Strategies for fire ventilation

Peter Sturm[1], Michael Bacher[1] & Alexander Wierer[2]
[1]Graz University of Technology, Austria
[2]ASFiNAG BMG, Innsbruck, Austria

ABSTRACT

Ventilation systems are a major aspect in tunnel safety. On the one hand, they need to ensure that sufficiently good air quality is made available for the safe passage of tunnel users. On the other hand, they need to facilitate rescue conditions in cases of smoke or fire. 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 way to ventilate a tunnel in cases of emergency is not always clear.

Although fire tests have been performed since the early 1960's, and although the topic of fire ventilation was raised in early national and international guidelines, relatively little interest was shown on the issue until several big fire events occurred in the 1990's. The 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 incidents with fire (commonly named 'fire ventilation') has become a major topic. This paper describes methodologies for fire ventilation with a focus on applications in existing tunnels undergoing upgrading.

KEYWORDS: ventilation of road tunnels, fire ventilation, smoke control

BACKGROUND

The issue of fire and smoke control has been already tackled in various PIARC publications (e.g. [1], [2], [3] and [4]). These publications mention several threats to human health arising in the presence of fire, e.g. high temperatures, the existence of various toxic gases, and low oxygen content. While low visibility reduces both the possibility of escape as well as the ability to approach an incident location, high temperatures and high heat radiation rates may also result in a continuous growth of the fire due to flashover. Hence PIARC concludes that fire and smoke control is essential in order to:

- save lives by facilitating user evacuation,
- make rescue and fire-fighting operations possible,
- avoid explosions,
- limit damage to tunnel structure and equipment and to surrounding buildings [2].

That means there is a need for controlled ventilation in the case of an incident with fire and smoke. Different countries have different philosophies regarding how best to ventilate in cases of fire. While some tunnel operators prefer to focus on the avoidance of backlayering of smoke upstream of the fire, other operators opt for maintaining low smoke propagation speed, 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 to 3 m/s), while the latter requires relatively low smoke propagation velocities as the walking speed within a smoke-filled zone is around 0.5 m/s. Hence, in practice, a compromise is often made by applying quite a low velocity in the range of 1.0 to 1.5 m/s upstream of the fire. This serves to both minimise backlayering effects on the upstream side and to maintain lower smoke propagation velocities downstream of the fire.

Another important aspect which has to be considered is the ventilation system itself. While in tunnels using longitudinal ventilation smoke has to be transported from the fire site through the whole tunnel, transverse ventilation systems allow for a concentrated smoke extraction inside the tunnel and hence for a smoke-free zone over large areas of the tunnel. However, transverse ventilation tunnels need to have quite a complex ventilation control system in order to confine the smoke to the extraction locations.

Directive 2004/54/EC [4] 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 technical 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, it describes only the requirements for technical installations and does not cover questions of emergency operation. The relevant information in such cases can be found in international (e.g. [2], [3], [4]) or various national guidelines (e.g. [6], [7], [8]). While existing guidelines are relatively easy to apply to new tunnels, very often a much greater effort is needed when attempting to apply guidelines to tunnels undergoing upgrading.

VENTILATION SYSTEMS AND PHILOSOPHY OF FIRE VENTILATION

During fire ventilation, smoke management is ideally achieved by dilution and/or removal of smoke. Polluted air has to be replaced by clean or smoke-free air, which is either supplied mechanically or drawn in through the portals. Dilution can increase tenability e.g. by reducing concentrations of toxic gases. The basic principles of smoke movement have already been described in detail in [3], those of smoke control in [4]. These principles are still valid. PIARC only provides recommendations. 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].

Longitudinal ventilation tunnels

Ventilation philosophy

The philosophy for fire ventilation in longitudinally ventilated tunnels is quite simple. Polluted air can only be removed via portals or ventilation shafts. The main questions here concern which air/smoke speed has to be applied and how fan activation is to be performed. Concerning air/smoke velocity, there is some controversy surrounding the issue of whether application of a ‘critical velocity’ or of a ‘low velocity’ is to be preferred.

A *critical velocity* philosophy is applied in order to avoid backlayering, i.e. to prevent or slow the upstream movement of smoke along the tunnel ceiling. Typical values for critical velocities are in the region of 2.2 to 3.5 m/s for fire sizes around 30 to 50 MW heat release rate. However, with a heat release rate of 30 MW it can be expected that the downstream velocity will increase by a factor of 2 to 3, resulting 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 the fire incident occurs at the top of a traffic stream.

A *low velocity* philosophy is recommended by PIARC [4], as well as in many national ventilation guidelines (e.g. [6], [7], [8]) for bi-directional tunnels as well as for tunnels with unidirectional traffic where the specific conditions prevailing at the site of the incident (e.g. fire within congestion or not, risk of flashover, etc.) remain unclear. Here, target velocities of the upstream (i.e. cold) air are in the range of 1.0 to 1.5 m/s. Such air/smoke velocities are a compromise between ‘accepting reduced backlayering’ and ‘moderate air/smoke velocities downstream the fire’. As the conditions obtaining in the near-field of the incident are in most cases not known, this ventilation philosophy is in many cases the most appropriate one. However, it requires control of the air velocity inside the tunnel and hence

the appropriate 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 in the near-fire zone dramatically. In addition, any change in boundary conditions such as heat release rate, outside wind pressure, etc. result in an unpredictable smoke movement inside the tunnel and hence in continually changing conditions in the near-field of the fire. Self-rescue, supported rescue, and fire-fighting possibilities are all strongly reduced. 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.

Fan activation

A second very important issue is the selection of active jet fans inside the tunnel. The fans have to fulfil two purposes. The first, is to control the air/smoke velocity; the second, is to maintain an overpressure in the non-affected tube in order 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 consequence is the usage of fans upstream and a very late activation of fans downstream of the fire location. Such a ventilation strategy (pushing strategy, Figure 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 as late as possible. In tunnels with unidirectional traffic - and no congestion - a strategy based on activation of fans downstream of the fire (pulling strategy, Figure 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 is unlikely.

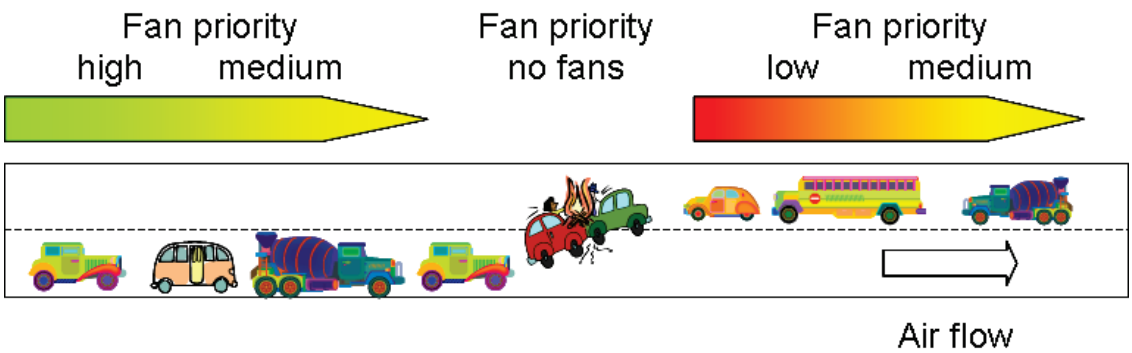

Figure 1 Fan activation strategy for tunnels with bi-directional traffic or tunnels with unidirectional traffic and congestion (pushing strategy)

Figure 2 Fan activation strategy for tunnels with unidirectional traffic and incident occurring at front of traffic queue (pulling strategy)

Due to the high turbulence introduced by running fans, any fan in close proximity to the fire zone must not be activated, i.e. fans already in operation have to be shut off.

Fire ventilation of short tunnels

Fires in short tunnels - especially those with higher gradients - can pose a big problem with respect to ventilation during a fire. In most cases the distance between fire location and fans might already be so small that the air/smoke velocity inside the tunnel cannot be controlled in an efficient manner [9]. 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 uncontrolled smoke propagation inside the tunnel. One such measure for example, could be the introduction of shorter distances between escape ways.

Transverse ventilation tunnels

Ventilation philosophy

Transverse ventilation tunnels provide the possibility of extracting the smoke close to the fire location. However, this requires remote-controlled dampers between traffic room 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, the directive [5] only applies to tunnels with bi-directional traffic longer than 3,000 m, with air/smoke extraction dampers which can be operated either separately or in groups. This limitation to tunnels with bi-directional traffic and a length greater than 3,000 m is totally misleading. Concentrated smoke extraction is only possible when the location of the extraction can be limited to the location of the smoke source, regardless of whether the traffic is unidirectional or bi-directional or shorter or longer than 3,000 m (see Figure 3). The effectiveness of a transverse ventilation system with smoke extraction depends solely on the possibility of confining the smoke to within a short region (control of air/smoke flow) and on the capacity of smoke extraction.

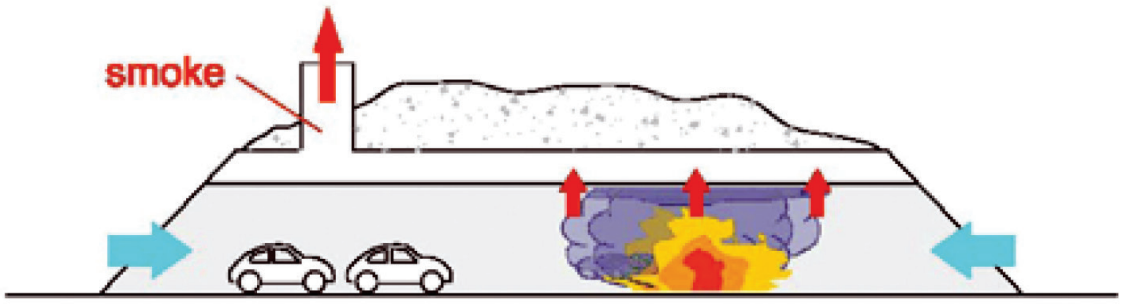

Figure 3 Transverse ventilation system with remotely controlled dampers and smoke extraction in fire ventilation mode (source: [4])

Typical air/smoke extraction rates vary between some 120 m³/s [6] and a multiple of the tunnel cross section [8]. The number of the dampers to be opened in the case of a fire is dependent on their size. The situation as shown in Figure 3 depicts the optimal situation for smoke extraction. The velocity of the air/smoke inside the tunnel is dependent on the extraction volume and on the tunnel cross section. Smoke control is required in order to ensure smoke movement towards the open damper(s). An additional requirement is the need for an air movement from both portals towards the extraction location (see Figure 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 prevents as many tunnel users as possible from being trapped in the smoke. In tunnels with uni-directional traffic the airflow from the fire side towards the extraction point should be much bigger. However, even in such situations it is likely - at least during the first phases of the incident - that smoke movement will occur

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 extraction location before the ventilation system went into full operation (see Figure 4).

Influence of fire detection and system start-up

The air velocity existing inside the tunnel at the time of an incident also has to be taken into consideration. This causes an air/smoke flow along the tunnel. The time required for detection, together with the start-up time of the ventilation system (emergency mode), determine how far the smoke moves in the tunnel before effective extraction begins. Figure 4 shows the smoke propagation within a tunnel with transverse ventilation. It is assumed that fire detection starts 180 s after the incident. Full extraction capacity is reached after another 180 s. This lasts almost 10 to 12 minutes after the incident until the final ventilation objective (smoke confined within incident location and open extraction damper) is reached. Note: the large zone with backlayering upstream of the fire location is an artefact of the calculation tool. The model used (FDS version 5.0) overestimated the length of the backlayering zone in the grid configuration employed.

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 frames needed for incident detection and on the start-up of the ventilation system in fire mode.

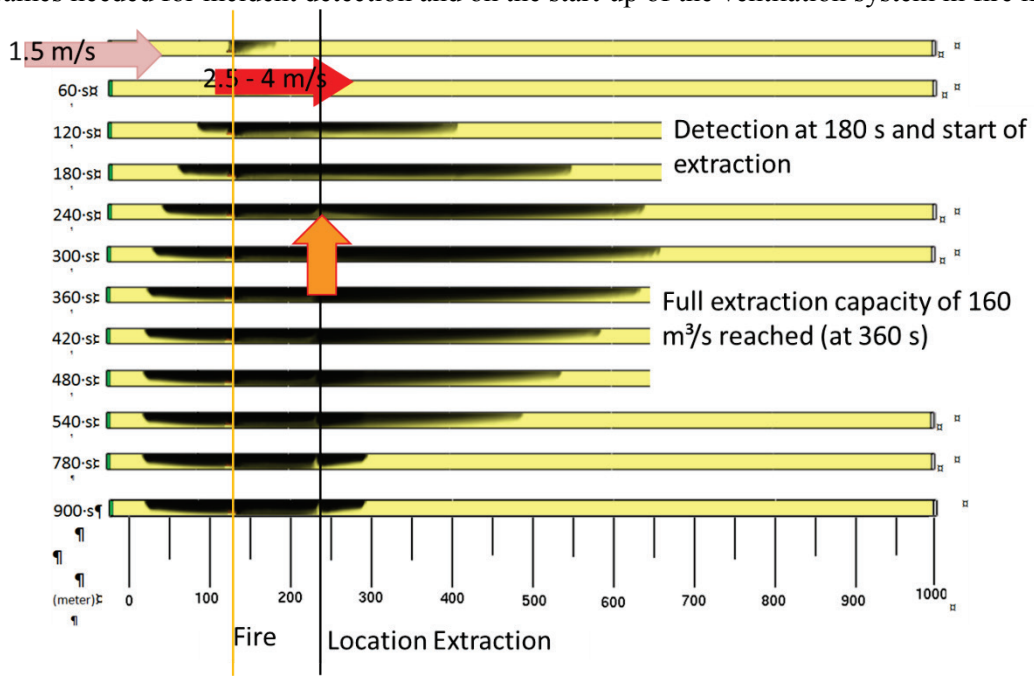

Figure 4 Smoke propagation in a transverse ventilation system with remotely controlled dampers and smoke extraction [11]

Need for control of air/smoke flow inside the tunnel

As shown in Figure 3 and Figure 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 the smoke movement inside the tunnel. Depending on the location of the smoke extraction damper in relation to the portals, on buoyancy effects caused by the fire, and on external pressure differences between the portals, it is necessary to control the air/smoke flow towards the open damper(s) using additional equipment such as jet fans (Figure 5) , a Saccardo type air injection system (Figure 6), or by some other means, in order to provide the required pressure balance inside the tunnel [12].

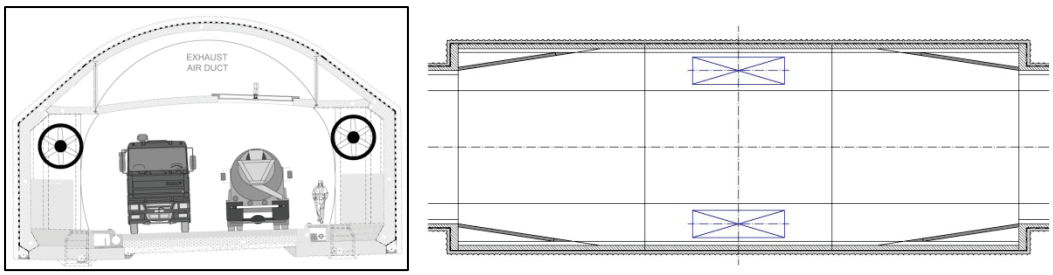

Figure 5 Jet fans in tunnels with transverse ventilation systems for smoke confinement [12]

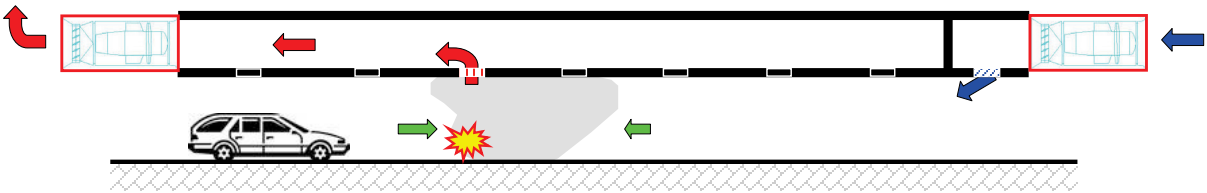

Figure 6 Sketch of a Saccardo type air injection in tunnels with transverse ventilation systems for smoke confinement [12]

Nowadays, even in long tunnels, the fresh air requirement is quite small, so that it is sufficient to design a semi-transverse ventilation system for smoke extraction in the case of fire. In such a case 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 bigger pressure differences a few big fans are often installed instead of a large number of smaller fans (see Figure 5). This increases construction costs but reduces costs associated with maintenance and related tunnel closure. In an existing full transverse ventilation system it might be favourable to use the existing fresh air fans to achieve the required pressure balance (see Figure 6). Both systems have their pros and cons. The pros for the usage 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 fresh air fans for air injection has its benefits on the cost side (existing equipment) but there are also disadvantages in that the control of the smoke movement is much more complex [12].

Sensors needed for fire ventilation

As shown above fire ventilation requires smoke control and a clear strategy for fan activation. Hence, it is necessary to have proper sensors inside the tunnel in order to ensure:

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

Numerous types of sensors are available to help 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 CCTV, while offering quick detection, are often accompanied by quite a high failure rate. Some countries such as CH require a combination of linear heat detectors and smoke detectors for incident detection. The more complex the tunnel system is, the more complex the control of the ventilation in fire mode will be [13].

The only information needed for ventilation control is the air/smoke velocity inside the tunnel. Thus, having correct and reliable measurements of the air/smoke velocity inside the tunnel is imperative. Plausibility checks for sensor values, as well as equipment redundancy installations are also essential. While this clearly increases the effort entailed in measurement, 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 allocate 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 RVS 09.02.31 [6] demand that fans continue to operate at least 50% of their full capacity.

FIRE VENTILATION FOR THE UPGRADED ARLBERG TUNNEL

When designing new tunnels the latest regulations can all be taken into account. A much more difficult situation arises when existing tunnels have to be upgraded. Matters become even more complicated where long transverse ventilation tunnels, designed decades ago as part of civil works projects, now need to be updated in order to comply with existing standards [13]. This is discussed in the section below with respect to the fire ventilation system and the upgrading of the 14 km long single tube Arlberg tunnel.

Existing ventilation system

The Arlberg tunnel has a length of approx. 14 km and connects Tirol to Vorarlberg in the western part of Austria. The tunnel was opened 35 years ago and has been operating since then as a single tube tunnel with bi-directional traffic. The average daily traffic volume is around 8,000 veh/day, and the peak traffic in holiday seasons is almost twice as high. The tunnel is equipped with a full transverse ventilation system with six ventilation sections, two vertical shafts (736 m and 218 m) and two portal stations. Each section is currently ventilated by one fresh and one exhaust air fan. Figure 7 depicts the ventilation scheme, where VS1 to VS6 denote the ventilation sections, F1 to F6 and E1 to E6, denote the fresh and the exhaust air fans.

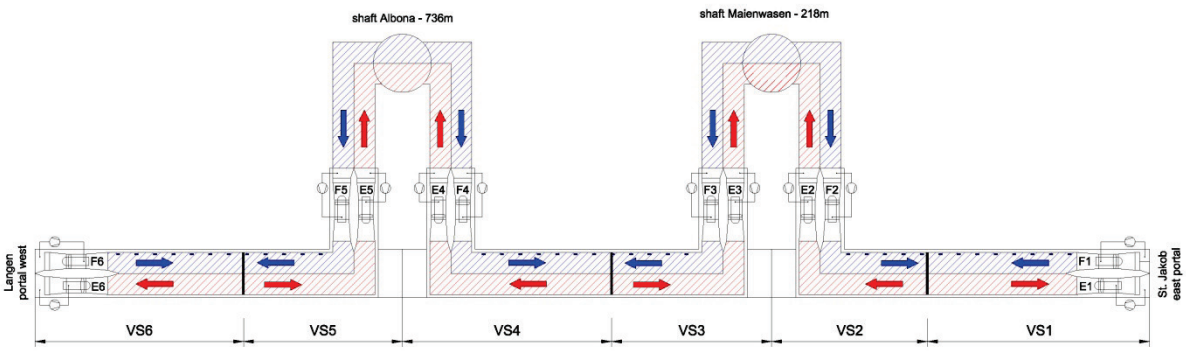

Figure 7 Sketch of the existing ventilation scheme of the Arlberg tunnel

Upgraded system

Currently escape galleries leading to the parallel railway tunnel are located every 1,700m. The Arlberg tunnel is part of the TERN road network. According to the EU directive [5] the distance between escape points has to be reduced to a maximum of 500 m. The distance between railway and road tunnel is quite big (up to 300 m) and there is no need for further escape routes for the railway tunnel. Thus, instead of introducing further cross passages to the rail tunnel of the following solution was chosen This means that between the existing cross passages to the railway tunnel (every 1,700 m) the fresh air ducts will in future also serve as egress ways. While this minimises construction costs, it does require additional installations for maintaining egress user safety. Figure 8 shows a sketch of the road and railway tunnel as well as of the existing and the new (green) egress ways.

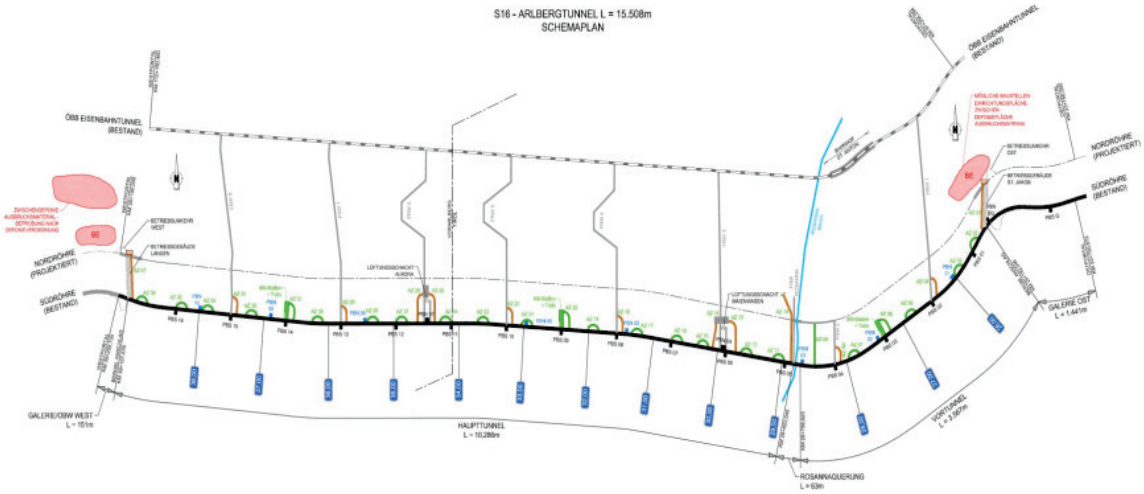

Figure 8 Sketch of the egress ways of the Arlberg tunnel (ASFiNAG)

Figure 9 shows images of the new egress way. Ramps will be installed instead of stairs in order to allow for usage by the handicapped.

Figure 9 Images of the new egress way as well as of the connection between traffic room and egress way via fresh air duct (source ASFiNAG)

Additional features which have to be installed are:

- high pressure water mist system in order to reduce the fire load and to protect the false ceiling,
- remotely controlled dampers in the fresh air duct in order to avoid smoke penetrating into the fresh air duct,
- egress ventilation

Requirements for tunnel ventilation systems have changed over the years. While in former years the need for fresh air supply was dominant, this is no longer the case. Originally, per ventilation section (~2.4 km), roughly 370 m³/s were required, nowadays only 10% of this amount is necessary. On the other hand, the demands relating to fire ventilation, and especially to smoke control, have become much stricter.

Fire ventilation

The principles for fire ventilation in the Arlberg tunnel follow the philosophy described above in the section 'Ventilation systems and Philosophy of fire ventilation',(see 'Transverse ventilation tunnels'). The main issue is the confinement of smoke in the region of the extraction damper. As the Arlberg tunnel represents a weather barrier the meteorological pressure differences between the two portals are quite high. They amount to 254 Pa as 95 percentile of the half-hour mean values of the pressure differences. Hence massive electro-mechanical installations in the form of jet fans or air injection nozzles are needed in order to maintain pressure gradients. A cost-benefit analysis indicated that usage of the existing fresh air fans for air injection is appropriate. This requires the installation of fresh air injection dampers (FAID) and sealing doors within the fresh air duct (see Figure 6). Figure 10 depicts the scheme of the upgraded ventilation system with the FAIDs and additional jet fans (JF1 to JF3) for smoke control. The advantage of this system is that existing fans can be used and structural adaptations inside the tunnel can be reduced to a minimum. The drawback of FAIDs is that each additional device raises the flow of air into the tunnel. The increase in momentum (thrust) brought into the tunnel is accompanied by an increase of the volume flow rate. Hence the air/smoke velocity inside the tunnel also increases. Use of a simple jet fan, in contrast, would only produce the required thrust in the traffic room. In order to overcome the problem of increasing volume flow rates, air extraction in other ventilation sections has to be utilised to achieve the required pressure balance (push – pull system). Such a concept was originally implemented in Austria in 2002, using a full closed loop control system for the 10 km long Plabutsch tunnel [14]. At that time, however, vertical air injection and extraction was employed without using the momentum of the injected air. Systems with FAIDs have since been applied successfully in Austria in several long road tunnels [12]. What is new in the Arlberg tunnel, is the parallel usage of multiple FAIDs and jet fans as well as air extraction in sections other than in the fire section.

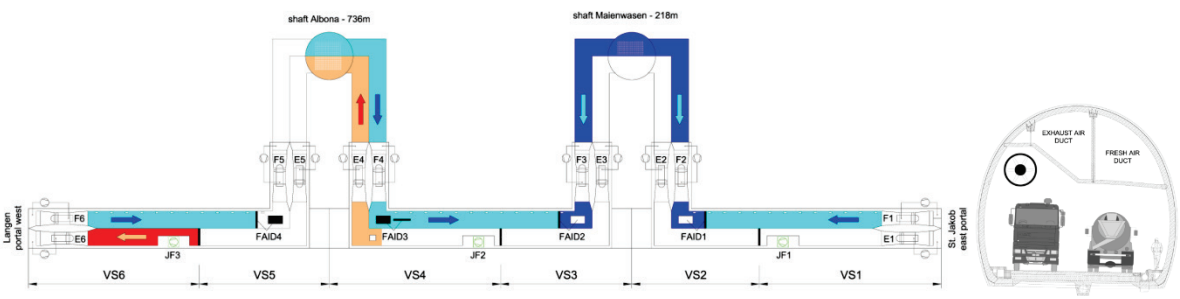

Figure 10 Sketch of the new ventilation scheme of the Arlberg tunnel (left) and of the cross section in the region of jet fan JF3 (right)

Figure 11 shows a scenario for a 30 MW fire in ventilation section VS6. Close to the fire location a mass flow of 144 kg/s smoke/air is to be extracted. In order to achieve a symmetrical flow from both portals towards the extraction location the usage of the FAID1 and 2 as well as of the jet fans JF1 and JF2 is needed. In addition air extraction is required in section VS6. In this particular case, various exhaust air and fresh air supply fans as well as the jet fans are needed at the same time in order to reach the required ventilation goal. The remaining fresh air fans are needed to vent the escape route via the fresh air duct. Figure 12 shows the velocity distribution inside the tunnel resulting from fan activation in this scenario. As can be seen, symmetrical air flow from both sides of the incident location towards the extraction point can be achieved.

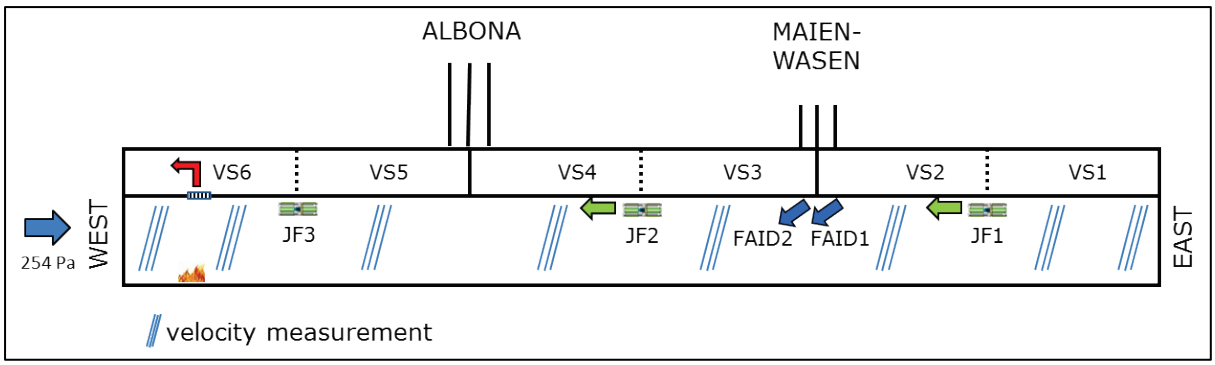

Figure 11 Fire ventilation for an incident in ventilation section VS66

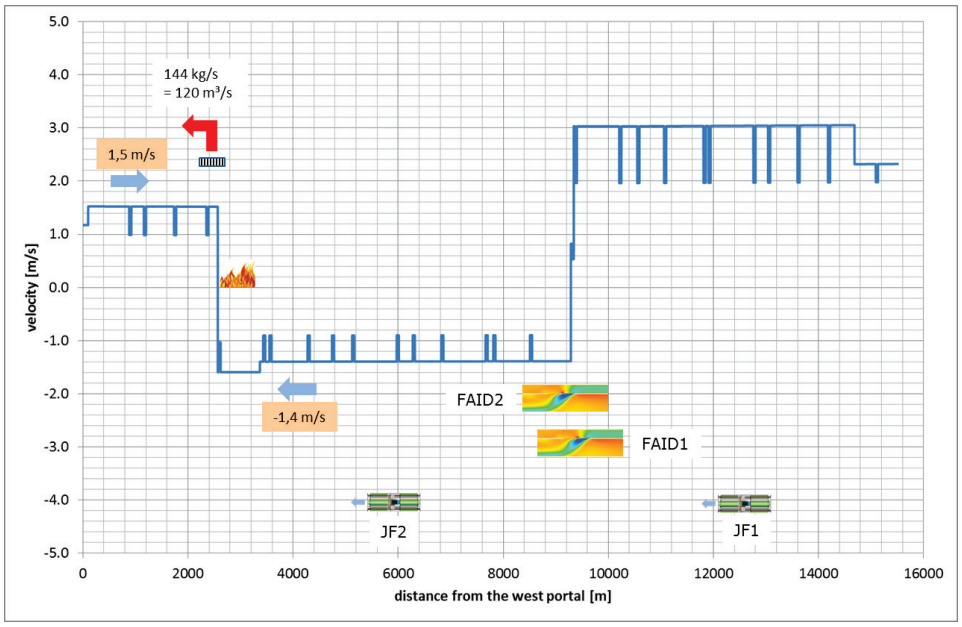

Figure 12 Air velocity distribution for an incident in ventilation section LA6

The ventilation system chosen for the Arlberg tunnel utilises as much existing equipment as possible and thus helps avoid new construction of major civil works that would otherwise be necessary in order to achieve current safety requirements. It represents a compromise between the requirements of cost efficiency, the time available for system refurbishing and upgrading, and technical feasibility. The tunnel is quite long, hence the air masses that need to be moved in the case of a fire are relatively large. As a result of the high level of inertia, the control behaviour of the flow is expected to be relatively slow. However, the equipment available to control the velocity inside the tunnel (FAID and air extraction) is powerful enough to cope. Sufficient time for adjusting the software parameters as well as for testing the whole system will be required. This has to be followed by a dense schedule of system tests in order to minimise the risks of producing an overly complex, or unwieldy ventilation system.

CONCLUSION

Fire ventilation - i.e. the use of ventilation during a fire event - is an important operating mode in any tunnel ventilation system. It raises the possibility of self-rescue during the initial phase of an incident. Various guidelines have already been established at international and national levels to ensure that relevant 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 correct measurement of the air/smoke velocity and sound control procedures for the fans are required. In turn, this will more or less automatically call for permanent testing of sensors (their functionality and plausibility)

and also for regular testing of fire ventilation systems, i.e. detection, activation and fan control. However, due to the increased demands required of road traffic infrastructure the time frames available for maintenance and tests are increasingly being shortened, even though the technical infrastructure now in place is much more complex compared to that used in former years. There is thus a risk that in one of those rare moments when the system is needed, failure of one part of the safety chain could result in the system not delivering the required result. Thus, either the systems have to be simplified, or more effort has to be invested in maintaining and testing safety equipment.

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, 2006.

[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, 2008

[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 N, Bern, www.astra.ch, 2008

[9] Zumsteg F., Steinemann U., Berner M., "Ventilation and Distance of Emergency Exits in Steep Bi-directional Tunnels", Proceedings of the 6th Symposium on Tunnel Safety and Ventilation, 273-280, ISBN: 978-3-85125-210-1, Graz, Austria, 23-25 April, 2012

[10] Zumsteg F., Steinemann U., Joseph C., "Tunnel Safety by Ventilation – an Illusion?", Proceedings of the 5th Symposium on Tunnel Safety and Ventilation, 5-11, ISBN: 978-3-85125-106-7, Graz, Austria, 3-4 May, 2010

[11] Sturm P., Forster C., Kohl B., Bacher M., "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, http://www.its-norway.no/ikbViewer/Content/881733/14%20Sturm_Graz_TU.pdf, 2013

[12] Sturm P., Beyer M., Bacher M., Schmölzer G., "The Influence of Pressure Gradients on Ventilation Design – Special Focus on Upgrading Long Tunnels", Proceedings of the 6th Symposium on Tunnel Safety and Ventilation, 90 - 99, ISBN: 978-3-85125-210-1, Graz, Austria, 23-25 April, 2012

[13] Sturm P., Bacher M., Brandt R., "Evolving Needs of Tunnel Ventilation in a Changing World", Proceedings of the 4th Symposium on Tunnel Safety and Ventilation, 8 - 21, ISBN: 978-3-85125-008-4, Graz, Austria, 21-23 April, 2008

[14] Almbauer R.A., Sturm P., Bacher M., Pretterhofer G., "Simulation of Ventilation and Smoke Movement", Proceedings of the 2nd Symposium on Tunnel Safety and Ventilation, 32-38, ISBN: 3-901351-95-7, Graz, Austria, 19-21 April, 2004