Towards Optimum Control and Operation of Tunnel Ventilation Systems

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ABSTRACT: Ventilation design for normal and emergency conditions is frequently carried out based on purely steady-state considerations. While this is allowable to some extent in comparatively simple cases, there are situations, where this approach completely fails. In such situations both ventilation and ventilation-control design must take dynamic effects into account. This is particularly important for ventilation control. This paper discusses the impact of transient effects on optimum ventilation strategies as well as practical ventilation-control issues and requirements.

KEYWORDS: Ventilation, Control, Optimum operation

1. INTRODUCTION AND OBJECTIVES

Design standards for ventilation systems for underground traffic infrastructures are well developed and allow for a reasonably straightforward design, at least for "standard" tunnels. Ventilation design can frequently be carried out based on purely static, steady-state conditions. Less obvious and equally important are the operational procedures to be applied in normal operating conditions and particularly in case of emergency.

The most relevant issues in normal operating conditions are user comfort, active safety and energy consumption. In case of fire, the main focus is protecting the users and supporting self-rescue for all relevant fire scenarios. This requires a rapid system reaction, for limiting as much as possible the uncontrolled smoke propagation which invariably characterizes the initial phase of fire scenarios. During the initial minutes after fire onset, vehicles are still moving in the tunnel and mechanical ventilation is possibly active in a normal-operation mode, which is generally entirely unsuited for smoke management. This issue is particularly delicate for road tunnels, where self-rescue is expected to be completed within a few minutes. Time pressure on decision makers is high and fully automatic procedures are generally adopted, for reducing the risk of human error due to stress. In a subsequent step, during rescue and firefighting, the initial ventilation patterns can be adapted by the first responders for supporting the selected intervention strategy. At this stage, the aerodynamic situation in the tunnel is generally stable and decisions can mostly be based on purely static considerations.

Optimum ventilation operation in case of fire is an intrinsically time-dependent problem. Major influence factors, particularly the motion of the vehicles in the tunnel, thermal effects in case of tunnels at slope, and the system's inertia, need to be accounted for in a dynamic manner. One-dimensional (1D) simulation represents a well-established tool for analyzing such scenarios and designing optimum ventilation-control procedures. All examples presented in this paper were simulated using TunSim, the author's comprehensive simulation package for road, rail and metro tunnels.

2. TRANSIENT TUNNEL AERODYNAMICS

2.1. Introduction

Longitudinal air velocity in a tunnel system can vary very rapidly over time, particularly in the initial stages of a fire incident. This is due in particular to vehicle motion in the tunnel, heat release through the fire (the so-called "stack-effect") and activation of the fire ventilation, which always has a powerful impact on tunnel aerodynamics and smoke propagation. These effects shall be illustrated by means of real-life examples.

2.2. Road Tunnels

A typical example of a situation, where rapid and powerful aerodynamic effects are observed, are short, steep tunnels. Figure 1 shows the evolution of longitudinal air velocity and smoke propagation in a 760 m long tunnel with 5% slope. The emergency exits are shown with green dashed lines, simplified person escape trajectories with continuous green lines. Traffic is bidirectional and symmetric conditions with vanishing air velocity were assumed initially. The effect of thermal buoyancy and traffic on smoke propagation is nevertheless so violent, that after only 5 minutes the whole tunnel is filled with smoke. The escape trajectories show that there is little hope for successful self-rescue for several tunnel users.

This scenario was simulated assuming natural ventilation. Longitudinal ventilation cannot be expected to be useful in such cases, since the natural reaction times related to detection, selection of the ventilation scenario and activation of the ventilation are too long compared to the time scales of smoke propagation. It is highly unlikely for a mechanical ventilation to be effective before the whole tunnel is filled with smoke.

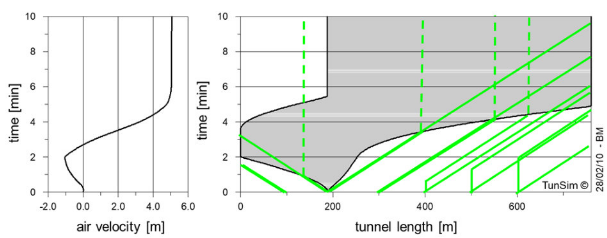

Figure 1 Longitudinal air velocity in the tunnel (left), smoke propagation and self-rescue (tunnel length 760 m, 5% slope rising from left to right, bidirectional traffic, natural ventilation).

Figure 2 shown a tunnel about twice as long as the previous one, operated with unidirectional traffic from left to right. It can be seen that flow reversal begins around 5 minutes after fire onset. In the whole, the tunnel's behavior is similar, but its time scales are larger. There is more time for detection and for activating the ventilation and there are real chances of successfully mastering this scenario.

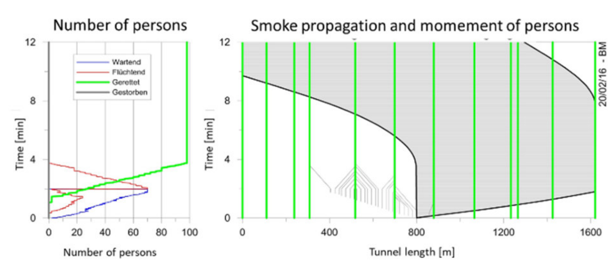

Figure 2 Smoke propagation and self-rescue in a 1600 m long tunnel (unidirectional traffic, rising from left to right, natural ventilation)

Figure 3 illustrate transient effects for ventilation systems with smoke extraction. Smoke propagation is well controlled about 8 minutes after fire onset. In the meantime, a very significant smoke propagation over roughly 500 m is observed. Purely static considerations would suggest perfect behavior of tunnel ventilation in this case, resulting in an overly optimistic assessment.

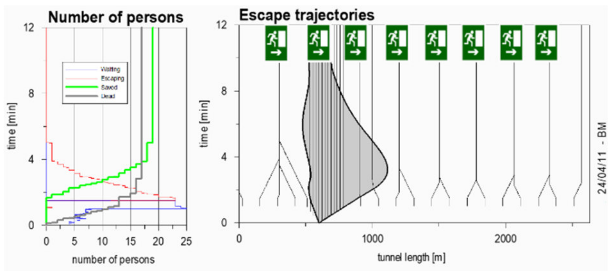

Figure 3 Smoke propagation and self-rescue in a 2100 m long tunnel (bidirectional traffic, no significant slope, concentrated smoke extraction)

2.3. Rail Tunnels

The powerful effect of trains transiting through the tunnel on longitudinal velocity is illustrated in Figure 5. Trains circulating through the tunnel generate a significant airflow. This is a key aspect for emergency management, as trains not involved in the fire leave the tunnel and rescue trains access the fire site.

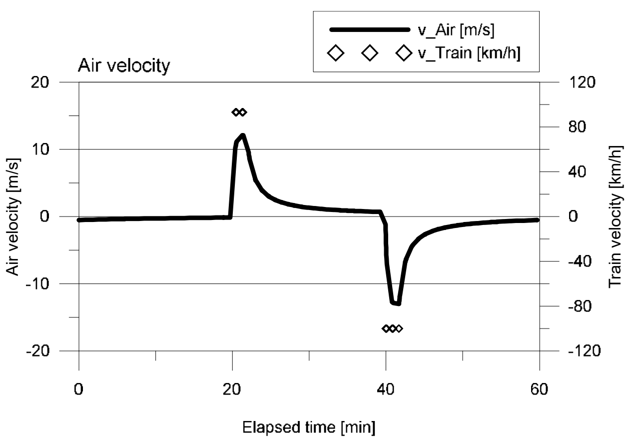

Figure 4 Longitudinal air velocity in a rail tunnel with two trains circulating subsequently in opposite directions (single-track tunnel, length 3’009 m, longitudinal slope 0.92%, cross section 36.9 m^2, train speed 100 km/h)

2.4. Smoke Propagation

A fundamental parameter impacting fire ventilation is the critical velocity. Figure 5 illustrates the physics of smoke propagation with longitudinal ventilation (in this case from left to right). At low ventilation velocity, significant backlayering is observed. This is reduced with increasing velocity. Backlayering entirely disappears (by definition) once the critical velocity is reached. Thus, the critical velocity is the key parameter for smoke management and is the most common design criterion for longitudinal ventilations.

A related concept is smoke stratification. At low velocities, up to 2-3 m/s, smoke is observed to propagate along the upper part of the tunnel cross section. This is perfect stratification. With higher air velocities, or as soon as vehicles drive through or jet fans are activated close to the smoke, stratification rapidly disappears. It is usually safe to assume, that stratification is lost if a longitudinal ventilation is operated around the critical velocity, as qualitatively illustrated on the right-hand side of Figure 5. This represents a fundamental conflict while using longitudinal ventilation with bidirectional traffic or in case of traffic congestion.

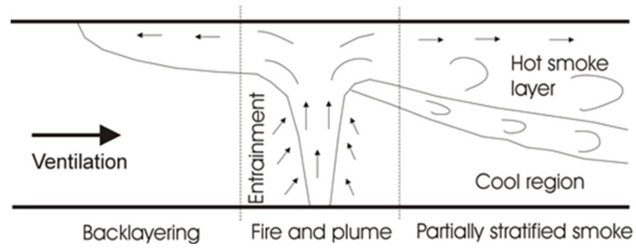

Figure 5 Principles of smoke propagation with longitudinal ventilation

3. COMPREHENSIVE SIMULATION OF FIRE SCENARIOS

3.1. 1D Simulation

One-dimensional (1D) simulation is a very powerful tool for the comprehensive simulation of fire scenarios in both rail and road tunnels. Beyer (2018) carried out a detailed validation of 1D approaches based on detailed measurements carried out in existing road tunnels. This investigation confirmed the capability and power of 1D simulation for tunnel aerodynamics and ventilation.

The 1D approach shall be illustrated based on the Autor’s own simulation tool, TunSim (Bettelini 2008, 2011, Bettelini et al. 2002, 2013, 2018). This tool was used for investigating hundreds of tunnels of all types over the last two decades. TunSim consists of the following modules:

- Tunnel module, for defining in full detail all relevant geometric characteristics of the tunnel system considered
- Road-traffic module, for defining the relevant traffic scenarios, including speed and composition
- Rail module, for defining characteristics and time schedule for all trains considered
- Fire module, which allows defining fire development according to the specific scenario considered
- Ventilation module, for defining in full detail the characteristics of the ventilation system and its operation during a fire scenario
- Control module, with a variety of open-loop and closed-loop control schemes, with the capability of simulating sensor signals e.g. from anemometers
- Self-rescue module, for analyzing the self-rescue process based on the location of emergency exits, passenger characteristics and strategy.

These are the ingredients needed for modeling in a very flexible manner all possible fire scenarios in road and rail tunnels. The capabilities of 1D tools shall be illustrated in the next section.

3.2. Illustrative Example – The Via Mala Tunnel

The simulation of a fire scenario in the Via Mala tunnel shall be presented as an illustrative example. This is based on the tragic fire which occurred in this tunnel in 2006, causing 9 victims.

The Via Mala is an Alpine tunnel located in Eastern Switzerland. Its main characteristics are:

- Single tube with bidirectional traffic on two lanes
- 8’000 vehicles/day
- 760 m length, 5% slope
- No emergency exits at the time of the fire
- Longitudinal ventilation with jet fans

The following fire scenario is presented:

- Fire located 200 m from the lower portal
- What-release rate 30 MW, developing in 5 min
- Traffic 600 veh/h per lane, 60 km/h
- No barometric pressure difference or external wind

On the time axis, fire ignition occurs at time 0, detection at 60 s, tunnel closure at 90 s. In this example, longitudinal ventilation is not activated.

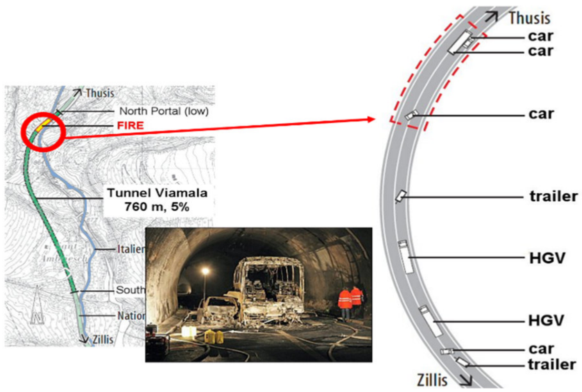

Figure 6 The fire in the Via Mala tunnel (the fire occurred arguably at the worst-possible location, about 200 m from the lower portal (north))

Typical simulation results are illustrated in Figure 7 to Figure 10:

- Figure 7 illustrates the evolution of longitudinal air velocity and smoke propagation. Note that active, thermally driven propagation of the smoke fronts is accounted for.
- Figure 8 illustrates the position of the vehicles in the tunnel.
- Figure 9 illustrates the behavior of the persons in the tunnel.
- Figure 10 illustrates the global outcome of the scenario considered, in terms of successful self-rescue or loss of live. For the victims, the initial and final position is illustrated, for a better understanding of the causes.

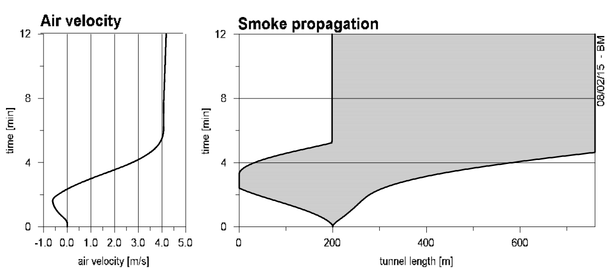

Figure 7 Longitudinal air velocity (left) and smoke propagation

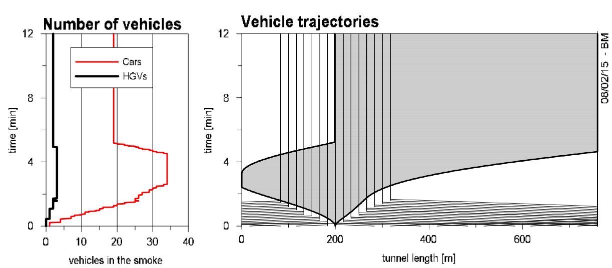

Figure 8 Number of vehicles trapped in the smoke (left) and vehicle trajectories

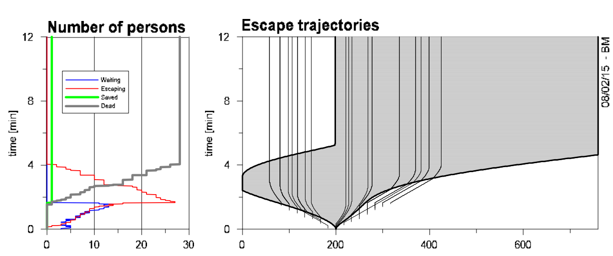

Figure 9 Cumulative number of persons waiting, escaping, in safety of perished (left) and escape trajectories of persons

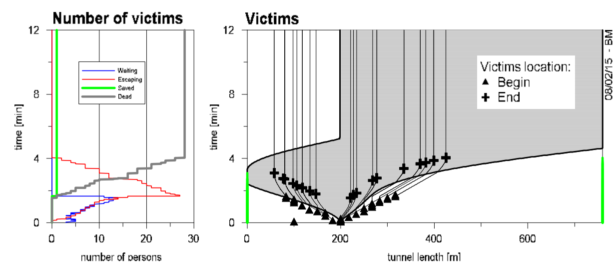

Figure 10 Cumulative number of persons waiting, escaping, in safety of perished (left), escape trajectories of persons during self-rescue, initial and final location of the victims

This and many other simulations confirm the extreme difficulty of finding a viable ventilation strategy for the Via Mala tunnel. For this reason, it was decided realizing a safety tunnel with closely spaced emergency exits. This represents the best-possible option for providing a realistic self-rescue chance in case of fire.

3.3. 3D Simulation

Three-dimensional (3D) simulation is a powerful tool for detailed investigations of fire development and smoke propagation. The simulations generally focus on smoke stratification, visibility conditions, thermal and radiative load on escaping persons etc.

A high price must be paid for these additional details, in terms of lack of consistent modelling of several relevant phenomena and long simulation times. Traffic can generally not be properly included, details of the ventilation system are represented in a highly simplified manner, and only part of the tunnel system is modelled. This globally makes 3D simulation not a viable option for assessing dynamic tunnel behavior and tackling optimum ventilation control.

4. REQUIREMENTS FOR EMERGENCY VENTILATION

4.1. General Requirements

The most fundamental requirements on fire ventilation are:

- Protect the users and support self-rescue in such a way, that all tunnel occupants can reach a protected area.
- Support intervention by means of an appropriate smoke-management strategy.

Ventilation control can be fully automatic, semi-automatic (whenever the operator operates a selection among several pre-defined scenarios, which then run automatically) or manual. The general process of ventilation control is illustrated in Figure 11.

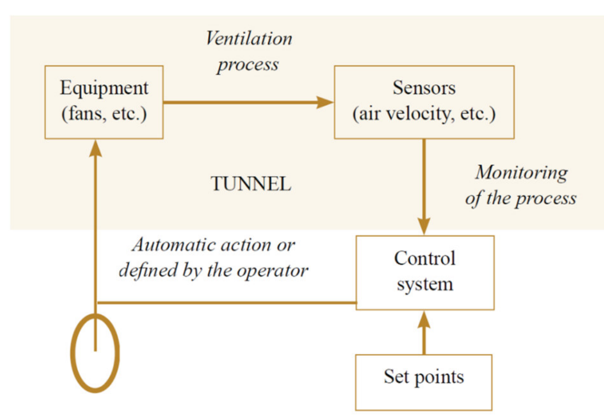

Figure 11 Overview of the tunnel ventilation control loop (PIARC 2011)

The time scales for the two main ventilation phases, self-rescue and intervention, are widely different. Self-rescue takes place within the very first minutes after fire onset. Here fully automatic procedures are generally recommended, for reducing the risk of fatal mistakes by the responsible staff in the control room. Ventilation strategies during intervention are frequently based on imposing the critical velocity, protecting the first responders from smoke.

An excellent review of fire-ventilation control and all related issues is found in Maevski (2017).

4.2. Ventilation Strategies for Road Tunnels

This important topic is addressed in several sources, including AIPCR/PIARC (2011). We will provide here only a short overview of the key aspects, starting with the most delicate case, longitudinal ventilation.

In case of unidirectional fluid traffic, the accepted ventilation strategy is ventilating with the critical velocity in traffic direction. The implementation details can vary from activating all jet fans available without control (the Author's recommended solution, for reasons of system robustness) to active regulation to a sufficiently high velocity. Ventilation control in this case is generally straightforward.

Unidirectional traffic with congestion and bidirectional traffic are significantly more challenging. The preferred strategy is generally ventilation with a low velocity (1.0 to 1.5 m/s) in the direction of the original traffic or airflow. This strategy is never entirely satisfactory. There are schools (e.g., Nakahori et al. 2015) promoting the alternative of "zero velocity". Here the control algorithm minimizes the longitudinal air velocity in the tunnel. The case for zero-flow control in case of fire was made in a quite convincing manner by Kohl et al. (2017) based on quantitative risk analysis (Figure 12) applied to a representative spectrum of tunnels. The "zero-flow" strategy was non consistently better but showed globally a better level of risk reduction. However, this strategy is not always satisfactory.

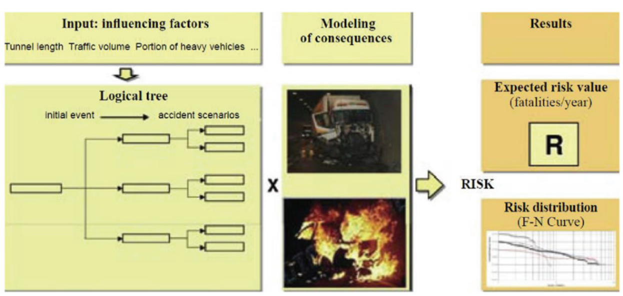

Figure 12 System-based approach to risk analysis as used in Austria

Other schools of thought prefer to use the critical ventilation for unidirectional tunnels also in case of congestion. This is clearly dangerous and should be avoided. Not activating the mechanical ventilation in case of doubts is sometimes an excellent option, e.g. in the case of tunnels with small slope.

The strategies in case of concentrated smoke extraction are generally straightforward, as long as a sufficient smoke-extraction rate is available. In case of bidirectional traffic or congestion, a symmetric extraction, with symmetric flow towards the extraction tone from both sides, is the accepted strategy. In case of unidirectional fluid traffic, the air velocity upstream of the fire can be increased up to the critical velocity, provided that there is a vanishing or negative velocity downstream of the fire. This ensures an adequate control of smoke propagation while fully protecting the users upstream of the fire.

4.3. Ventilation Strategies for Rail Tunnels

The issues relevant for road tunnels are in principle encountered also in rail tunnels. The important difference is that fire location on the train should also be accounted for, if known. A further complication relates to the presence of crossing trains in double-track tunnels. Train crossing is generally not allowable in case of developed fires and for trains to leave backwards the fire tunnel is only in special cases a viable option. If the information on train location or on fire location on a passenger train is missing, which is very frequently the case in real life, it is difficult even selecting a ventilation direction. The issues are further complicated in case of mixed traffic, passengers and goods. Solutions are available but are far from being generally applicable. An example is the tight integration of train and ventilation control systems to achieve high service frequency while maintaining passenger safety (Duckham et al. 2017).

Summing up the different issues, the conditions required for optimum ventilation in rail systems are seldomly met and compromises are always required. The key reason is lack of information and the very high requirements on robustness. Under such conditions, solutions based on moderate longitudinal air velocities, typically 1.0 to 1.5 m/s, are generally preferred.

The option of purely natural ventilation, for preventing smoke destratification, shall always be accounted for while designing a ventilation control system.

5. ISSUES AND SYSTEM REQUIREMENTS

This chapter shall discuss important issues related to optimum ventilation control and the related system requirements.

5.1. Control of Longitudinal Air Velocity

In case of longitudinal ventilation, strategies based on maintaining as much as possible smoke stratification are appropriate in several situations, for example:

- Road tunnels with bidirectional traffic
- Road tunnels with unidirectional traffic and high congestion frequency
- Rail and metro systems with fire in the middle of a composition and escaping persons on both sides of the fire.

Achieving a vanishing or moderate longitudinal air velocity of 1 to 1.5 m/s can represent a quite challenging issue under unfavorable conditions. Typical examples are:

- Short, steep road tunnels, where the "stack effect" due to the local temperature increase generated by the fire results in strong, rapidly changing airflows.
- Tunnels under meteorologic barriers, characterized by very high barometric pressure differences.
- Short tunnel exposed to string portal winds.
- Long rail and road tunnels, where the aerodynamic perturbations generated by vehicles leaving the tunnel decay very slowly.

Key objectives of emergency-ventilation control are:

- Achieving the target air velocity in short time, while minimizing oscillations.
- Rapid and reliable compensation of disturbances, arising e.g. from vehicle motion or "stack effects".

Appropriate control of longitudinal ventilation is also essential for systems with smoke extraction. This important issue tended to be neglected or underestimated in the past, where at times no proper means for controlling air velocity were installed in tunnels with transverse or semi-transverse ventilation. We now know that a proper control of longitudinal air velocity is an essential requirement for optimum smoke extraction. As discussed in Section 4.2, the best suited strategy depends primarily on traffic conditions. Systems with powerful smoke extraction are generally robust and uncritical in terms of control of longitudinal air velocity. In case of comparatively small smoke-extraction rates, proper control becomes a demanding issue.

In earlier years, control of longitudinal air velocity was generally carried out by means of simple routines based on discontinuous multi-point controllers for different fire conditions. Simple closed-loop control systems offer several advantages and are generally the preferred solution in new tunnels. The most common option is the PI(D) controller. With this system, the system's behavior is basically controlled by the proportional component ("P") while the integral component ("I") ensures that the systematic error characterizing P-type controls is compensated. The use of a derivative component ("D") is not common in tunnels since it could lead to disturbances and oscillatory behavior. A comprehensive experimental investigation of ventilation control systems at commissioning stage was carried out by Schmölzer (2016). The investigations have shown that a PI controller in parallel with an adequate anti-windup should be used and delivered detailed recommendations on parametrization, calibration and validation at commissioning stage.

More complex control systems, such as Model Predictive Control (MPC), are used sporadically but do not represent a standard. Altenburger et al. (2013) compared MPC with standard PI and PID controllers. They could show that MPC is faster than all other examined controllers, but it is also complex, with a large number of parameters to be defined. The availability of simulation-software is limited. The authors concluded recommending the use of a standard PI controller.

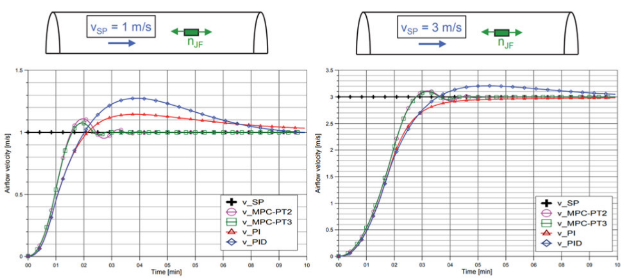

Figure 13 Comparison MPC, PI and PID controller for a 4.2 km tunnel (Altenburger et al., 2013)

A very successful application of complex control systems is based on the research carried out by Prof. A. Vardy and coworkers at the University of Dundee and at Dundee Tunnel Research. This powerful approach, called MPVC (Model-Based Predictive Ventilation Control) is based on a model-based prediction of the conditions to be expected in the tunnel. The prediction is based on the current state of ventilation, airflow and pollution in the tunnel and (in normal operating conditions) the expected traffic for the next control interval. Based on this, comparison of viable ventilation strategies is carried out for assessing the best possible ventilation strategy. MPVC was applied in several tunnels in Japan (e.g. Nomura et al. 2009, Nakahori et al. 2010, Azuma et al., 2011) with great success. This approach allowed among others significant energy savings with pollution control in normal operating conditions.

It should be finally pointed out, that one key of successful regulation in both normal operation and in case of fire is the availability of adequate power reserves, which allow for rapid flow control.

5.2. Fan Control and Frequency Converters

In most cases, longitudinal air velocity in road and rail tunnels is controlled by means of jet fans. Saccardo nozzles represent a viable alternative but are used much less frequently and their application is generally limited to tunnel renovation. Full flexibility in flow control with jet fans is achieved using frequency converters. Some countries tend to avoid frequency converters whenever, for reasons of system's robustness and durability. A particularly effective approach to longitudinal ventilation with variable-frequency jet fans was developed by Nakahori et al. (2010 and 2015).

5.3. Ventilation Sensors

5.3.1. Flow Measurement

Closed-loop control is commonly used in traffic infrastructures. The control procedure acts on the difference between the measured air velocity and the target velocity. The accuracy and reliability of the anemometers installed in a tunnel are fundamental. The key requirements are accuracy, adequate time responses and plausibility verification. The latter require the continuous availability of at least 3 measurements carried out outside the smoke-filled zone. A very well-established strategy applied e.g. in Switzerland (FEDRO 2021), is based on several measures carried out using clustered anemometers. Each cluster consists of 3 independent anemometers, which can be used for generating a point velocity measurement with full plausibility check. FEDRO 2021 requires 2 clusters for each ventilation sector and, additionally, 2 clusters for each smoke-extraction sector longer than 1500 m, as shown in Figure 14. A procedure for plausibility verification is outlined in RVS 09.02.31.

Several types of anemometers could be used. Excellent results can be achieved with ultrasonic point or line anemometers. A good calibration at commissioning is required for achieving an adequate level of accuracy.

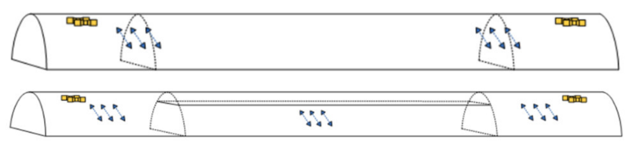

Figure 14 Installation of anemometers in Swiss road tunnels, with longitudinal ventilation (top) and smoke extraction (bottom)

5.3.2. Fire and Smoke Detection

Fire detection is the key for rapid system response. Locally accurate detection is particularly important for systems with smoke extraction.

Linear thermal detectors represent the most widespread technology in road tunnel. This is frequently supported by visual detection using CCTV. Optical smoke detection generally allows for more rapid fire detection. The drawback is that accurate fire localization can be extremely difficult and prone to uncertainty. Smoke detection also plays an important role for preventing the activation of jet fans in zones with stratified smoke. This is essential for reducing the risk of smoke destratification.

This important topic shall not be investigated in further detail herein.

5.4. Congestion Detection in Road Tunnels

The ventilation strategy in case of tunnel with unidirectional traffic depends on the initial traffic patterns, as discussed in section 4.2. The impact of congestion on ventilation control is very important in particular in case of longitudinal ventilations.

The technical options for congestion detection in road tunnels are mainly:

- Induction loops in the pavement
- CCTV
- Rotating radar
- Point sensors over the lanes

A large-scale investigation carried out in the tunnels of Zurich's Northern Ring Road was documented by Bettelini and Rigert (2018). They could show, that rotating radar and CCTV achieved similar, excellent results. CCTV generally shows weaknesses at the portals, because of the unfavorable light conditions, while radar-based systems tend to be more delicate from the point of view of installation and calibration and commissioning.

It should in any case be pointed out, that congestion detection is a key requirement for optimum ventilation control. Experience shows that this issue is frequently neglected or underestimated.

6. CONCLUSION AND OUTLOOK

The selection of the best-suited ventilation strategy in a given tunnel depends on many individual factors, such a tunnel and traffic characteristics. Robust design requires that the ventilation performs properly in a range of variable conditions and influencing factors, which are only partially known or controllable. Possible ventilation strategies should be tested for a wide spectrum of conditions and scenarios at design stage. As shown by the illustrative example presented in chapter 2, several ventilation scenarios are too complex and cannot be properly established based on common sense or intuition.

Optimum ventilation control in underground traffic infrastructures requires a proper management of several intrinsically time-dependent phenomena, such as vehicle motion and fire development. Moreover, several important governing parameters, such as barometric pressure difference or wind, are generally unknown. The comprehensive simulation of fire scenarios is therefore an essential component of optimum ventilation design.

Ventilation control for state-of-the-art road and tunnels tends to be complex. The number of predesigned, automatic or semiautomatic scenarios is large and complex. While perfectly reasonable from a functional point of view, this tends to result in difficulties of understanding by tunnel operators and first responders. Moreover, several scenarios are so complex, that no possible validation without comprehensive simulation is possible.

Figure 15 Who is in control? (Vardy 2021)

Comprehensive fire simulation can significantly contribute improving the overall ventilation strategy and the quality of the individual ventilation scenarios. Most important, it can contribute improving the understanding of the scenarios and identifying the range of conditions suited for automatic ventilation control.

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