, V. Butty, S. Frey, HBI Haerter AG, Switzerland

1 ABSTRACT

Swiss guidelines require new or refitted road tunnels be equipped with two systems for fire detection, namely temperature analysis and smoke analysis. The smoke analysis shall differentiate between a moving and a stationary smoke source. This requirement has led to the development of sophisticated algorithms, which are now widely employed in Swiss road tunnels.
Many tunnels can be modelled as single tubes. But branching tunnels need to be covered as well. These scenarios are more complex and pose difficulties to the smoke analysis.
This paper presents the challenges faced when trying to implement smoke analysis within a tunnel with significant branching.

2 INTRODUCTION

Fires in tunnels pose great danger to people and infrastructure. In the confines of a tunnel heat and smoke cannot easily escape. Ventilation is therefore very important to control the smoke propagation and to provide fresh air to fleeing people.

Prior to 2001 regulations and guidelines relating to tunnel safety on national highways in Switzerland varied between different Cantons (member states of the Swiss federation). Since then, ownership and the administration of the national highways has been centralised. This led to a review of the guidelines regarding fire prevention in tunnels as well as fire detection and response to an event. It resulted in the first national regulations and guidelines in Switzerland on these topics.

Today fire detection in road tunnels in Switzerland mainly relies on two detection methods: linear thermal detectors for the detection of elevated or rapidly rising temperatures, and smoke detectors. Both methods are typically employed at the same time.

For smoke detection, Swiss guidelines (1) since 2007 mandate that two distinct scenarios must be distinguished: a moving smoke source should be detected and traced, while a stationary smoke source should trigger the emergency response of the ventilation system. This distinction is important, especially in cases where there is not only a longitudinal ventilation system, but also a smoke extraction system present: while a smoke extraction system (according to Swiss guidelines and regulations) typically extracts air at three points over a length of around 200 [m], extracting air at a wrong location along the tunnel can lead to undesired transport of smoke within the tunnel from its source to the points of extraction, see Figure 1. Accordingly, a moving smoke source (or the first detection of smoke) should not yet activate the exhaust system.

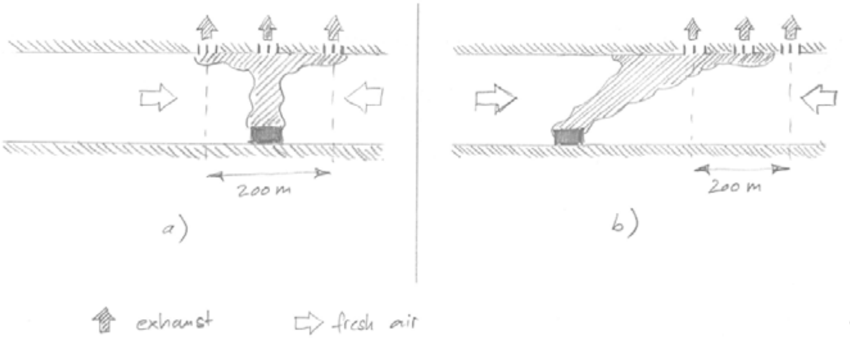

Figure 1: a) smoke distribution with extraction close to the smoke source. b) smoke distribution with extraction far from the smoke source.

Section 3 introduces some definitions and specifications used in this paper. Section 4 gives a short description of a smoke detection algorithm for single tubes providing the distinction between moving and stationary smoke sources and details some limitations. Section 5 then expands on this single tube algorithm concept and illustrates the challenges faced when adapting it for branching tubes. Section 6 introduces a way to combine multiple algorithms, thus enabling the detection of smoke also in branching, non-single tube tunnels. Section 7 finally provides some discussion of the presented work.

3 DEFINITIONS AND NOTICES

A branch of a tunnel is – in the context of this paper – called a significant branch if the length of the branch makes it necessary to install smoke detectors along this branch and a dedicated ventilation strategy has been defined for this branch.

Any branches that do not meet the above description are not considered in this paper.

In addition, the following are two definitions made by Swiss guidelines and adopted for this paper. They are listed here for comprehension:

- Visibility threshold 1 (GW1): 10 [1/km]
- Visibility threshold 2 (GW2): 30 [1/km]

The visibility thresholds GW1 and GW2 relate to low density smoke, GW1, and high density smoke, GW2. They are well above extinction coefficients expected for poor air quality (air quality warning threshold is 7 [1/km] and air quality alarm is 12 [1/km]).

Two abbreviations occurring often in this paper are the two types of alarms that the smoke detection algorithm can raise. They are:

- $Alarm_{mov}$	Alarm "moving smoke source"
- $Alarm_{stat}$	Alarm "stationary smoke source"

For each smoke detector (RM), there are the following signals that are measured or inferred:

- Position of RM number x:	$P(RM_x)$	[m]
- Cross section of the tube at location of RM_x:	$A(RM_x)$	[m^2]
- Measured extinction coefficient at RM_x:	$M(RM_x)$	[1/km]
- Local velocity in the cross section of RM_x:	$V(RM_x)$	[m/s]
- Timestamp of threshold transgression at RM_x:	$T(RM_x)$	[s]

Some parameters and variables which are used in this paper are the following:

- t_{mov}	Waiting time to raise $Alarm_{mov}$	[s]
- n_{mov}	Number of RMs with $M(RM_x)$>GW_1 needed to raise $Alarm_{mov}$.	[-]
- t_{stat}	Waiting time to raise $Alarm_{stat}$	[s]
- u_f	Velocity of the "significant smoke front".	[m/s]

In the following some aspects of the algorithm are omitted. This mainly relates to issues of stability, such as temporal averaging or the capping of values, the handling of defective smoke detectors, the handling of portals and issues relating to timing and time keeping.

4 ALGORITHM FOR SINGLE TUBES

A single tube with no significant branching is the simplest and also the most common geometry to be encountered. A great number of tunnels fall in this category, both single tube tunnels with bidirectional traffic and multiple tube tunnel systems with unidirectional traffic in the individual tubes. Different algorithms have been implemented for this type of geometry. The following simplified description is based on an algorithm developed by HBI Haerter AG.

Input signals to the single tube smoke detection algorithm (RDA, "**R**auch-**d**etektions-**a**lgorithmus" in German) are the smoke detector readings $M(RM_x)$ and the measured flow velocities at the location of RM_x, $V(RM_x)$. Airflow velocities at the location of a smoke detector must be derived from measurement data via the cross sections at each location, *i.e.*

$$V(RM_x) = \frac{V(LM_1) \cdot A(LM_1)}{A(RM_x)}$$

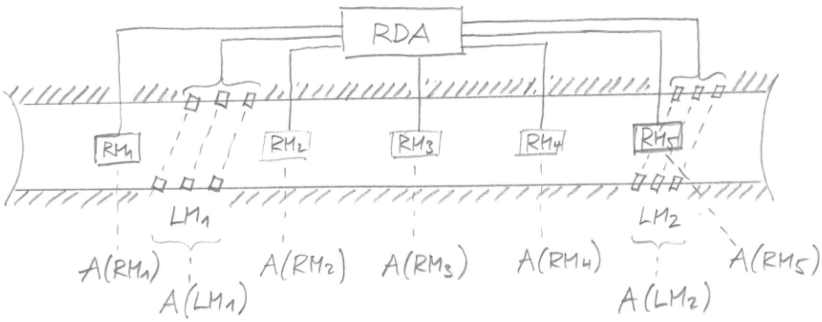

Figure 2: Simple setup, showing five smoke detectors (RM_x), two groups of anemometers (LM_y), and the cross sections at these locations (A_z).

A simple setup is shown in Figure 2. In this example there are five smoke detectors (RM_1 to RM_5) and two groups of anemometers measuring flow velocity (LM_1 and LM_2). A smoke plume emanating from a source will have two fronts, a right hand one and a left hand one. Only one plume is considered, and this single plume is continuous, i.e. it extends from the right hand front all the way to the left hand front.

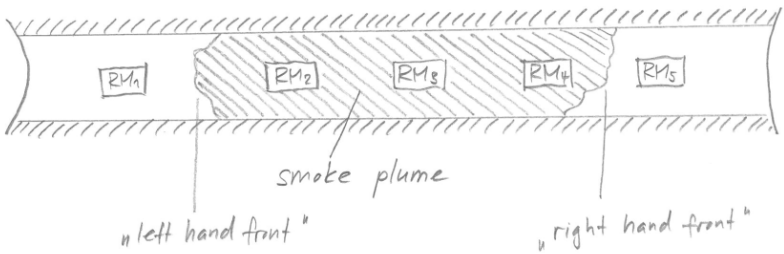

Figure 3: Definitions of the two fronts of a smoke plume.

With each new transgression of the threshold GW_1 at a smoke detector, a new front velocity u_f can be calculated, based on the locations of the smoke detectors and the timestamps of the GW_1 transgressions, *i.e.*

$$u_f = \frac{P(RM_t) - P(RM_{t-1})}{T(RM_t) - T(RM_{t-1})}$$

With each newly calculated front velocity a comparison between the two front velocities is made and the front with the higher front velocity is considered the "significant front".

The alarm $Alarm_{mov}$ is raised, if

- the same smoke detector reading surpasses GW_1 for amount of time t_{mov}; or
- n_{mov} smoke detector readings surpass GW_1.

The alarm $Alarm_{mov}$ is attributed to, *i.e.* localised at, the smoke detector representing the "significant front".

The raising of $Alarm_{mov}$ is a necessary precondition to raise the alarm $Alarm_{stat}$, the main alarm activating the emergency response of the ventilation system.

If no subsequent GW_2 transgressions are registered, but elevated levels above the GW_1 threshold persist at least at one location, relevant personnel are prompted to review the situation and decide on further measures. If, however, registered levels start to drop and ultimately fall below the GW1 threshold at all locations, then the alarm $Alarm_{mov}$ is automatically acknowledged.

If, however, the measured smoke densities rise and lead to GW_2 threshold transgressions, more involved evaluation of the readings takes place. The significant front velocity is then compared to measured flow velocities within the tube and to a velocity threshold.

Swiss guidelines and regulations define a velocity threshold u_{sr} for a stationary smoke source: u_{sr} = 5 [m/s] for bidirectional traffic and u_{sr} = 9 [m/s] for unidirectional traffic. A "significant smoke front" with an estimated speed below this threshold is considered stationary and the alarm $Alarm_{stat}$ is raised. Alternatively, if the difference between the velocity of the "significant smoke front" and the measured flow velocity in the tube is smaller than a given tolerance, the smoke front is assumed to be transported passively with the flow within the tube, the smoke source is considered stationary and the alarm $Alarm_{stat}$ is raised. After raising the alarm $Alarm_{stat}$ the RDA stops and evaluation is terminated.

In case that information on flow velocity is not available (and therefore no comparisons described above can be made), there is also a time-criterion that can raise the alarm "stationary smoke source": if no new GW_1 threshold transgressions are registered within the time expected of the "significant front" from reaching the next smoke detector, then the alarm $Alarm_{stat}$ is also raised. As above the RDA stops and evaluation is terminated.

The key challenge of the algorithm for a single tube resides not only in its graceful degradation capacity to manage smoke detector and anemometer failure but also in its robustness to manage smoke detector analysis delay and handle asynchronous processes.

This kind of evaluation works for single tubes. However, it cannot readily be applied to significantly branching tubes.

5 CHALLENGES POSED BY SIGNIFICANTLY BRANCHING TUBES

The algorithm detailed in the previous section can handle a single smoke plume with two smoke fronts. However, if there are significant branches more than two smoke fronts can be expected: every branch introduces the possibility of one additional smoke front, as can be seen in Figure 4.

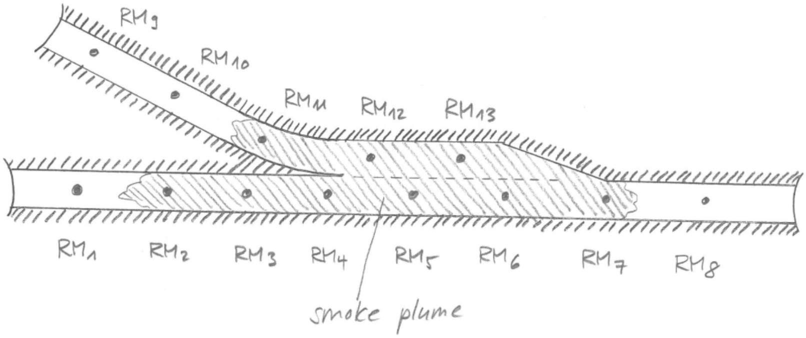

Figure 4: Tube with significant branch. There are three smoke fronts seen.

In order to detect and track these additional smoke fronts extra pieces of algorithm have to be introduced, each handling the smoke detectors associated with one additional branch. However, because of the "two-front-concept" the algorithm for single tubes is based on, these additional pieces of algorithm also require information shared with other branches. Figure 5 illustrates this. In this example branch 1 (in green) could be seen as the "main tube" with a significant branch (in orange) leading away from it. Also shown is a section called "shared branch". This is the part of the "main tube" which also needs to be part of the evaluation of branch 2 for the algorithm along branch 2 to work properly.

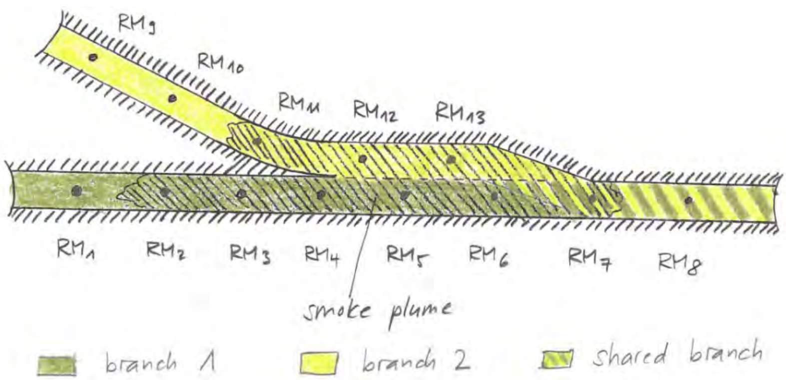

Figure 5: For the evaluation of both branches, both require information from the "shared branch".

To limit functional changes to the single tube algorithm, while enabling smoke detection in significantly branching tunnels, the concept of "possible paths" is introduced. Figure 6 shows the same branching tunnel with the two possible paths colored in green and orange. Each path is to be assigned to an independent RDA. Smoke detectors that are part of both paths, in the given example RM_7 and RM_8, provide their information to both RDAs (see Figure 7).

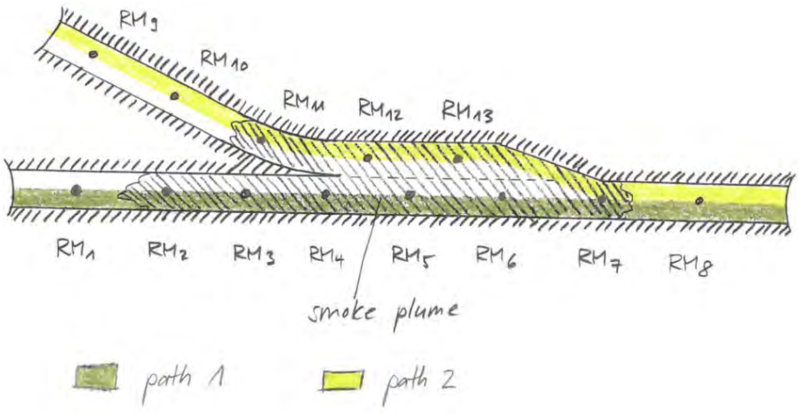

Figure 6: Definition of two paths in the given geometry.

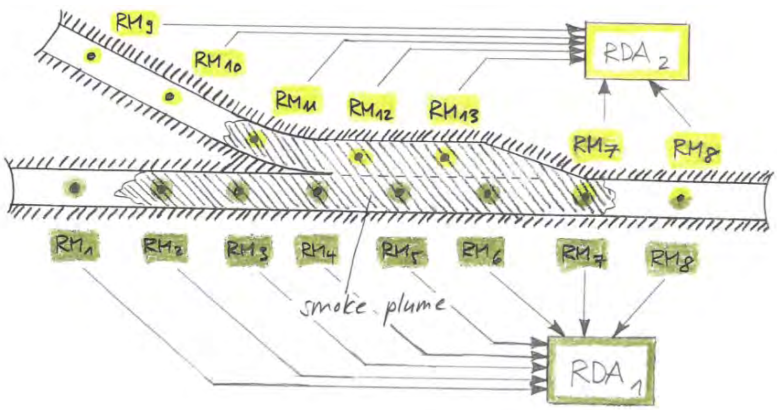

Figure 7: Assignment of RMs to RDA in the given geometry. Notice RM_7 and RM_8 providing information to both RDAs.

Independent RDAs working alongside each other but observing nominally independent paths (or branches) is a simple workaround to the problem described before. For smoke releases strictly confined to sections of tubes only observed by one single RDA this arrangement will work fine. However, it is not difficult to come up with a more problematic scenario: a source emitting smoke travels along path 1, but then changes lanes and travels further following path 2 and comes to a full stop close to the location of RM_{10}. Figure 8 illustrates this scenario.

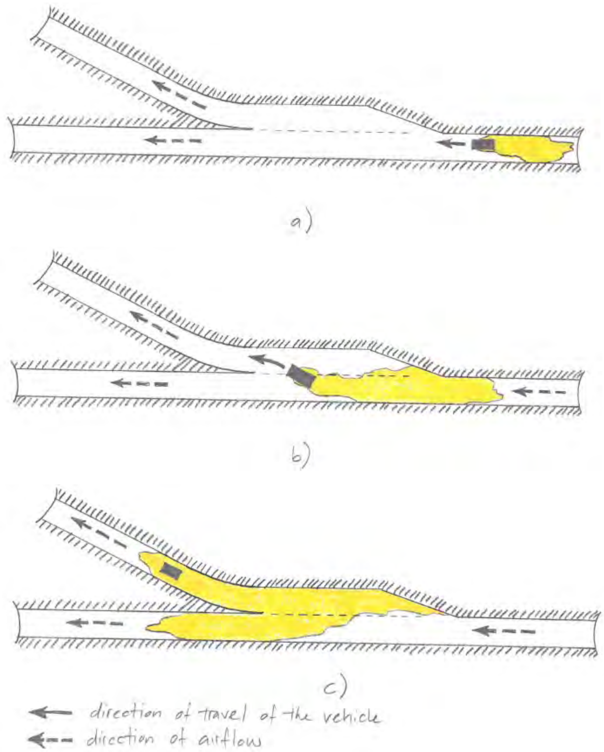

Figure 8: Development of a smoke plume over time: a "two front"-plume (a) develops via (b) into a "three front"-plume (c).

In this scenario there will be two (possibly completely unconnected, independent) plumes of smoke being tracked and evaluated. Both RDAs will raise the alarms $Alarm_{mov}$ and / or $Alarm_{stat}$. Which RDA is tracking the smoke source and which tracks a passively transported smoke plume?

To answer this question a so called "weighting algorithm" is introduced. The basic idea of this extension is to examine the state of each RDA and, based on the measurement data provided by the individual RDAs, to decide which RDA is tracking the smoke source and which alarms can safely be ignored.

One basic assumption guides the evaluation process: that smoke, once produced, can only decrease in density, but not increase. Once released smoke cannot accumulate in ambient air. It therefore immediately follows that the highest measured smoke density should be associated with the smoke source. The following section is a description of the "weighting algorithm" as proposed for a current project.

6 WEIGHTING ALGORITHM FOR SIGNIFICANTLY BRANCHING TUBES

In the case of a single RDA observing one single tube, the RDA communicates directly with the control and management system of the tunnel. In the case with multiple RDAs running in parallel, the "weighting algorithm" is inserted in between the RDAs and the control and management system and acts like a filter: certain information is passed through, while other information is held back.

The alarm $Alarm_{mov}$ is passed from an RDA to the control and management system without delay. However, the alarms $Alarm_{stat}$ are held back. Only after a single, probable stationary smoke source is confirmed, the corresponding alarm is passed on to the control and management system and the smoke detection as a whole stopped.

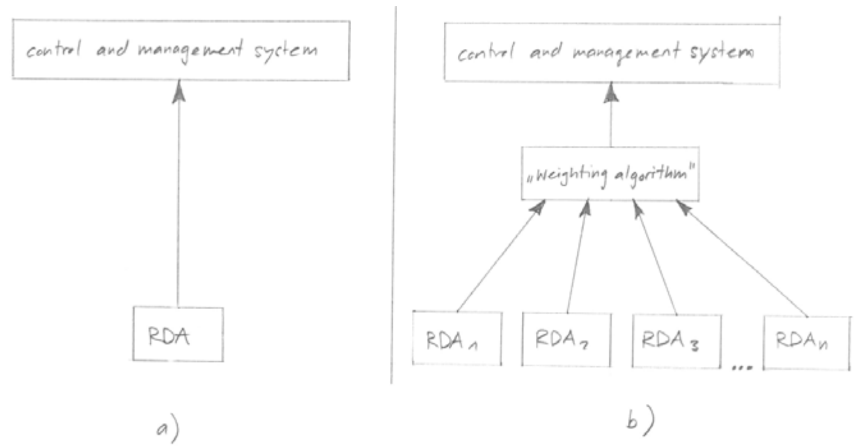

Figure 9: Communication paths; a) with one single RDA; b) with multiple RDAs and a "weighting algorithm".

From each RDA running in parallel, the weighting algorithm receives the alarm state $Z(RDA_y)$ (none, $Alarm_{mov}$ or $Alarm_{stat}$), the highest currently measured value $M(RDA_y)$ among the smoke detectors assigned to each RDA, the timestamp $T(RDA_y)$ of the last raising of an alarm (0 if no alarm raised) and, if an alarm is active, the remaining time before an alarm "stationary smoke source" is generated, $C(RDA_y)$.

From the pool of RDAs that are in an alarm state (either "moving smoke source" or "stationary smoke source") the weighting algorithm assigns one RDA during each cycle to be the "main RDA". This RDA is considered to track the smoke source. Other RDAs which have raised an alarm, be it a moving or stationary smoke source, are considered to be affected by smoke but to not directly observe the smoke source.

The criteria to choose the "main RDA" are, with decreasing priority, the following:

- $M(RDA_y)$, the "main RDA" measures the highest value; or
- $T(RDA_y)$, the "main RDA" registered the most recent change in alarm state; or
- the "main RDA" is first in the evaluation order.

The last criterion is the ultimate tie-braker if the two higher priority criteria fail to allow a proper choice. Evaluation order simply means the order in which the algorithm processes the data from the individual RDAs.

As long as at least one of the RDAs timers is still running (*i.e. C(RDAy)* not yet expired) the “weighting algorithm” will keep tracking the individual RDAs alarm states. Only after *C(RDAy)* expired for all raised alarms, the “main RDAs” alarm $Alarm_{stat}$ is provided to the control and management system. This ensures that a moving smoke source remains being tracked amid passively transported plumes in other branches, which lead to earlier alarms $Alarm_{stat}$.

7 SUMMERY, CONCLUSION AND DISCUSSION

Real world smoke tests are often difficult to interpret as conditions in a tunnel might not quite be ideal, the environment may be difficult to control, and the repeatability of a test is not guaranteed. In addition, the very local environment of any given individual smoke detector will in the end define what it is actually measured.

It is in part due to these circumstances that the single tube smoke detection algorithm has been developed. Together with simulated digital datasets the performance of the algorithm can be assessed in a routine way. The algorithm has been optimized using onsite data from past smoke tests (2).

The use of parallel RDAs together with the proposed weighting algorithm has been tested with CFD data and simplified geometry. An implementation on site will soon follow in a national highway tunnel in Switzerland with a total of 2 x 6 paths, in which the smoke detection system will be replaced and updated. In each direction, six parallel RDAs will be observed by a weighting algorithm. The smoke tests in that tunnel, and the following evaluation of the algorithm function, are highly anticipated.

With the algorithms in place and with intended functionality, smoke detection as presented in this report can be regarded as highly optimized, and not much further improvement is expected. System precision with respect to time and location of a smoke source, i.e. temporal and special resolution, can be improved but are a direct function of the smoke detector spacing (typically around 100 [m]). Hence, increasing the resolution requires decreased spacing between detectors at increased cost.

Obviously, other means of fire and smoke detection exist, the aforementioned thermal linear detectors being among them. However, each detection method has its strengths and weaknesses. Image processing, for example, could offer higher temporal and spatial resolution, though requiring very detailed mapping of the camera image to the real world as well as dedicated hardware to handle calculations. Additionally, image processing needs to adapt to highly variable lighting conditions due to things such as changing sunshine, reflections on wet and polished surfaces, fog and headlights. These are challenging conditions for image processing.

The presented algorithms are robust and can be implemented on programmable logic controllers (PLC). The underlying detection method is a de facto standard today. However, inputs to the algorithms can come from any source that can estimate the velocity of a smoke front and as such alternative detection methods could be used as well.

8 REFERENCES

(1) Guideline ASTRA 13001, "Lüftung der Strassentunnel", V3.01, 2021
(2) "Smoke detection in road tunnels leading to automatic incident response", presented at the 9th International Conference 'Tunnel Safety and Ventilation' 2018, Graz