

New Aspects in Tunnel Ventilation

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ABSTRACT: For tunnel fire life safety, the crucial questions are where people are situated, where to escape, and how the smoke spreads. Designing or even operating a tunnel ventilation system to achieve the critical velocity must be questioned. Most fatalities in tunnel fires were caused by quick spread of toxic smoke, often due to the inappropriate operation of the tunnel ventilation system. Instead, the longitudinal airflow must be carefully controlled. This new aspect and the resulting consequences for the design and operation of tunnel ventilation systems are described in this paper, based on almost two decades of development and implementation in European tunnels. Engineering know-how and experience, high redundancy of critical elements, quality control in all stages of implementation and thorough testing on site under different conditions are key issues to achieve reliable operational safety.

GENERAL TUNNEL SAFETY CONSIDERATIONS

Tunnel ventilation is one of many elements that may contribute to tunnel safety, but must be seen as part of a general safety concept with different educational, operational and technical safety measures. The main goals of such safety measures are, in order of importance:

1. To prevent incidents.
2. To minimize damage to life and health of the involved persons (passengers, emergency services) if an incident does occur.
3. To protect the tunnel structure and maintain the traffic link.

The most significant risk in road tunnels, as on open roads, are traffic accidents. In comparison to that, the fire risk is usually much lower. Approximately only one of 1 Million road traffic fatalities die in a tunnel fire. Therefore, tunnel safety measures should focus on avoiding collisions between vehicles and other vehicles, the tunnel structure or fixed objects. The same principle is described for instance in the Technical Specifications for Interoperability (TSI-SRT) for rail tunnels. Measures that focus only on the mitigation of consequences in case of a fire incident, like e.g., emergency exits, fire fighting equipment or fire ventilation, might be questioned from a cost-benefit point of view. Nevertheless, fire safety received a high media presence after the fatal Mont Blanc and Tauern tunnel fire incidents in 1999, resulting in new regulations and the investment of significant sums for fire safety equipment (including new ventilation systems). But do all those safety

measures really improve safety of tunnel users and services? Risk assessments show that many requirements in present guidelines are not useful, and may even increase the risk, considering that safety equipment may have a detrimental effect in case of inappropriate operation. An example for that is smoke extraction in unidirectional highway tunnels, as is described below (see Figures 8 and 9)

SMOKE SPREAD

In fire incidents, it is mainly the smoke, respectively its toxic components, that endangers people. The linear structure of tunnels may lead to a fast smoke spread. In dense smoke, you lose orientation and are exposed to possible toxic fumes. In fact, most fatalities in tunnel fires occurred because they were trapped by quick spread of smoke, in many cases caused by the inappropriate operation of the tunnel ventilation system. And yet, a high airflow velocity, leading to fast smoke movement in case of fire, is the design case according to many tunnel ventilation standards and guidelines.

Without forced ventilation, the smoke moves predominantly by meteorological forces, which cannot be controlled, and by traffic as long as it keeps moving. In steep tunnels, the chimney effect by the fire can get very strong and drives the smoke quickly upwards. This caused for instance 155 fatalities in the Kaprun funicular in Austria in 2000, or 9 fatalities in the Viamala road tunnel in Switzerland in 2006.

But fast smoke spread can also be caused deliberately by the operation of the ventilation system. Fire ventilation is often understood as simply driving the smoke away from the fire location. People on one side of the fire get the chance to escape in

a smoke-free area and emergency services get better access to the incident site. This works fine as long as there are no people exposed to the smoke on the other side, where it is blown, for instance in highway tunnels with unidirectional traffic and low probability of congestions. Unfortunately, pushing the smoke towards one side in reality is often performed without considering where endangered people may be. That led to approximately 300 fatalities in the metro Baku (Azerbaijan) in 1995, and many casualties in the Mont-Blanc, Tauern and Gotthard road tunnel fires in the Alps (see for instance Duffé, 1999). As an example, Figure 1 shows the fire in the Gotthard tunnel fire in 2001. The picture is taken from the safe side, but behind the fire, the tunnel was smoked up over a length of approximately

8 km, where 11 people died despite having access to emergency exits.

PURPOSE OF TUNNEL VENTILATION

Tunnel ventilation helps to prevent accidents by ensuring appropriate visibility, may dilute dangerous substances from vehicle emissions, and control smoke spread in case of fire. On the other side, metro / mass transport tunnel ventilation systems are designed to provide temperature control, especially during hot periods—an aspect that gains importance in times of global climate change.

Until the 1980s, before vehicle emission restrictions came into effect in the US and most European countries, road tunnel ventilation systems were required to ensure an acceptable air quality and prevent visibility impairment due to dust and soot. Even today, when vehicles have become quite clean, an operating ventilation may contribute to a safe range of vision under particular circumstances.

A special case is the fogging of windscreens of cars driving into a tunnel with bidirectional traffic in humid weather (see Figure 2). Here the collision risk can be substantially reduced through implementation of an adequate operational ventilation.

Most tunnel ventilation systems today are design for the fire case, assisting self-rescue of passengers and access of emergency services. To assess the usefulness of fire ventilation concept and operation, the crucial question is where people may be situated in case of a fire in the tunnel, where do they can escape, how the smoke will spread and how it can be controlled.

SMOKE EXHAUST

Until the 1990s, linear exhaust systems were used in most tunnels with transversal or semitransversal ventilation systems. Unfortunately, such systems were unable to control smoke spread, and could even deteriorate conditions in large parts of the tunnel, as was tragically demonstrated for instance in the fire incidents in the Mont-Blanc, Tauern and Gotthard road tunnels. The reason for that is shown in Figure 3: Linear exhaust leads to high flow velocities from the outside, spreading the smoke depending on the fire location and momentary boundary conditions.



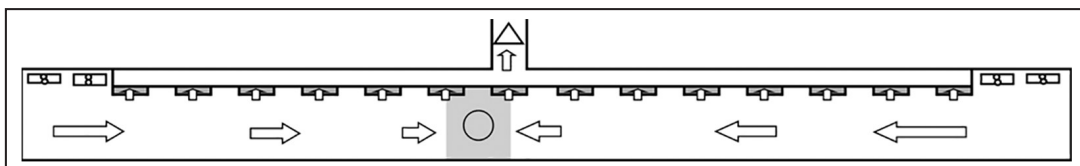
Source: Public domain

Figure 1. Fire in the Gotthard road tunnel 2001



Source: Public domain

Figure 2. Fogged windscreens—cause of many accidents in tunnels



Source: Pospisil 2013

Figure 3. Linear exhaust in a tunnel

To remove exhaust air, fumes and smoke close to the source would be the best concept in principle, when the smoke is extracted directly above a burning vehicle. To achieve that in practice, smoke exhaust dampers would have to be placed in very short distances, in the order of the length of a vehicle. Furthermore, the exhaust dampers need to be very large, since the amount of extracted smoke may be immense, e.g., for a burning Heavy Goods Vehicle. And the exact location of the fire source would have to be detected reliably. Such a system would be neither technically nor economically feasible.

Conceptually, a compromise was found by placing the dampers at certain distances along the tunnel (usually in the range of 50 to 100 m), and open a number of dampers for local exhaust. After the fire in the Mont Blanc tunnel, French

experts proposed to open exhaust dampers over a length of 600 m—by definition not really a concentrated extraction (Duffé 1999). According to national design standards, dampers were to be opened over 300 m, later reduced to 200 m in Switzerland. In Austria, one large open damper was the basis of design.

In reality, several conceptual issues have to be considered, as described in the Road Tunnel Ventilation Compendium (Pospisil, 2013). With increasing distance between dampers, there is a high probability that the smoke is not extracted at the location of the fire, but driven through the tunnel over a certain length even under ideal conditions. The position of a burning vehicle and therefore the distance to the closest exhaust damper is a random variable. Ideal conditions like in Figure 4 would be subject to pure luck.

If several dampers are opened, then the removal of smoke within the exhaust zone between the first and the last open damper is difficult to achieve. In the case of an ideally symmetrical exhaust and two open dampers, no smoke is extracted between the open dampers. Supposed that the fire is situated between the open dampers, high smoke concentrations would be achieved there, see Figure 5.

Further, the dynamic behavior has to be taken into account, as shown in Figure 6.

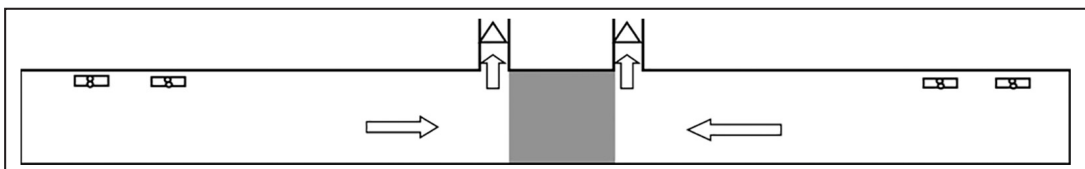
At the moment of incident detection, the smoke has previously spread over a large part of the tunnel. As soon as the exhaust is started, under ideal conditions the smoke spread is slowed down and reversed, until the smoke is confined in a limited zone, usually between the open dampers. The time to drive the smoke back is in the same order like the assumed escape time of people in the first phase, which is in the range of several minutes, see Figure 10. In Figure 7, the limit of steady-state smoke confinement is shown.

In practice, the detection of the exact fire location might be faulty, or the wrong dampers may be opened erroneously, therefore the section filled with smoke might be even longer. In other words, the conditions in the vicinity of the fire might be the same or even worse as they would be without smoke exhaust. And that's exactly where vehicles are blocked and most endangered people are supposed to be situated.



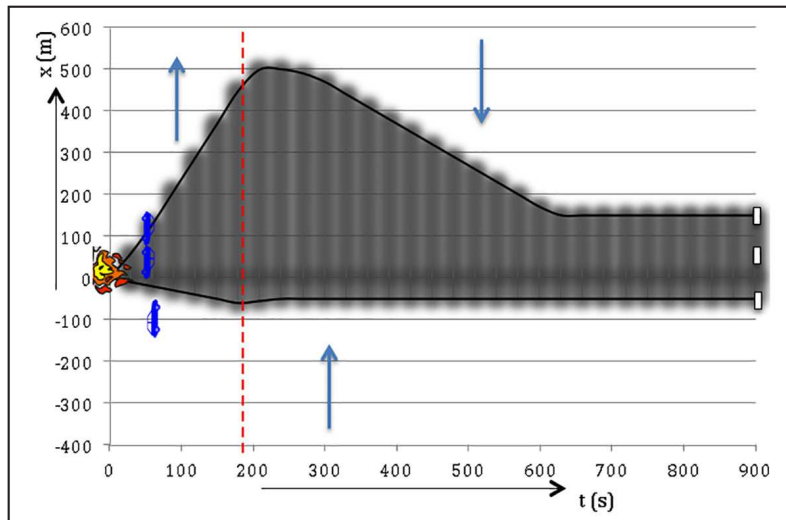
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Figure 4. The ideal case: smoke exhaust through one damper above the fire source



Source: Pospisil 2013

Figure 5. Symmetrical exhaust with two open dampers



Source: Pospisil 2013

Figure 6. Sequence of smoke spread and confinement in a tunnel with 3 open dampers



Source: Authors archive

Figure 7. Front of smoke area under outermost open exhaust damper

A smoke exhaust is only effective in a tunnel when a precise and reliable incident detection and flow control, which is described below, are guaranteed. The most important benefit of a concentrated smoke exhaust is that the spread of smoke is limited, whereas with a continuous longitudinal ventilation, the smoke spreads towards one or even both tunnel portals, as is explained e.g., in the PIARC document 2011R02. This is an important advantage in long tunnels, where people at a larger distance from the fire may be trapped and cannot escape, especially when there are no emergency exits or protected shelters at all.

From a cost benefit-point of view, represented by costs per life saved, a smoke exhaust system is hardly justifiable for most tunnels, and makes sense only when it is used not only for fire ventilation, but also for normal operation in long tunnels with bidirectional traffic and a high traffic load. In such

tunnels, the local concentrated exhaust of fumes from vehicle emissions may be an adequate ventilation system, instead of expensive transversal ventilation systems that were applied when vehicle emissions were much higher than today.

A special case to be considered are twin-tube highway tunnels with unidirectional traffic. Even in case of fire, the risk to tunnel users in such tunnels is very low, provided that the vehicles leave the tunnel between the incident site and the exit portal. Blockage of vehicles can and must be avoided by appropriate traffic management measures, like closing the tunnel entrance portal if necessary to avoid congestions inside the tunnel. Irrespective of the tunnel length, the smoke can be blown in the direction of traffic movement, since vehicle speed is faster than the speed of smoke propagation. People who are stuck in front of the incident site are situated in a smoke-free, safe area.

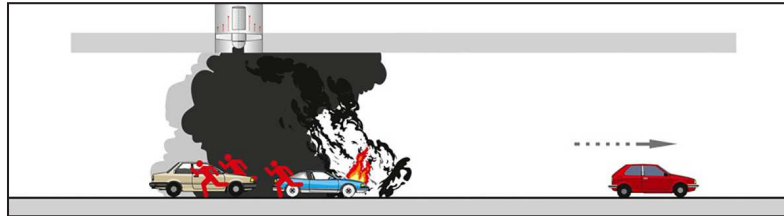
A smoke extraction in tunnels with unidirectional traffic may be useful when vehicles and passengers get trapped downstream of the incident site, for instance in case of traffic congestion in an urban tunnel. However, in twin-tube highway tunnels, the passengers still have a means of escape over the cross passages to the other tube. There might be other arguments to be taken into account, for instance the benefit of a smoke extraction for occasional situations with bidirectional traffic in one tube. However, from a probabilistic view, the likelihood of such incidents is quite low.

On the other hand, a smoke extraction leads to a significant additional risk, due to a possible erroneous operation. When opening the exhaust dampers



Source: Pospisil 2013

Figure 8. Smoke movement in a tunnel with unidirectional traffic without exhaust



Source: Pospisil 2013

Figure 9. Smoke exhaust at the wrong position, endangering people

upstream of the fire location, for instance due to false detection, the area where blocked cars and people are located would be smoked-up by flow reversal, as is shown in Figure 9.

Another additional risk from exhaust systems in road tunnels is the slab that separates the traffic space from the air duct in the ceiling. There were incidents when this slab had fallen down and killed people. This happened for instance in 2006 in the Boston Central Artery Tunnel (U.S.) where a woman was killed, and in 2012 in the Sasago Tunnel (Japan) with 9 fatalities. In a long Swiss highway tunnel, the slab had fallen down too, but luckily nobody was harmed.

Summarizing, smoke extraction for highway tunnels with unidirectional traffic has a limited usefulness, may rather increase the risk in particular aspects, and increase costs massively.

FLOW CONTROL

Two decades ago, the generally accepted purpose of tunnel fire ventilation was to blow the smoke towards one or the other side. The so-called critical velocity, which is the value that must be achieved to prevent back-layering of smoke, is the ‘golden calf’ of many tunnel fire ventilation standards, without questioning its usefulness. Does that make sense ?

In fact, backlayering does not endanger people, as long as a stratification is ensured, but blowing the smoke with high velocity towards one side may fan the fire, increase its heat release rate, and speed up the smoke propagation, thus endangering people in the tunnel. An important aspect is that the airflow is not only determined by the operation of the

ventilation, but rather by the traffic, meteorological conditions and fire buoyancy.

As a consequence from the major road tunnel fire incidents around the millennium, the importance to control the longitudinal airflow has become apparent. The dynamic closed-loop control, based on precise and reliable flow measurement and sophisticated control algorithms, has become proven standard in Swiss and Austrian tunnel ventilation systems, regardless of whether the ventilation system is pure longitudinal or with a concentrated exhaust. By that, smoke movement can be stabilized to a reduced velocity that is slower than the supposed escape speed of people, and in the vicinity of the fire a smoke stratification is facilitated, providing tenable conditions for the escape of people and operation of emergency services. Basic principles of flow control are described for instance in the Swiss research reports (Pospisil et al. 2010, Altenburger et al. 2013).

The desired target velocity depends on the specific situation. For instance, according to the Slovak guideline TP049, for tunnels with bidirectional traffic or congestion, when people are supposed to be situated on both sides of a fire, the target value is 1–1.5 m/s. For highway tunnels with unidirectional traffic, when the probability of people being blocked downstream is assessed as low, the target value is 1.5–2 m/s. The target value must be achieved within two minutes after the fire alarm, not exceeding the given bandwidth. An important requirement is that jet fans in the vicinity of the fire location must not be operated, since they would immediately destroy smoke stratification and spread the smoke over the whole tunnel cross section.

The critical velocity as an operational state is useful when it can be assured that no people are situated downstream. In practice, this is only the case for fires close to the tunnel portals, when the goal is to prevent the smoke from spreading into the tunnel.

When applying Fixed Fire Fighting Systems, like for instance in urban road tunnels in Australia, Japan, Singapore and the U.S., smoke stratification is not an issue, nevertheless limiting the flow velocity is important to enable an efficient fire suppression.

Since self-rescue has to be completed within approximately 10–15 Min. after the occurrence of an incident, a short time delay to achieve the desired state of flow is essential, see Figure 11.

However, the technical effort to successfully implement a reliable dynamic flow control under tunnel conditions must not be underestimated, and requires extensive know-how and experience. Most

important for a functioning flow control is a precise, reliable flow measurement in the tunnel, which is a delicate matter, requiring a sophisticated signal evaluation. The air velocity and flow direction serve as input parameter for the controller, and must be determined by multiple independent measurements which have to be checked for plausibility against each other. Calibration of the installed anemometers by a precise reference measurement is essential, see Figure 12.

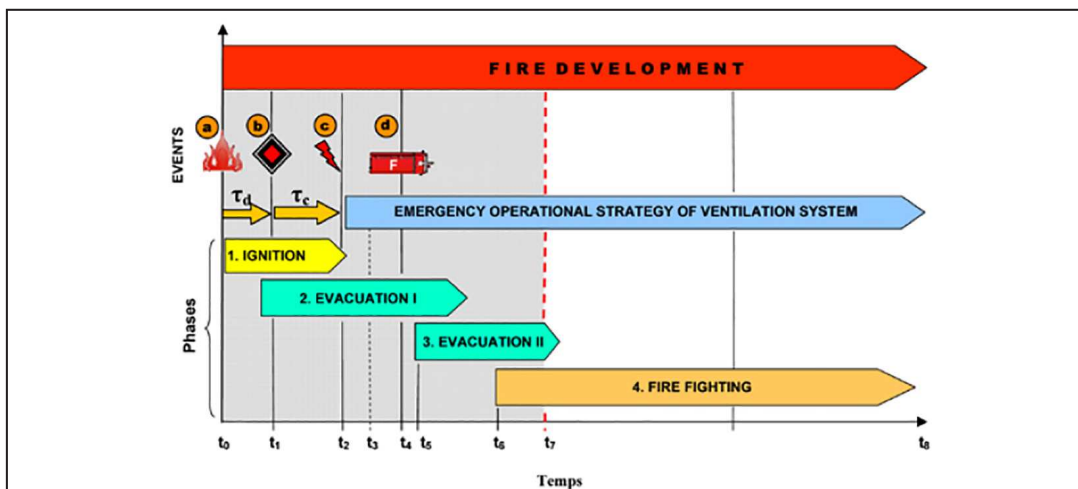
The ventilation system must not be designed only for a steady state, but on basis of dynamic simulations for many different scenarios, taking into account the inertia of moving air, wind fluctuations (specially in short tunnels) and other meteorological forces, moving traffic behavior, and assumptions on fire dynamics and buoyancy.

One of the first projects with a reliably functioning closed-loop flow control in road tunnels was for instance the 1.2 km long, longitudinally ventilated Balmenrainntunnel in Switzerland (2003). The control worked by stage switching of jet fans, where the number of fans to be switched on and off was determined by the measured flow velocity and matrices based on tunnel model calculations ('model based control'). Later, the use of dynamic PID-Controllers became usual (see Altenburger et al. 2013). But by switching jet fans on and off, the target condition mostly cannot be achieved fast enough, and often only with a large deviation. Moreover, successive switching operations may lead to fan failure due to overheating of motors. A continuous flow control by Variable Speed Drives (VSD) and PID-Controllers has been implemented for instance in the 2.5 km long Isla Bella tunnel on the A13 highway in Switzerland in 2008. At excessive tests, it was shown that the



Source: Authors archive

Figure 10. Smoke stratification at controlled flow conditions



Source: PIARC 2011R02

Figure 11. Typical fire accident phases



Source: Authors archive

Figure 12. Grid measurement for calibration of anemometers (according to ISO 5802)

desired state of flow could be achieved within less than two minutes from different initial conditions. In the past decade, this has been the accepted state-of-the-art. However, such a flow control system has not only advantages. Common problems are Electromagnetic Compatibility (EMC) issues, due to long shielded cables between VSDs and Fans. Reliability of VSDs, PLCs and communication lines are other aspects that must be considered.

INTEGRATED FLOW CONTROL SYSTEM

The next step in increasing reliability and reducing overall costs is to realize a dynamic closed-loop feedback control of airflow by means of an integrated, decentralized flow control system with increased redundancy and system reliability, previously tested and applied as a ‘plug-and-play’ solution. Key component of such a system is a control unit where the VSD, PLC with dynamic controller, switchgear and communication terminals are integrated in a tight housing which can be installed close to the jet fans in niches, cross passages or in the tunnel ceiling, being suitable for the highly corrosive tunnel environment. By short cable length between Fan and VSD, EMC compliance is assured.

Since jet fans for flow control are operated only in cold air, a high temperature rating for the jet fans is useless from a technical point of view. Nevertheless, high temperature ratings are required by most national standards on behalf of the fire brigade. For that, the temperature rating of the control units is guaranteed by application of a bypass switch.

Such control units have first been applied in the 1 km long bidirectional Polana tunnel in Slovakia in 2017, and are since then operating reliably, see Figure 13.

An integrated decentralized flow control system comprises of jet fans (or other devices, e.g., dampers, exhaust and supply fans), control units, anemometers and other ventilation related



Source: Authors archive

Figure 13. Jet fans and control units in the Polana tunnel

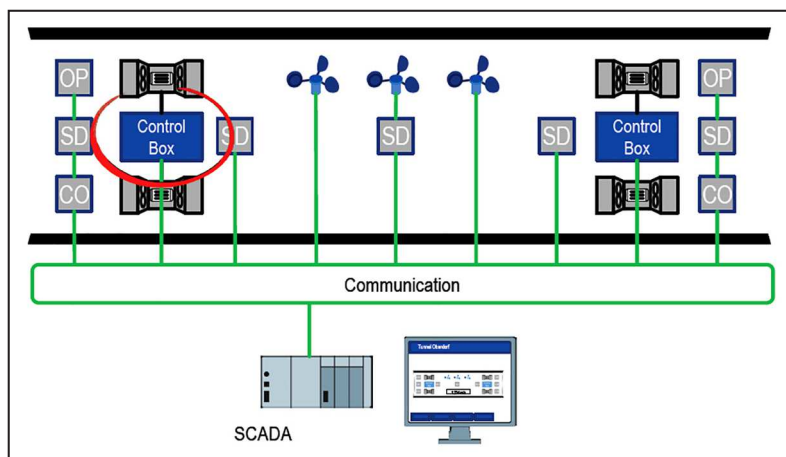
sensors (e.g., smoke detectors), and a redundant communication ring which connects together all components and provides the interface to the SCADA system and the fire alarm system, see Figure 14. The dynamic flow control works fully automatic. The ‘intelligence’ with signal evaluation, control routines and dynamic controller is implemented in each PLC in the control unit. The SCADA serves for supervision and manual input.

The use of standardized industrial components results in high reliability and low product costs. Redundancy is achieved at different levels. Failure of single components, e.g., fans, control units, measuring instruments, or a communication line does not affect the system functionality of the flow control. Even when the complete communication fails, a reduced autonomous operation is guaranteed as long as the power supply works. In case of failure, damage, or aging, a control unit can easily and quickly be replaced. The need for access is very low due to high reliability.

The basic problem of a flow control, compared to simple switching, is that increasing complexity leads to additional expenses for hard- and software, implementation and testing. In this respect, the integrated control system has a big advantage: It can be preassembled and the flow control can be checked and optimized before implementation in the tunnel by application of a ‘Hardware in the Loop’ Tunnel Simulator via Open Platform Communications (OPC) interface to the PLC. By that, precious time and costs for implementation, commissioning and testing on site in the tunnel can be saved.

CONCLUSION

Tunnel ventilation is an important safety element, but when not appropriately operated, it may exacerbate the conditions in tunnel fires. It became apparent that the ‘traditional’ way of designing and operating tunnel ventilation systems for fire ventilation, with the critical velocity to be achieved or exceeded, is not useful in practice—with some exceptions. In case of



Source: Authors archive

Figure 14. Schematic of decentralized flow control system

fire, high flow velocities are detrimental. The effect of different meteorological conditions and traffic behavior must be taken into account. From today's point of view, smoke spread must be controlled by stable flow conditions at moderate flow velocities. As state of the art, the dynamic closed-loop flow control to achieve a defined target velocity has been established. That requires sophisticated engineering know-how and extensive practical experience. High redundancy of critical elements, quality control in all stages of implementation and thorough testing on site under different conditions are key issues to achieve reliable operational safety. In this respect, the integrated flow control as turn-key system with functional performance guarantee may be the next step towards increased safety at lower costs.

ABBREVIATIONS

CO	Carbon Monoxide
EMC	Electromagnetic Compatibility
OP	Opacity Measurement
OPC	Open Platform Communications
PIARC	World Road Association
PID	Proportional Integral Derivative (Controller)
PLC	Programmable Logical Control
SCADA	Supervisory Control and Data Acquisition
SD	Smoke Detector
TSI-SRT	Technical Specifications for Interoperability on Safety in Railway Tunnels
VSD	Variable Speed Drive

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