

ON SMOKE DETECTION SYSTEMS IN ROAD TUNNELS – A QUANTITATIVE COMPARISON

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ABSTRACT

Reliable incident detection is crucial for safety and operation of road tunnels. On the one hand, rapid and accurate detection of incidents allows for timely activation of electromechanical equipment such as tunnel closure or ventilation systems. On the other hand, high reliability or low false alarm rates is a prerequisite for daily operations and user satisfaction.

In Swiss road tunnels, smoke sensors based on visibility measurement have been in use for nearly 20 years. Combined with an evaluation logic to distinguish between moving and stationary smoke sources, this has become an established solution. Nevertheless, continuous optimisation and development is being performed regarding sensor technology, sensor placement as well as evaluation logic. Video based Automatic Incident Detection (V-AID) is only sporadically used for fire detection, primarily due to the perceived lack of quality and reliability.

As part of a general study on smoke detection in road tunnels, the performance of conventional smoke detection and of modern V-AID systems is quantitatively compared, based on a large number of smoke tests. The tests include both moving and stationary smoke sources as well as different longitudinal airflows (intensity and direction). Each test was performed at least 3 times to account for variations. The performance of both systems is evaluated and compared using various parameters and, in particular, a dimensionless number accounting for the spatial and temporal sequence of smoke detection.

The work shows promising results using V-AID regarding the detection quality but also reveals a certain number of points to be addressed, prior to a wide use of modern V-AID systems for smoke detection.

Keywords: Smoke Detection, Video Automatic Incident Detection (V-AID), Comparison, Quality of Detection, Smoke Tests

1. INTRODUCTION

For nearly 20 years, fire detection in road tunnels in Switzerland has been relying on two detection methods: linear thermal detection for either elevated or rapidly rising temperatures, and smoke detection using optical sensors. As described in [1] and [2], smoke detection systems must be able to make a distinction between a moving smoke source and a stationary smoke source and must be able to cope with the transition from moving to stationary. The

related challenges are described for example in [3] or [4]. A major disadvantage of such systems is the pointwise measurement with sensors typically spaced by 100 m (compared to e.g. 5 - 10 m for thermal detection) and the fact that sufficient quantities of smoke must be transported to the detector and persist for a sufficient period of time. The main advantage of such systems is the fact that the measurement has a direct physical meaning including the integration of (multiple) thresholds and that the detection of fog can be eliminated when using integrated heating elements.

Even though widely spread, video automatic incident detection (V-AID) is primarily used for selected incident types such as a stopped vehicle, a vehicle moving in the wrong direction or pedestrians. As opposed to other countries, V-AID is in Switzerland not in use for smoke or fire detection, mainly due to the associated false alarm rates in conjunction with the fact that operators are not solely responsible for tunnel operation but primarily for general emergencies response. Modern V-AID systems, based on general image analysis (machine learning, with or without artificial intelligence), instead of pixel-based image processing are advertised as an important step forward regarding detection quality as well as robustness. Especially regarding smoke detection, V-AID systems offer one important advantage: volumetric detection instead of pointwise detection. Therefore, a single detector (a camera) can detect smoke independently of its effective position within the field of sight of the camera. On the contrary, as there is only a binary information: “absence of smoke” or “presence of smoke” thresholds cannot be used and no information on smoke concentration is available.

As part of a more general study on smoke detection in road tunnels, the performance of conventional smoke detection and modern V-AID is quantitatively compared in order to evaluate the future use of V-AID smoke detection in Swiss road tunnels. The purpose of this study is to evaluate and compare the effectiveness of traditional and video-based smoke detection systems under varied tunnel conditions so as to shape future tunnel safety strategies.

2. METHODOLOGY

2.1. Experimental Setup

As smoke source, two different types of smoke generators (paraffine oil based as well as propylene glycol based) mounted on a trailer are used. The set up allows for smoke production rates of up to 1700 m³/min. The produced smoke is at ambient temperature, dense, long lasting and resistant to slight temperature increase. **Figure 1** shows the trailer with the smoke generators. The smoke generators are mounted slightly tilted upwards or are equipped with deflector nozzles to achieve a more realistic smoke propagation.



Figure 1: Experimental setup with smoke generators on trailer

The tests consisted basically of the smoke source traveling at constant speed over up to 2'000 m. In order to reflect the situation in bidirectional tunnels, tests are conducted at

airspeeds in the tunnels of 1,5 – 2,0 m/s, 2,5 – 3,0 m/s as well as 4,0 – 4,5 m/s, whereas the direction of travel of the smoke source was in the direction of the airflow as well as opposed to it. **Figure 2** shows the different combinations of airflow direction and direction of travel. To verify the repeatability of the results, each test is repeated three times under the same conditions. This results in a set with a total of 36 tests. So far, the tests have been carried out in two different tunnels with different types of smoke detectors and the same type of V-AID system.

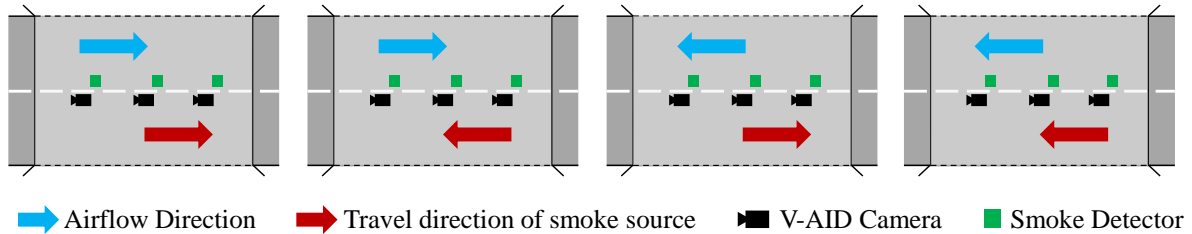


Figure 2: Combinations of airflow direction and direction of travel (schematic representation)

2.2. Tunnels under Investigation

The results from two Swiss tunnels are reported hereafter. The parameters relevant for this investigation are shown below. The cross section and the speed of travel are similar in both cases. Important differences are the smoke detector technology used and the applied thresholds. The V-AID algorithms are similar and distinguish smoke from fog.

Table 1: Tunnel parameters relevant to the investigation

Parameter	Tunnel 1	Tunnel 2
Tunnel cross section area	45,0 m ²	48,3 m ²
Type	Bifurcation in the centre	Single tube w/o bifurcation
Mean altitude	657 m.a.s.l	428 m.a.s.l
Smoke detector	Sigrist FireGuard 2	Sick VISIC50SF-1000
Extinction thresholds 1 and 2 in the smoke detectors	10 / 30 mE/m	20 / 70 mE/m
V-AID algorithm	Citilog CT-ADL 2024R1.E	Citilog CT-ADL 2024R2.3 (V9.1R2E5.P3)
Smoke source's speed of travel	33 km/h	34 km/h

2.3. Quantitative (Statistical) Evaluation

2.3.1. Delay of Detection Δt_{VS} and Sequence of Detection τ

This study examines how much time elapses between passing by a sensor and the effective detection at this sensor (detection delay), and whether the sensors detect the actual order of passing by (detection sequence). The detection delay Δt_{VS} is given in seconds, and the detection sequence is the dimensionless number τ described below. For a better understanding of the following, please refer to **Figure 3**.

Given are the position $x_{S,i}$ of sensor i in the tunnel, the timestamp $t_{V,i}$ when passing by sensor i and the timestamp $t_{S,j}$ of the detection of the sensor to the threshold S at position $x_{S,j}$.

Therefore, there are two time series: $(t_{V,i}, x_{S,i})$ the time series of travel, and $(t_{S,j}, x_{S,j})$ the time series of detection, which are linked to each other by the sensor positions $x_{S,i}$ and $x_{S,j}$.

For each sensor j on the route of the vehicle which reacts to the threshold S during a test, there is a timestamp $t_{V,j}$ of passing by and a timestamp $t_{S,j}$ of detection. The difference

$$\Delta t_{VS,j} = t_{S,j} - t_{V,j}$$

is called detection delay. Due to the test setup, the detection delay only takes positive values.

Inconsistent, heavily varying detection delays may lead to an inconsistent detection sequence: e.g. sensor 3 detecting prior to sensor 2 within the sequence $1 \rightarrow 2 \rightarrow 3$. Therefore, a number describing the quality of the detection sequence is sought after, which is independent of the vehicle's velocity and of the distance in between sensors, allowing to compare different tests and technologies against each other.

The time interval of the detection sequence is made of the two consecutive timestamps of detection $\Delta t_{S,j} = t_{S,j} - t_{S,j-1}$. The indices are chosen to look backwards ($j - 1$ and j) because algorithms distinguishing moving from stationary smoke sources look backwards too. The sequence of the indices is not connected to the spatial detection sequence, but to the time of detection. Using the spatial connection of the two timeseries described above, the timestamps $t_{V,l}$ respectively $t_{V,k}$ of passing by under the sensors $x_{S,j}$ resp. $x_{S,j-1}$ are assigned to the timestamps of the detection. Thus, the interval of passing $\Delta t_{V,j} = t_{V,l} - t_{V,k}$ between these sensors is determined. $\Delta t_{V,j}$ can take any, especially negative, values.

- A positive value means that the vehicle passed by the sensor $x_{S,j-1}$ earlier than by the sensor $x_{S,j}$, which means that the sequence of detection corresponds to the sequence of passing by.
- A negative value however indicates an inversed sequence of detection, related to a much bigger detection delay $\Delta t_{VS,j}$ at sensor j than $\Delta t_{VS,j-1}$ at sensor $j - 1$.

Scaling the interval of detection $\Delta t_{S,j}$ by the assigned interval of passing by $\Delta t_{V,j}$ leads to the dimensionless sequence of detection $\tau_{S,j}$, defined as the ratio of $\Delta t_{S,j}$ and $\Delta t_{V,j}$:

$$\tau_{S,j} = \frac{\Delta t_{S,j}}{\Delta t_{V,j}}$$

The sequence of detection $\tau_{S,j}$ allows for a more accurate interpretation than $\Delta t_{S,j}$ alone. The values of τ can be interpreted as follows:

- $\tau < 0$: the detection sequence is inverted (opposed to travel direction),
- $0 < \tau < 1$: this can be written as $0 < \Delta t_{S,j} < \Delta t_{V,j}$, which means that the sequence of detection is in the right order, but slower than the passing by,
- $\tau = 1$: travel and detection are perfectly marching in step,
- $\tau > 1$: this can be written $\Delta t_{V,j} < \Delta t_{S,j}$, which means that the sequence of detection is in the right order, but faster than the passing by.

In conclusion: The delay of detection Δt_{VS} answers the question how fast a technology detects smoke, whereas the sequence of detection τ evaluates how good the detection of moving smoke is. A technology is good, when there are no negative values of τ and all values are gathered around 1.

Figure 3 illustrates these relationships. Both cases discussed above are represented, case 1 for $\Delta t_{V,j} > 0$ and case 2 for $\Delta t_{V,j} < 0$. The green field represents values of τ greater than zero and the red one values smaller than zero. The vectors v_{smoke} represent the velocity of the smoke calculated from the detection points. The horizontal bold dashed line shows the target value $\tau = 1$.

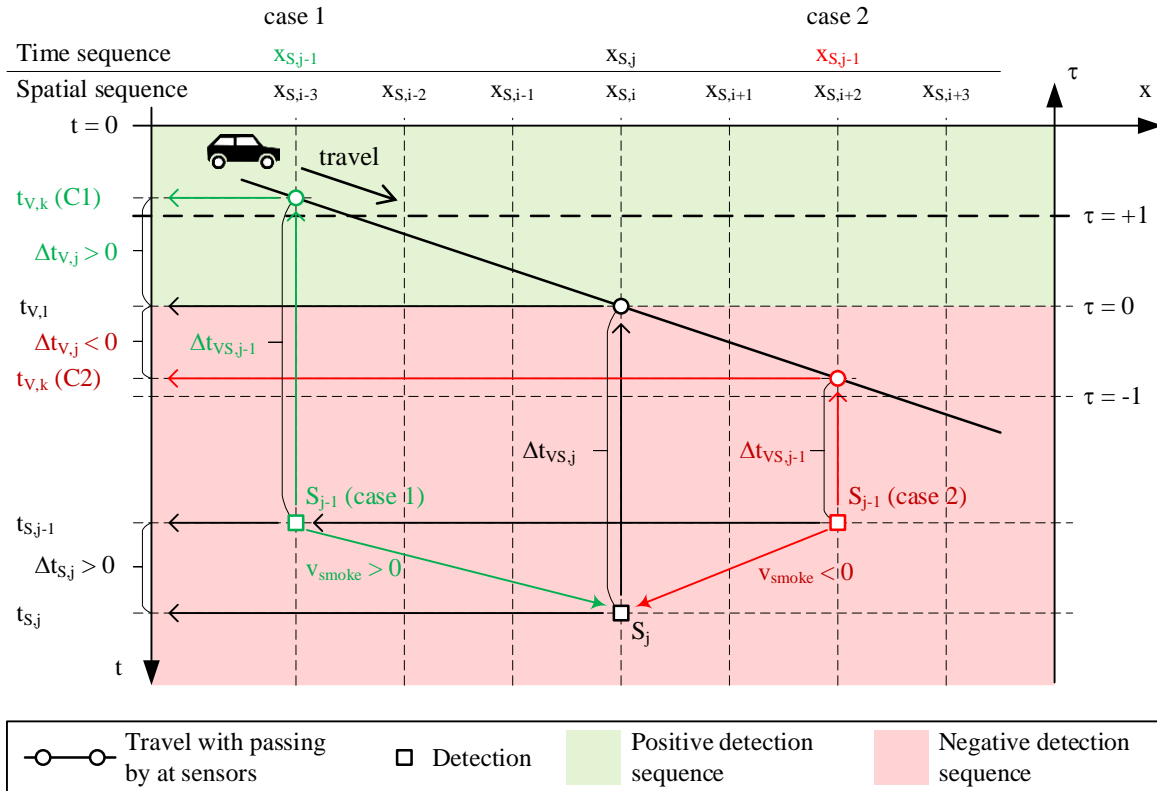


Figure 3: Schematical space-time chart for the time interpretation of τ

2.3.2. Space-Time-Velocity Charts and Boxplots

The results of the tests are evaluated and represented using two different types of plots:

- Space-time-velocity charts for representing the time and location of the detection points and the travel of the vehicle in the tunnel for each test. These charts allow to judge qualitatively the results and repeatability of a series of tests, as well as to detect patterns and anomalies in the tests.
- Boxplots for the statistical evaluation of the delay and sequence of Δt_{VS} and τ over several tests for different categories of parameters.

The so-called boxplot of a random variable uses boxes and lines to represent its distribution on one line, instead of on a plane like a histogram (cf. for an example **Figure 5**). Such plots show at a glance:

- The median of the distribution: the line in the box.
- The quartiles: 50% of the data lies inside the box; the lower edge is the lower quartile (25%) and the upper edge the upper quartile (75%).
- The extrema: the minimum and maximum of the distribution lie at the end of the line (“whiskers”) below and above the box.
- The outliers: the points below and above the extrema.

The notch around the median “displays the variability of the median between samples” [5].

3. RESULTS

3.1. Space-Time-Velocity Charts

Two examples of space-time-velocity charts from both tunnels presented in section 2.2 are shown in **Figure 4** in the appendix. They have in common: the speed of travel (between 33 and 34 km/h), the intermediate air speed (between 2.5 and 3.0 m/s) and the direction of travel against the flow direction. The examples are chosen to illustrate how different the experimental results can be even for similar setups.

Whereas in **Figure 4a** all sensor types display a well behaved delay and sequence of detection, this is not the case in **Figure 4b**: The delay of detection is very long for all three sensors, the sequence of detection of the smoke detectors using threshold 1 (SD:TH1) is very chaotic, and most smoke detectors detect at threshold 2 (SD:TH2) only during the extraction of the smoke after the regular end of the test. The cameras (V-AID:SM) are behaving in a similar manner.

The reasons for this behaviour are yet not well understood and a matter of ongoing research.

3.2. Delay of Detection Δt_{VS}

Several boxplots of the delay of detection Δt_{VS} are presented in **Figure 5**. The data are divided into four categories: by sensor, by tunnel, by flow velocity and by driving direction with respect to the flow direction. The main parameters of the distributions: median, quartiles and sample size (number of samples), are presented in **Table 2** for the smoke detectors and in **Table 3** for the V-AID.

Figure 5a displays on the left the delay of detection of the smoke detectors relative to threshold 1 (SD:TH1) in tunnel 1. The median delay is shorter when driving in flow direction than when driving against the flow direction. In both directions, the median delay and the width of the distribution decrease with increasing flow velocity. On the right the same data are displayed for tunnel 2. Here also the median delay is always shorter when driving in flow direction than in the opposite direction. However, the median delay and the width of the distribution do not decrease with the flow velocity, as noted in tunnel 1, but rather increase. This is consistent with the behaviour observed in the space-time charts in **Figure 4b**. In tunnel 1 the median delay lies between 73 and 29 seconds, and in tunnel 2 between 115 and 21 seconds.

Table 2: Median, quartiles and sample size of delay plots in **Figure 5a** (SD:TH1)

Tunnel	Parameter	Unit	1,5-2,0 m/s		2,5-3,0 m/s		4,0-4,5 m/s	
			Against	With	Against	With	Against	With
1	Median and quartiles	[s]	73,0 ^{92,2} _{56,5}	38,6 ^{51,7} _{32,3}	64,4 ^{71,0} _{56,0}	33,2 ^{37,8} _{30,4}	61,8 ^{66,8} _{54,5}	29,2 ^{30,0} _{27,7}
	Sample size	[pc.]	69	72	116	118	69	72
2	Median and quartiles	[s]	85,7 ^{125,9} _{67,1}	71,2 ^{97,1} _{47,8}	114,8 ^{141,0} _{98,5}	37,2 ^{43,6} _{32,3}	114,0 ^{153,2} _{87,4}	21,4 ^{23,2} _{20,0}
	Sample size	[pc.]	84	66	93	84	49	77

Figure 5b displays the delay of smoke detection of the V-AID (V-AID:SM). In tunnel 1 the distributions are very narrow at all flow velocities and directions, with median delays between 35 and 40 seconds. The data displays a slight increase in the median with increasing flow velocity. The slight differences observed with respect to the driving direction are statistically insignificant, as the notches overlap at a given velocity. In tunnel 2, when driving in the direction of the flow, the distributions are also very narrow, the median delay lies between 17,4 and 17,9 seconds and no effect of the flow velocity is observed. However, when driving

against the flow direction, the distributions are very broad, the median delays very high and the sample sizes small. This is consistent with the behaviour observed in the space-time charts in **Figure 4b**.

Table 3: Median, quartiles and sample size of delay plots in **Figure 5b** (V-AID:SM)

Tunnel	Parameter	Unit	1,5-2,0 m/s		2,5-3,0 m/s		4,0-4,5 m/s	
			Against	With	Against	With	Against	With
1	Median and quartiles	[s]	36,4 ^{38,0} _{34,2}	35,2 ^{36,7} _{33,5}	38,7 ^{41,1} _{37,1}	38,7 ^{39,9} _{37,4}	38,5 ^{40,8} _{37,2}	39,7 ^{41,2} _{38,7}
	Sample size	[pc.]	57	72	97	111	54	65
2	Median and quartiles	[s]	94,1 ^{127,7} _{56,3}	17,4 ^{19,1} _{15,5}	83,8 ^{115,2} _{40,7}	17,9 ^{19,6} _{16,2}	83,5 ^{105,3} _{54,8}	17,8 ^{19,4} _{16,4}
	Sample size	[pc.]	41	86	57	129	35	115

The tunnels are equipped with different types of smoke detectors configured to react at different levels of smoke concentration. However, the data presented above displays certain similarities. The delay in detection using smoke detectors is very sensitive:

- a) to the flow velocity in the tunnel: it decreases with increasing flow velocity,
- b) to the driving direction relative to the flow direction: it is much shorter when driving with the flow than opposite to the flow direction.

The tunnels are equipped with similar V-AID cameras and algorithms. The delay in smoke detection using V-AID is:

- a) independent from the flow velocity,
- b) independent from the driving direction relative to the flow direction, if one only considers tunnel 1.

Regarding the delay of detection, V-AID delivers reproducible results, independent from flow velocity and direction. It appears that this is much less the case with traditional smoke detectors. The significant difference in delay of the V-AID between the two tunnels is potentially caused by the parametrization of the image processing algorithm.

3.3. Sequence of Detection τ

Several boxplots of the sequence of detection τ are presented in **Figure 6**. The data are divided into three categories: by tunnel, by flow velocity and by sensor. The main parameter of the distributions: median, quartiles, sample size and negative samples, are presented in **Table 4**.

Figure 6a displays on the left the sequence of the smoke detectors, threshold 1 (SD:TH1) and the V-AID (V-AID:SM) in tunnel 1. The median sequence of the V-AID:SM lies very close to one at all flow velocities; the distributions are very narrow, the whiskers lie above zero with few outliers below zero (less than 5,4%), which indicates a correct and repeatable sequence of detection independent of the flow velocity most of the time. In contrast, the median sequence of the smoke detectors is poor, much lower than 1, but increases with increasing flow velocity (between 0.56 and 0.84). Also, the percentage of negative sequences is much higher (15,7 to 21,5%). The algorithms distinguishing moving from stationary smoke sources must specifically be able to cope with such cases. The trends are similar in tunnel 2: median sequence close to 1 and independent of flow velocity for the V-AID, low median sequence increasing with flow velocity for the smoke detectors. However, the performance of both detection systems in tunnel 2 is inferior to tunnel 1: all median sequences are lower in tunnel 1, especially for the smoke detectors; the distributions of the V-AID sequence is much wider, and the percentage of negative sequences is much higher, about 20% for the V-AID and up to

42% for the smoke detectors. This is consistent with the behaviour observed in the space-time-charts in **Figure 4b**.

Table 4: Median, quartiles, sample size and negative samples of sequence plots in **Figure 6**

Tunnel	Parameter	Unit	1,5-2,0 m/s		2,5-3,0 m/s		4,0-4,5 m/s	
			SD: TH1	V-AID: SM	SD: TH1	V-AID: SM	SD: TH1	V-AID: SM
1	Median and quartiles	[-]	0,56 ^{1,08} _{0,04}	0,98 ^{1,16} _{0,76}	0,73 ^{1,19} _{0,23}	1,00 ^{1,14} _{0,75}	0,84 ^{1,06} _{0,28}	0,95 ^{1,15} _{0,74}
	Sample size	[pc.]	130	112	223	184	133	101
	Negative samples ($\tau < 0$)	[%]	21,5	3,6	15,7	5,4	17,3	5,0
2	Median and quartiles	[-]	0,03 ^{0,29} _{-0,17}	0,87 ^{1,07} _{0,21}	0,34 ^{0,84} _{0,00}	0,88 ^{1,06} _{0,24}	0,77 ^{1,04} _{0,11}	0,89 ^{1,07} _{0,33}
	Sample size	[pc.]	132	105	148	164	109	137
	Negative samples ($\tau < 0$)	[%]	41,7	21,9	24,3	20,1	16,5	19,0
All	Median and quartiles	[-]	0,17 ^{0,66} _{-0,10}	0,93 ^{1,13} _{0,61}	0,60 ^{1,07} _{0,06}	0,91 ^{1,10} _{0,66}	0,81 ^{1,05} _{0,20}	0,90 ^{1,10} _{0,53}
	Sample size	[pc.]	262	217	371	348	242	238
	Negative samples ($\tau < 0$)	[%]	31,7	12,4	19,1	12,4	16,9	13,0

Figure 6b shows the sequence of detection when the datasets of tunnels 1 and 2 are merged. This merger assumes that the results of two different smoke detector technologies can be compared directly. The same general trends as described above are observed here. The sequence of detection using the smoke detectors:

- Is very sensitive to the flow velocity; its median is low (close to zero) at low velocity and increases with increasing velocity (close to one),
- Displays a high percentage of negative sequences, above 17% and up to 32% in this case.

On the other hand, the sequence of smoke detection using V-AID:

- Is independent of the flow velocity,
- Is very close to one in the median,
- Displays a low percentage of negative sequences, below 13% in this case.

As a summary, the smoke detection using V-AID delivers reproducible and correct sequences of detection that are independent from the flow velocity in the tunnel most of the time. This is not the case with smoke detectors.

4. CONCLUSION AND OUTLOOK

The quantitative evaluation of the smoke tests uses the delay of detection Δt_{VS} and the dimensionless sequence of detection τ . It shows that within the executed tests, the smoke detection by V-AID performs significantly better than the detection with smoke detectors based on extinction measurements, because:

- V-AID detects faster with a smaller dispersion,
- V-AID detects dependably with a smaller dispersion, which means that the sequence of detection is closer to 1 and scatters less than in case of smoke detectors,
- V-AID is less prone to false detection of reverse sequences ($\tau < 0$).

As the sample size for τ of SD:TH1 and V-AID:SM of both tunnels is greater than 800 data points, these conclusions are very reliable.

The tests have shown that the quality of detection of the smoke detectors at threshold 1 depends on the direction of travel with respect to the flow direction and velocity. The quality of detection increases with increasing flow velocity and is better when driving with the flow direction than opposite to it. Yet it is assumed that this is heavily related to smoke density and local flow structures in the wake of the vehicle

It has to be noted that V-AID can lead to bad results under certain conditions. These conditions are not understood yet. As with smoke detectors, this could be related to the lower smoke density when driving against the flow. On the other hand, the lack of quality can also be related to parametrization and training of the image processing algorithm.

In order to gather a better understanding of V-AID systems but also of traditional smoke detectors, the study must be extended to more objects and, in particular, more V-AID algorithms. Furthermore, effects related to fog, camera placement, pollution of the cameras, changes in lighting condition etc. must be analysed prior to qualifying V-AID based smoke detection as potential replacement of traditional technologies. Also, regarding the reliability and in particular the distinction of moving / stationary smoke sources, the impact of the lack of thresholds has to be investigated and parametrization of V-AID systems must potentially be optimized.

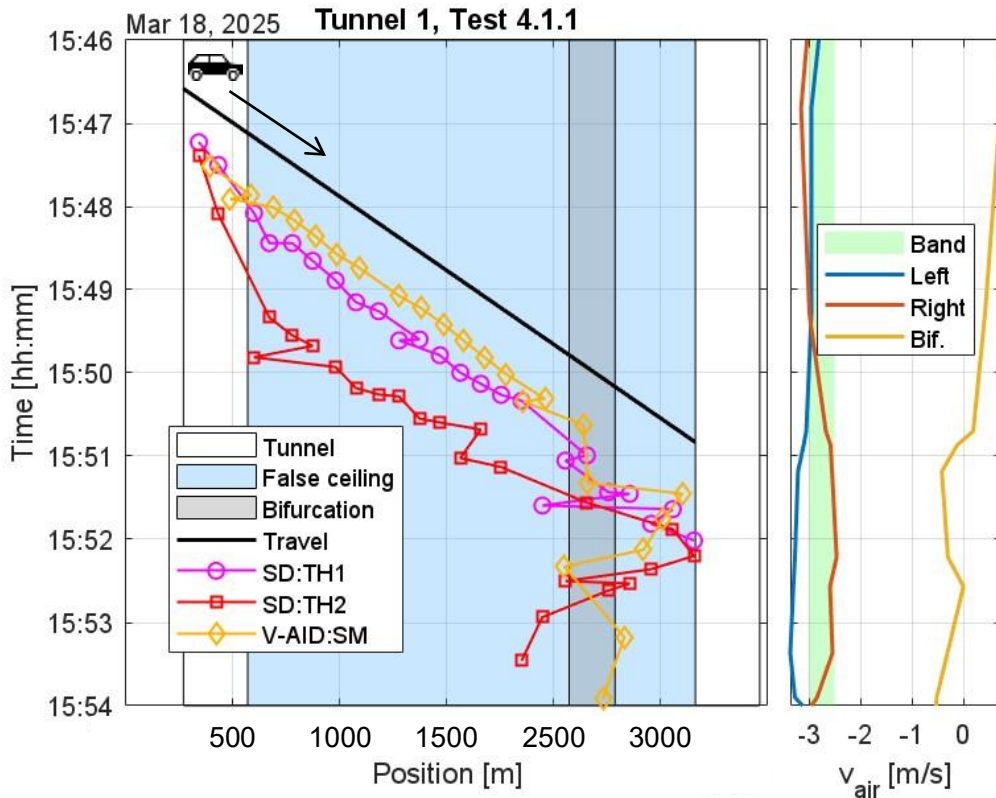
5. LIST OF ABBREVIATIONS

Table 5: List of abbreviations

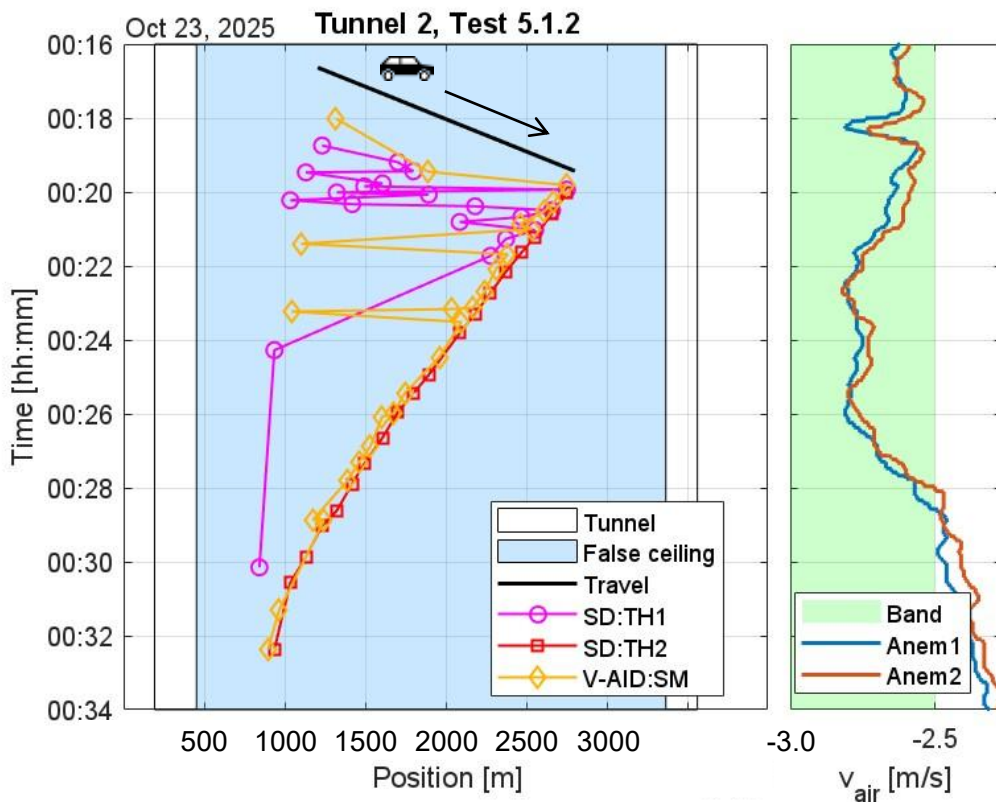
Shorthand	Meaning
Bif.	Bifurcation
SD:TH1	Smoke detector, detection of smoke at threshold 1
SD:TH2	Smoke detector, detection of smoke at threshold 2
V-AID	Video based automatic incident detection
V-AID:SM	Video based automatic incident detection, detection of smoke
v_{air}	Air velocity in tunnel

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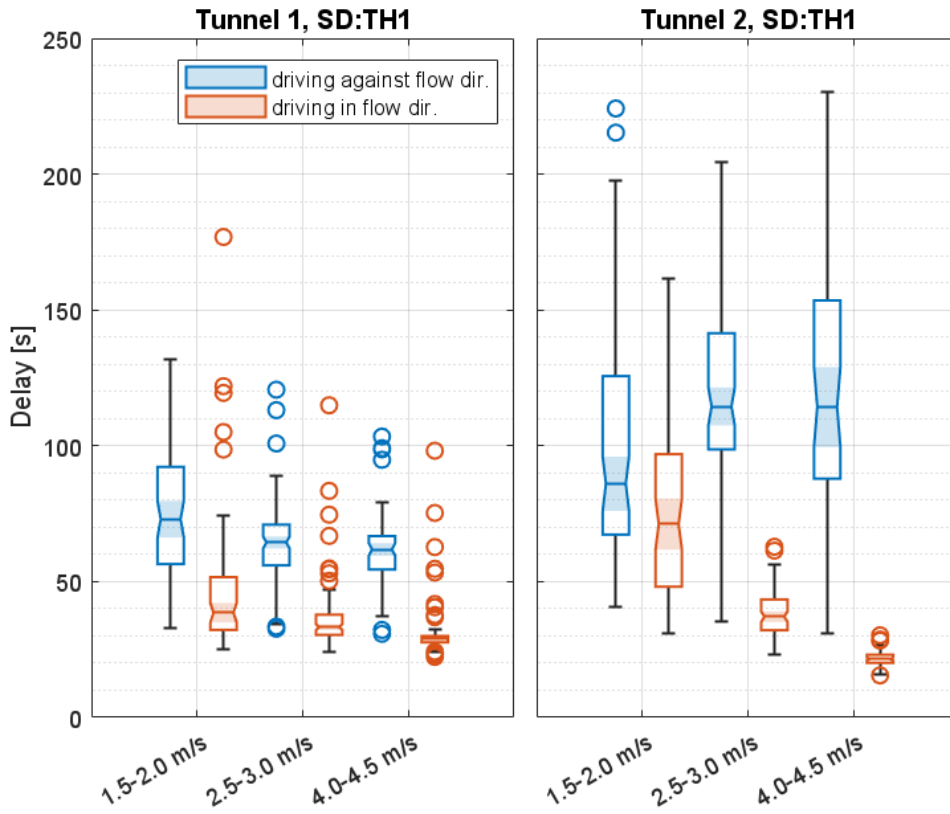


(a)

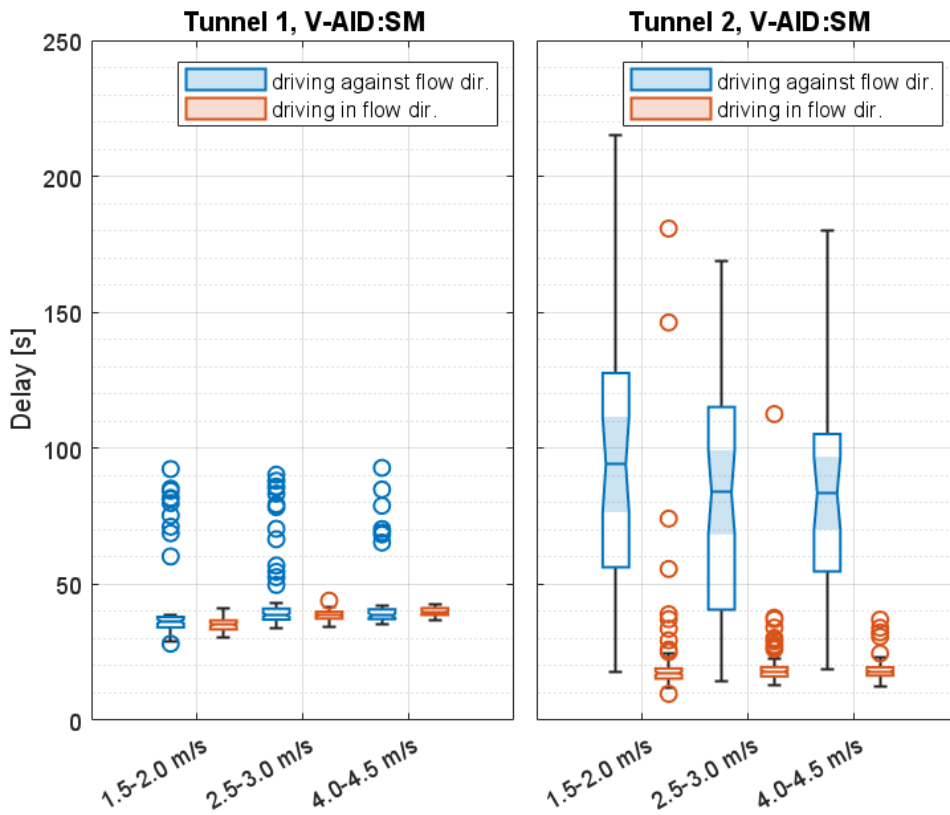


(b)

Figure 4: Space-time-velocity charts, two examples of two different tunnels at intermediate flow rate. travel direction against flow direction.

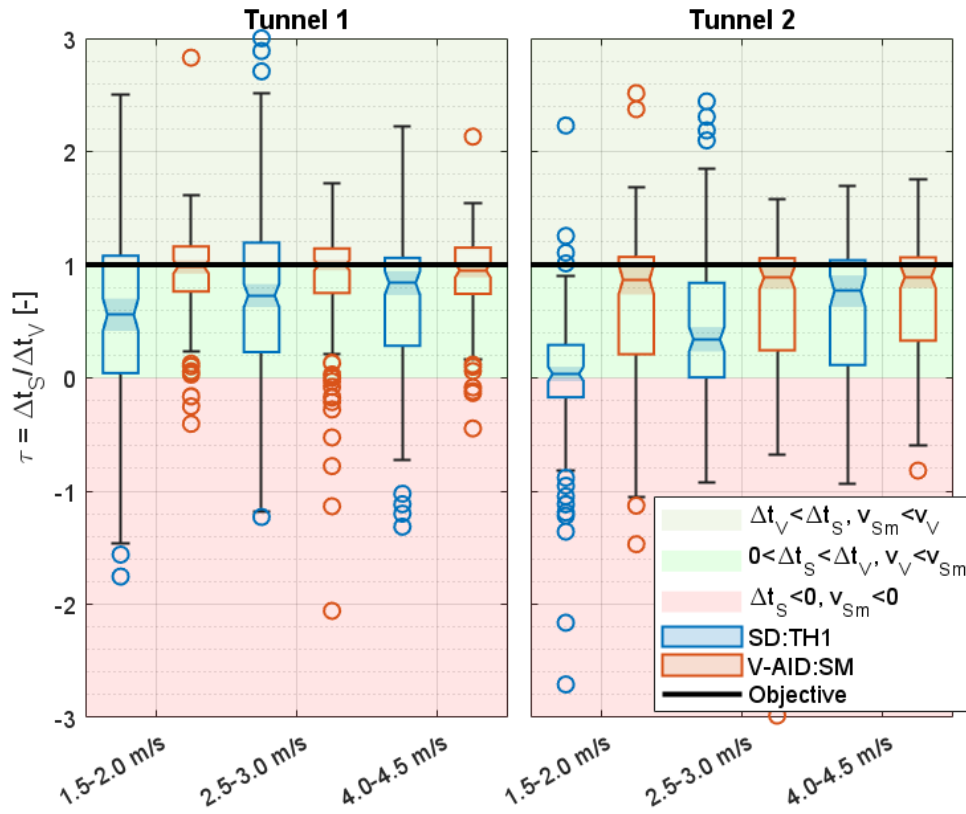


(a)

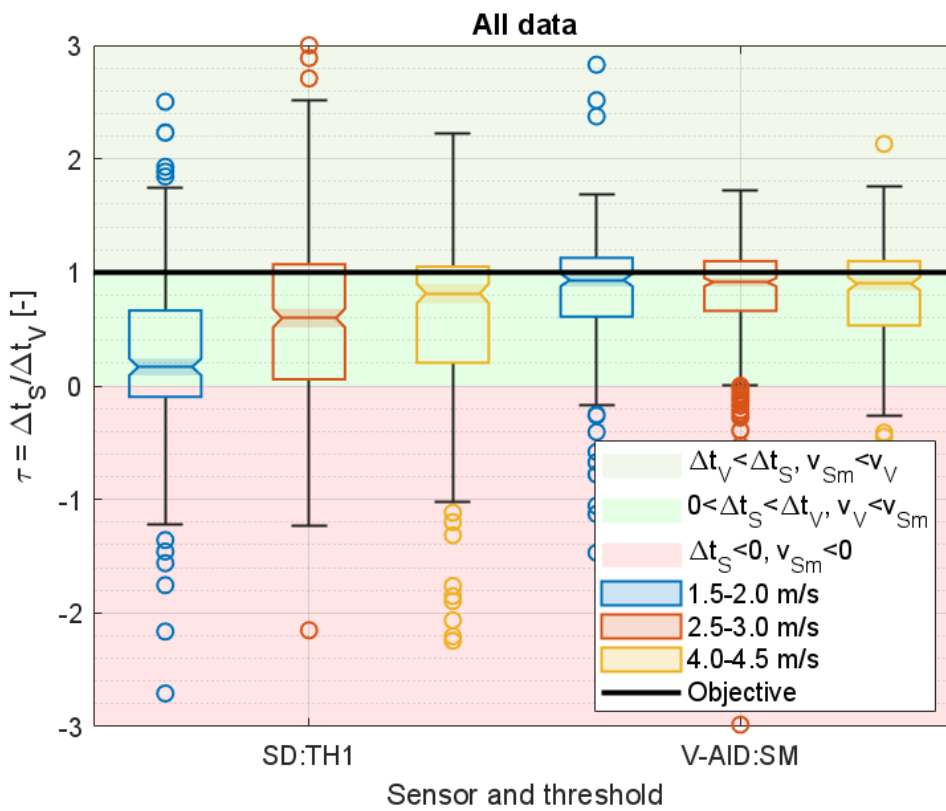


(b)

Figure 5: Boxplots of the delay of detection by flow velocity, by driving direction relative to the flow direction and by tunnel (a) for smoke detectors, threshold 1, and (b) for V-AID, smoke



(a)



(b)

Figure 6: Boxplots of the sequence of detection for smoke detectors, threshold 1, and V-AID, smoke, by flow velocity and (a) by tunnel and (b) all data merged