Case Studies in Fire Safety xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Case Studies in Fire Safety

journal homepage: www.elsevier.com/locate/csfs

Case study

On the problem of ventilation control in case of a tunnel fire event

Peter Sturm[*], Michael Beyer, Mehdi Rafiei

Graz University of Technology, Austria

ARTICLE INFO

Article history:
Received 18 August 2014
Received in revised form 3 November 2015
Accepted 18 November 2015
Available online xxx

Keywords:
Ventilation of road tunnels
Fire ventilation
Smoke control
Background

ABSTRACT

The proper operation of a ventilation system plays a key role in tunnel safety. Foremost, the ventilation system needs to provide acceptable air quality for the safe passage of tunnel users. Further, it needs to provide tenable environment and to facilitate rescue conditions during a smoke or fire event. While accomplishing the first task (normal operation), i.e. providing sufficient fresh air, is relatively straightforward, dealing with the second issue is the subject of considerable debate since defining the best means to ventilate a tunnel during a fire emergency is not always clear.

Although fire tests in tunnels have been performed since the early 1960s, and although the topic of fire ventilation was raised in early national and international guidelines, relatively little interest was given to fire ventilation until several big fire events occurred in the 1990s. The tunnel ventilation systems and ventilation methodologies existing at that time proved to work well under normal operation, but failed during fire ventilation. Nowadays, the design and operation of the ventilation system during fire incidents (commonly called 'fire ventilation') is a major topic. While the design might follow the well-established principles, the question, 'how to control tunnel ventilation during a fire event?', is quite controversial. This paper discusses methods of fire ventilation with a focus on the methodologies themselves as well as on the requirements for sensors and control technologies.

1. Background

The issue of fire and smoke control is presented in various publications (e.g. [1–4]). These publications address the threats to human health due to fire events, e.g. high temperatures, the existence of various toxic gases, and low oxygen content. While low visibility poses risk to evacuation as well as the ability to rescue and firefighting, high temperatures and high radiation heat also result in a spread of the fire as it happened in the Mt. Blanc and the Tauern tunnel fire incidents in 1999 [3]. Hence fire and smoke control is essential to:

- save lives by facilitating user evacuation,
- support rescue and fire-fighting operations,
- reduce risk of explosions,
- reduce damage to tunnel structure and equipment and to surrounding facilities [2].

---

[*] Corresponding author. Fax +43 316 873 30202.
E-mail address: sturm@ivt.tugraz.at (P. Sturm).

http://dx.doi.org/10.1016/j.csfs.2015.11.001

Please cite this article in press as: P. Sturm, et al., On the problem of ventilation control in case of a tunnel fire event, Case Stud. Fire Saf. (2015), http://dx.doi.org/10.1016/j.csfs.2015.11.001

The fire and its influences to the tunnel environment must be controlled, typically by tunnel ventilation. Different countries have different philosophies regarding fire ventilation. While some prefer to focus on preventing backlayering, that is, the movement of smoke upstream of the fire, others opt for maintaining low tunnel air velocities to reduce smoke propagation rates, at least during the self-evacuation phase. This is somewhat controversial as the first option requires relatively high velocities upstream of the fire (2.5–3 m/s), while the latter requires relatively low smoke propagation velocities as the walking speed within a smoke-filled zone is about 0.5 m/s [2]. Hence, in practice, a compromise is often made by applying a low velocity in the range of 1.0–1.5 m/s upstream of the fire. This minimises backlayering effects of the smoke on the upstream side and maintains lower smoke propagation downstream of the fire.

Another important consideration is the ventilation system itself. While in tunnels using longitudinal ventilation smoke usually is transported from the fire site downstream the whole tunnel, modified transverse ventilation systems allow for a local smoke extraction inside the tunnel and hence for a smoke-free zone over large areas of the tunnel to both sides of the fire. However, transversely ventilated tunnels need to have a complex ventilation control system in order to confine smoke to the extraction locations [13].

It is of vital importance to have correct information about air/smoke movement within the tunnel recognizing the importance of controlled operation of transverse ventilation. Monitoring of air/smoke movement strongly depends on correct air/smoke velocity readings, i.e. on reliability of the sensors and on their location inside the tunnel.

Directive 2004/54/EC [5] defines minimum safety requirements for road tunnels within the Trans European Road Network (TERN). The directive covers the need for ventilation as well as the requirements for equipment. Although explicitly valid only for the TERN road network, it nevertheless represents the state of the art for application in many tunnels within Europe and throughout the world. However, the Directive defines requirements for technical installations only and does not cover questions of emergency operation. The relevant information in such cases can be found in international documents (e.g. [2–4]) or various national guidelines (e.g. [6–8]).

2. Ventilation systems and philosophy of ventilation during a fire

In the context of this article ventilation during a fire incident including smoke production will be called fire ventilation. During fire ventilation, smoke management is ideally achieved by dilution and removal of smoke. Smoke filled air has to be replaced by clean or smoke-free air, which is either supplied mechanically or drawn in through the portals. Dilution can improve tenability e.g. by reducing concentrations of toxic gases. The basic principles of smoke movement have already been described in detail in Ref. [3] and those of smoke control in Ref. [4]. These principles are still valid, yet PIARC publications only provide guidance. More detailed and binding instructions are mostly given in national guidelines. However, whatever the guidelines state, one must always be aware that fire ventilation is only one part of tunnel safety, and that it is subject to several constraints in the form of design criteria (e.g. fire load) and operation possibilities [10].

2.1. Longitudinal ventilation

2.1.1. Ventilation philosophy

The philosophy for fire ventilation in longitudinally ventilated tunnels is quite simple. Polluted air is discharged via portals or ventilation shafts. The main consideration is the air velocity that is generated and the sequence of fan activation. Concerning the air/smoke velocity, there is controversy regarding the preference of 'critical velocity' or 'low velocity'.

A *critical velocity* philosophy is applied in order to avoid backlayering, i.e. to prevent any upstream movement of smoke along the tunnel. Typical values for critical velocity are in the range of 2.2–3.5 m/s for fire sizes around 30–50 MW heat release rate. However, with a heat release rate of 30 MW the downstream air velocity will increase by a factor of 2–3 compared to the velocity upstream of the fire location. This results in smoke propagation velocities much too high to allow for self-rescue downstream of the fire. Hence, such a ventilation philosophy can only be recommended for tunnels with unidirectional traffic where traffic downstream of the fire has the possibility to exit the tunnel (i.e. tunnels with low congestion levels).

A *low velocity* philosophy is recommended by PIARC [4], as well as in many national ventilation guidelines (e.g. [6–8]) for bi-directional tunnels and for tunnels with unidirectional traffic where the specific conditions prevailing at the site of the incident (e.g. fire within traffic congestion) remain unclear. Here, target velocities of the upstream (i.e. cold) air are in the range of 1.0–1.5 m/s. Such air/smoke velocities are a compromise between 'accepting some backlayering' and 'moderate air/smoke velocities downstream the fire'. As the traffic conditions near the fire are in most cases not known, this ventilation philosophy the most appropriate is in many cases. However, it requires control of air velocity inside the tunnel and hence the appropriate control equipment.

A *near zero velocity* philosophy should not be applied, as the local concentrations of toxic gases as well as the local temperature will increase strongly and will reduce the tenability near the fire zone dramatically. In addition, any change in tunnel conditions such as heat release rate, outside wind pressure, etc. result in unpredictable smoke movement inside the tunnel, particularly near the fire. Self-rescue, supported rescue, and fire-fighting efforts are significantly impacted. Thus PIARC [4] classifies such a ventilation philosophy as being 'less favourable'. In fact such a ventilation strategy is very risky and should be avoided whenever possible.

Please cite this article in press as: P. Sturm, et al., On the problem of ventilation control in case of a tunnel fire event, Case Stud. Fire Saf. (2015), http://dx.doi.org/10.1016/j.csfs.2015.11.001

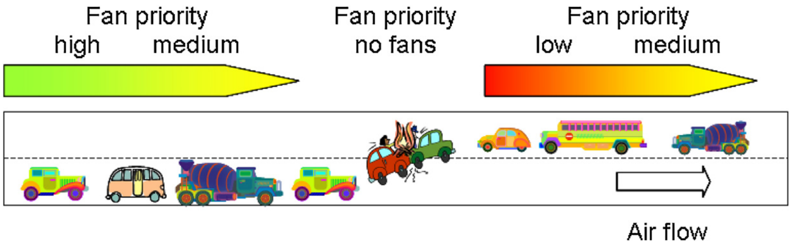

Fig. 1. Fan activation strategy for tunnels with bi-directional traffic or tunnels with unidirectional traffic and congestion (pushing strategy), fans with high priority label shall be activated first.

2.1.2. Fan activation

A second very important issue is the selection of jet fans for activation inside the tunnel. The fans need to fulfil two purposes. The first is to control the air/smoke velocity; the second is to maintain pressurization in the non-affected tube to avoid smoke penetration through open cross-passage doors.

Any active jet fan induces a lot of turbulence in the air/smoke movement. Thus, fans which are active within the smoke filled zone destroy any existing smoke layer and hence fill the full tunnel cross section with smoke. The logical sequence is to activate upstream fans first followed by a very late activation of fans downstream of the fire location. Such a ventilation strategy (pushing strategy, Fig. 1) creates an overpressure upstream of the fire and a low pressure region downstream. This strategy is applicable for tunnels with bi-directional traffic, as any activation of fans within the smoke zone is to be postponed. In tunnels with unidirectional traffic – and no congestion – a strategy based on activation of fans downstream of the fire (pulling strategy, Fig. 2) is likely to be preferable since any downstream location – compared to the non-incident tube – will automatically have a lower pressure. Hence, smoke penetration into the non-incident tube or any other path of egress is unlikely.

Due to the high turbulence introduced by jet fans, any fans in close proximity to the fire zone should not be activated, i.e. fans already in operation at those locations have to be shut off.

2.1.3. Fire ventilation of short tunnels

The definition of short tunnels in the context of this paper refers to physical tunnel lengths in combination with the road slope. While for short flat tunnels the critical length might not exceed 600–800 m, for tunnels with slopes it might differ (be much longer), depending on the acting buoyancy forces [9]. Fires in short tunnels – especially those with higher grades – can pose a significant ventilation problem. In most cases the distance between fire location and fans might already be too small for an effective control of the air/smoke velocity inside the tunnel [16,17]. Further, there may not be sufficient space for enough jet fans to manage the tunnel air velocities during a fire event. In such situations it might be beneficial not to activate any ventilation at all. However, other measures then have to be introduced in order to overcome the problems resulting from an uncontrolled smoke propagation inside the tunnel. One such measure for example, could be the introduction of shorter distances between escape routes [9].

2.2. Transverse ventilation

2.2.1. Ventilation philosophy

Transverse ventilated tunnels provide the possibility of extracting smoke close to the fire location. However, this requires remote-controlled dampers between the roadway and the smoke extraction duct. According to the EU directive [5] transverse or semi-transverse ventilation systems with the capability to evacuate smoke in the event of a fire are to be used in tunnels where longitudinal ventilation is not allowed. However, this directive requirement [5] applies to tunnels with bi-directional traffic longer than 3000 m only, with air/smoke extraction dampers which can be operated either separately or in groups. Concentrated smoke extraction is only possible when the location of the extraction can be limited to the location of

Fig. 2. Fan activation strategy for tunnels with unidirectional traffic and incident occurring at front of traffic queue (pulling strategy), fans with high priority label shall be activated first.

Please cite this article in press as: P. Sturm, et al., On the problem of ventilation control in case of a tunnel fire event, Case Stud. Fire Saf. (2015), http://dx.doi.org/10.1016/j.csfs.2015.11.001

the smoke source, regardless of whether the traffic is unidirectional or bi-directional and independent of the tunnel length (see Fig. 3). The effectiveness of the transverse ventilation system with smoke extraction depends solely on the possibility of confining smoke within a short region (control of air/smoke flow) and on the capacity of smoke extraction.

Typical air/smoke extraction rates vary between 120 m^3/s [6] and a multiple of the tunnel cross section [8] (e.g. in case of a cross section area of 70 m^2 and a multiplication factor of 3 the extraction rate would result in 210 m^3/s). The number of the dampers to be opened in the case of a fire is dependent on their size and the smoke/air volume to be removed. However, the more damper locations that are opened, the less efficient concentrated smoke extraction will be. The situation as shown in Fig. 3 depicts the optimal situation for smoke extraction. Smoke control is required to force smoke movement towards the open damper(s). An additional requirement is the need for air movement from both portals towards the extraction location (see Fig. 3). In tunnels with bi-directional traffic, achieving similar air/smoke volume flow rates from both portals towards the extraction point is recommended as this reduces the number of tunnel users exposed to smoke [14]. In tunnels with uni-directional traffic the airflow from the fire side towards the extraction point should be much larger than that from the other side. However, even in such situations it is likely – at least during the first phases of the incident – that smoke movement will occur for a relatively long way downstream of the extraction point. Hence, having some air flow from the exit portal towards the extraction location is regarded as favourable. This allows for the extraction of smoke which was transported beyond the

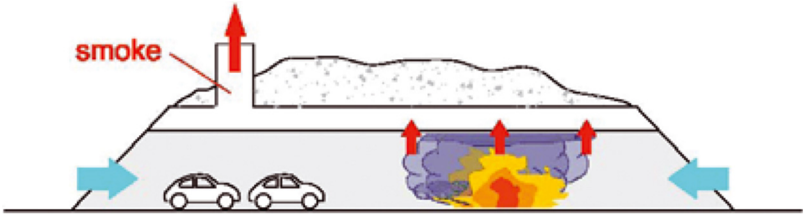

Fig. 3. Transverse ventilation system with remotely controlled dampers and smoke extraction in fire ventilation mode (source: Ref. [4]).

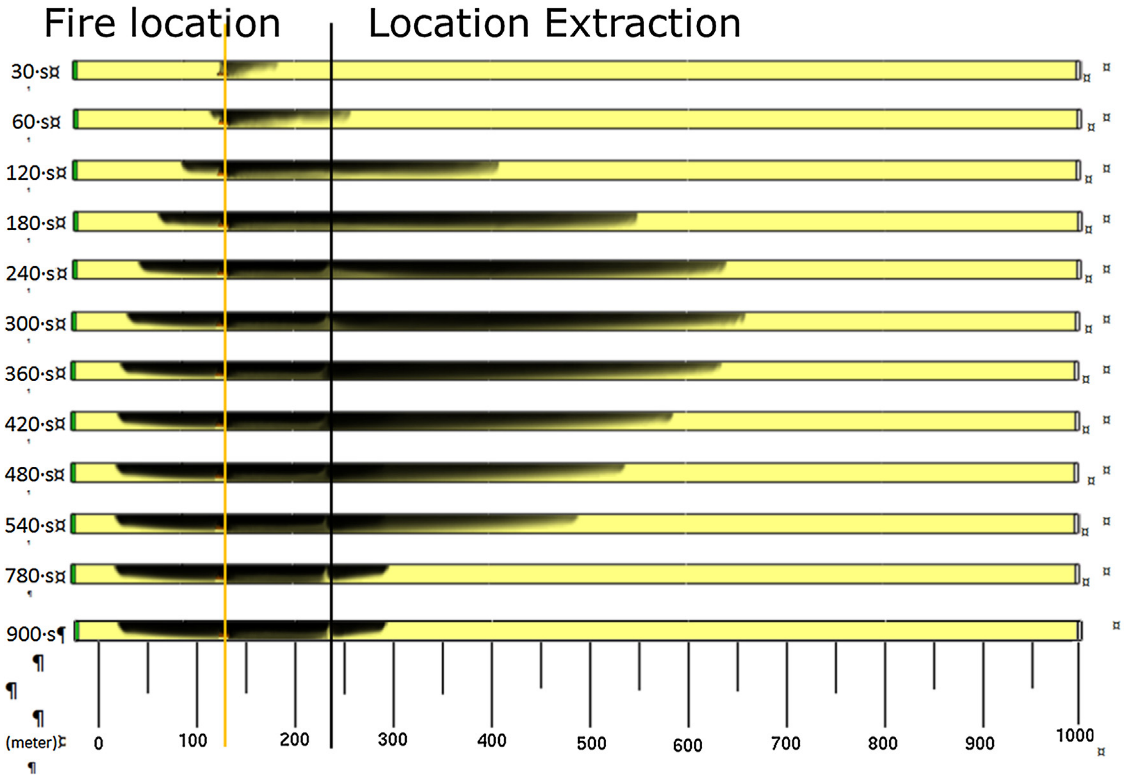

Fig. 4. Smoke propagation in a tunnel with a transverse ventilation system and remotely controlled dampers for smoke extraction; the vertical lines represent the location of the fire (see vertical line at position 130 m from entrance portal) and the extraction damper (see vertical line at position 240 m from entrance portal), fire detection including ventilation response (opening of extraction damper and startup of extraction fan) happened at 180 s, full extraction capacity of 160 m^3/s has reached at 360s.

Please cite this article in press as: P. Sturm, et al., On the problem of ventilation control in case of a tunnel fire event, Case Stud. Fire Saf. (2015), http://dx.doi.org/10.1016/j.csfs.2015.11.001

extraction location before the ventilation system went into full operation (see Fig. 4). The resultant velocity of the air/smoke inside the tunnel is dependent on the extraction volume and on the tunnel cross section.

2.2.2. Influence of fire detection and system start-up

The air velocity existing inside the tunnel at the time of an incident is also a consideration. This will cause an air/smoke flow along the tunnel. The time required for detection, along with the start-up time of the ventilation system (emergency mode), determine how far the smoke moves in the tunnel before the effective extraction begins. Fig. 4 shows the smoke propagation within a tunnel with transverse ventilation. It is assumed that a fire with a heat release rate of 30 MW (25% radiation loss) happened at 125 m from the portal (orange vertical line in Fig. 4). Due to the traffic prior to the incident the air velocity upstream of the fire is 1.5 m/s. However, the heat production due to the fire results in a smoke spread downstream at a velocity of 3–5 m/s. It is assumed that fire is detected 180 s after the incident. The extraction damper at 100 m downstream of the fire (black vertical line in Fig. 4) is opened at this time. In the time between fire ignition (0 s) and incident detection (180 s) smoke is already transported quite far downstream of the damper position. Until the full extraction capacity is reached, 180 s after detection, smoke is still transported towards the exit portal. From this time on all smoke produced by the fire is extracted via the damper. In addition the excess smoke that passed beyond the damper towards the exit portal is transported backwards and extracted. However, it lasts almost 10–12 min after the start of the incident until the final ventilation objective (smoke confined within incident location and open extraction damper) is reached.

Thus, while it can be concluded that transverse ventilation systems with remotely controlled dampers do provide a safety benefit in terms of smoke extraction, this benefit is strongly dependent on the time needed for incident detection and on the start-up of the ventilation system in fire mode [11].

2.2.3. Need for control of air/smoke flow inside the tunnel

As shown in Figs. 3 and 4 there is a need to confine smoke to the region between fire and open damper(s). Applying smoke extraction alone is not sufficient as many parameters influence smoke movement inside the tunnel. The required pressure balance inside the tunnel needs to be controlled for the airflow towards the open damper(s) depending on the location of the smoke extraction damper relative to the portals, depending on buoyancy effects caused by the fire, and on external pressure differences between the portals [14]. This can be achieved using additional equipment such as jet fans (Fig. 5), Saccardo type air injection system (Fig. 7)[12].

Nowadays the fresh air requirement is quite small even in long tunnels, so that it is sufficient to design a semi-transverse ventilation system for smoke extraction in the case of fire. Smoke confinement is often achieved by the usage of additional jet fans installed inside the tunnel. The thrust – and hence the number of jet fans – needed to confine the smoke, depends on the pressure difference between the portals. For larger pressure differences a few big fans (see Figs. 5 and 6 are often installed instead of a large number of smaller fans. This increases construction costs but reduces costs associated with maintenance and related tunnel closure. Fig. 6 shows such an installation for the Bosruck tunnel, Austria. Instead of having roughly 40 jet fans per tube which would fit into the existing tunnel, four ventilation niches with eight big jet fans (2700 N each) were erected.

In an existing full transverse ventilation system it may be favourable to use the supply air fans to achieve the required pressure balance. The working principle is shown in Fig. 7. While the extraction of smoke is performed by the extraction fan (left hand side of Fig. 7), smoke confinement is supported by supply air injection via the fan at right hand side of Fig. 7. Fig. 8 shows a section of the fresh air duct with the fresh air injection nozzle and a movable separation bulkhead in the rear. This compartment serves as a Saccardo type supply air injection as it is installed in the Katschberg tunnel in Austria [12].

Both systems have pros and cons. The advantages for the use of additional jet fans are related to the relative ease with which the air/smoke velocity inside the tunnel may be controlled. The cons are to be seen in the additional costs for fans and civil works. The usage of existing supply air fans for air injection has its benefits on the cost side due to the utilization of existing equipment (and no additional constructions) but there are also disadvantages in that the control of the smoke movement is much more complicated [12].

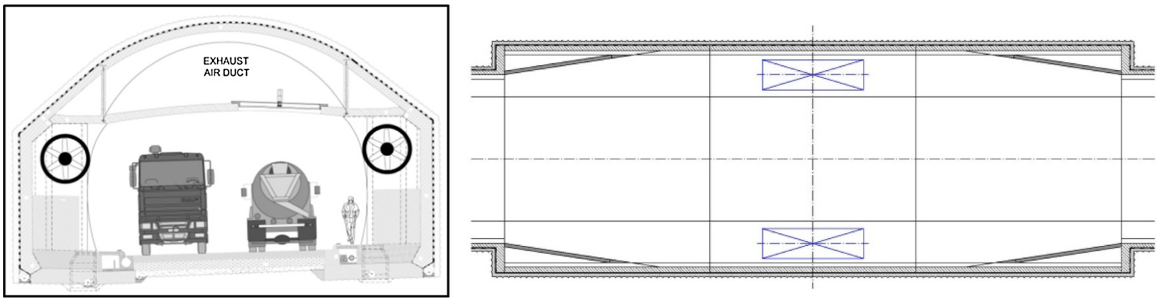

Fig. 5. Jet fans in tunnels with transverse ventilation systems for smoke confinement, cross section left, plan view of ventilation niche right [12].

Please cite this article in press as: P. Sturm, et al., On the problem of ventilation control in case of a tunnel fire event, Case Stud. Fire Saf. (2015), http://dx.doi.org/10.1016/j.csfs.2015.11.001

Fig. 6. Example of jet fans for smoke confinement in tunnels with transverse ventilation systems, installation in the Bosruck tunnel, Austria.

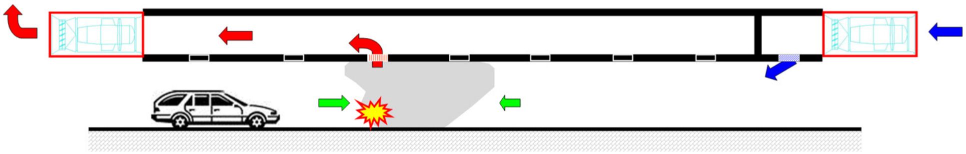

Fig. 7. Sketch of a Saccardo type air injection in tunnels with transverse ventilation systems for smoke confinement, axial fan on the left used for extraction, axial fan on the right is used for air injection [12].

2.3. Sensors needed for fire ventilation

As shown above fire ventilation requires a smoke control strategy and a clear methodology for fan activation. Closed loop control systems have to be employed to achieve the required ventilation target. Hence, it is necessary to have proper sensors inside the tunnel to provide:

- reliable and quick detection of the incident,
- determination of fire location,
- accurate and reliable measurement of the air/smoke movement inside the tunnel.

Numerous types of sensors are available to identify the location of an incident. While linear heat detectors are reliable with respect to relatively large, stationary heat sources, they can be problematic in the detection of smouldering or smoky fires. On the other hand, systems such as fully automatic CCTV analytics, while offering quick detection, are often accompanied by a high failure rate. Some countries require a combination of sensors. For instance, Switzerland requires a combination of linear heat detectors and smoke detectors (spot sensors) for incident detection. The more complex the tunnel system is, the more complex the control of the ventilation in fire mode will be [13].

Fig. 8. Example of a motorized damper used for fresh air injection (right), and duct separation wall (left), installation in the Katschberg tunnel, Austria.

Once activated, the only information needed for controlling ventilation is the air/smoke velocity inside the tunnel. Thus, having correct and reliable measurements of the air/smoke velocity inside the tunnel is imperative. Ultra-sonic beam measurements over the tunnel cross section prove to be the most appropriate means for monitoring air velocity inside the tunnel [15]. High quality sensors for dynamic pressure might also serve this purpose, as long as more than one sensor is applied within one cross section. Single point (spot) sensors are in most cases not suitable. Nevertheless as all air velocity sensors (beam or spot measurement) deliver a signal which is valid only for a certain part of the tunnel cross section, calibration measurements are required to correlate those values to the average air velocity over the tunnel cross section. In addition, plausibility checks for sensor values, as well as equipment redundancy installations are also essential [6]. While this clearly increases the measurement efforts, it is more than justified by the resulting improvement in fire ventilation functionality.

Despite the relatively large number of sensors required inside the tunnel, a full sensor blackout may still occur. Where it is not possible to determine the location of an incident, keeping the status of ventilation unchanged, or shutting it off completely, might be the wiser choice. This depends on the situation. In cases where there is no information on the velocity of the air/smoke movement inside the tunnel it might be better to maintain a certain level of smoke movement. This would allow the tunnel users to adjust themselves to the situation. In such cases national regulations such as the Austrian guideline RVS 09.02.31 [6] demand that fans continue to operate at least at 50% of their full capacity.

3. Conclusion

Fire ventilation – i.e. the use of ventilation during a fire event – is an important operating mode in any tunnel ventilation system. It enables and improves self-rescue during the initial phase of an incident. Various guidelines have already been established at international and national levels to ensure that safety standards are met. The focus lies on the control of the air/smoke velocity in the near-field region of the fire. In most cases a ‘low velocity’ philosophy is the most appropriate one in order to enable self-rescue, even in the smoke-filled zone. In order to achieve this goal reliable measurement of the air/smoke velocity and control procedures for the fans are required. In turn, this will more or less automatically call for periodic testing of sensors (their functionality and plausibility) and also for regular testing of fire ventilation systems, including detection, activation and fan control. However time frames available for maintenance and tests are increasingly being shortened, due to the increased requirements on road traffic infrastructure, even though the technical infrastructure now in place is much more complicated compared to that used in former years. Thus there is a risk that in one of those rare moments when the system is needed, failure of one component of the safety chain could result in the system not delivering the required result. Hence, either the systems have to be simplified, or more efforts have to be invested in maintaining and testing safety equipment.

Acknowledgements

Special thanks to Norris Harvey (Hatch Mott Mc Donald) and Igor Maevsky (Jacobs Engineering) for their input and the valuable discussions.

References

[1] PIARC, Report to the XXth World Road Congress, Montreal (Canada-Québec), PIARC Committee on Road Tunnels, report 20.05. B, 1995.
[2] PIARC, Fire and Smoke Control in Road Tunnels, PIARC Committee on Road Tunnels Operation (C5), report 05.05. B-1999, ISBN: 2-84060-064-1, 1999.
[3] PIARC, Systems and Equipment for Fire and Smoke Control, PIARC Committee on Road Tunnels Operation (C3.3), report 05.16. B-2006, ISBN: 2-84060-175-3, 2007.
[4] PIARC, Operational Strategies for Emergency Ventilation, PIARC Committee on Road Tunnels Operation (C3.3), report 2011-R02, ISBN: 2-84060-234-2, 2011.
[5] European Commission, Directive 2004/54/EC of the European Parliament and of the Council on Minimum Safety Requirements for Tunnels in the Trans European Road Network, 29th April 2004.
[6] RVS 09.02.31, Tunnel, tunnel equipment, ventilation, basic principles, Forschungsgemeinschaft Straße, Schiene, Verkehr, Wien, 2014.
[7] RABT, Richtlinien für die Ausstattung und den Betrieb von Straßentunneln, Forschungsgesellschaft für Straßen- und Verkehrswesen, Arbeitsgruppe Verkehrsführung und Verkehrssicherheit, 2006.
[8] ASTRA; Lüftung der Strassentunnel, Systemwahl, Dimensionierung und Ausstattung, Ausgabe 2008 V2.01, Bundesamt für Strassen, Abteilung Strassennetze, Bern, CH, www.astra.ch, 2008.
[9] F. Zumsteg, U. Steinemann, M. Berner, Ventilation and distance of emergency exits in steep bi-directional tunnels, Proceedings of the 6th Symposium on Tunnel Safety and Ventilation, Graz, Austria, 23–25 April, 2012, pp. 273–280 ISBN: 978-3-85125-210-1.
[10] F. Zumsteg, U. Steinemann, C. Joseph, Tunnel safety by ventilation—an illusion? Proceedings of the 5th Symposium on Tunnel Safety and Ventilation, Graz, Austria, 3–4 May, 2010, pp. 5–11 ISBN: 9783-85125106-7.
[11] P. Sturm, C. Forster, B. Kohl, M. Bacher, Impact of quick incident detection on safety in terms of ventilation response, Proceedings of the 2nd Symposium on Tunnels and ITS, Bergen, Norway, 18–20 September, 2013. http://www.its-norway.no/ikbViewer/Content/881733/14%20Sturm_Graz_TU.pdf.
[12] P. Sturm, M. Beyer, M. Bacher, G. Schmölzer, The influence of pressure gradients on ventilation design–special focus on upgrading long tunnels, Proceedings of the 6th Symposium on Tunnel Safety and Ventilation, Graz, Austria, 23–25 April, 2012, pp. 90–99 ISBN: 978-3-85125-210-1.
[13] P. Sturm, M. Bacher, R. Brandt, Evolving needs of tunnel ventilation in a changing world, Proceedings of the 4th Symposium on Tunnel Safety and Ventilation, Graz, Austria, 21–23 April, 2008, pp. 8–21 ISBN: 978-3-85125-008-4.
[14] R.A. Almbauer, P. Sturm, M. Bacher, G. Pretterhofer, Simulation of ventilation and smoke movement, Proceedings of the 2nd Symposium on Tunnel Safety and Ventilation, Graz, Austria, 19–21 April, 2004, pp. 32–38 ISBN: 3-901351-95-7.

[15] ASTRA, Airflow measurements in road tunnels, Forschungsauftrag ASTRA 2010/025_OBF auf Antrag des Bundesamt für Strassen (ASTRA), Bern, CH, www.astra.ch, 2011.
[16] F. Zumsteg, U. Steinemann, Ventilation of short road tunnels in case of an incident, Conference "Tunnel Safety and Ventilation", Graz, 2006.
[17] M. Bettelini, N. Seifert, On the safety of short road tunnels, Conference, "Tunnel Safety and Ventilation", Graz, 2010.

Please cite this article in press as: P. Sturm, et al., On the problem of ventilation control in case of a tunnel fire event, Case Stud. Fire Saf. (2015), http://dx.doi.org/10.1016/j.csfs.2015.11.001