Flow Control in Tunnels

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ABSTRACT

Most fatalities in tunnel fires are caused by the spread of toxic smoke. Controlling the spread of smoke is crucial to provide a survivable environment for emergency egress. A properly designed and tuned feedback control loop is required to achieve a target flow that is slow enough to allow pedestrians to escape under different boundary conditions. Feedback control loops are also helpful in optimizing energy consumption under moving traffic conditions. A reliable feedback flow control system requires sophisticated engineering know-how and experience, careful selection of instruments and controlled variables, and thoughtful implementation from design through field testing and commissioning.

GENERAL ASPECTS

In road and rail tunnels, most of the time there is a longitudinal airflow, generated by the piston effect of moving traffic and meteorological conditions such as wind and buoyancy. This is called natural ventilation.

Mechanical ventilation systems are required when tenable conditions cannot be achieved in the tunnel through natural ventilation alone. Influencing factors may include temperature limits for the operation of train engines and A/C units in rail tunnels or admissible concentrations of emissions in and around road tunnels. In the case of a tunnel fire, controlling the spread of smoke is essential to enable people to escape, identify the incident's location and provide access to emergency services.

Requirements for tenable conditions in critical situations define the design scenarios that lead to the determination of the airflows a ventilation system needs to provide. A mechanical ventilation system is usually designed to dilute pollutants or heat emitted by vehicles, or control smoke movement, considering defined adverse boundary conditions. This is often called the 'worst case' scenario, a term that is misleading.

It is essential to understand the difference between design and operation. In reality, boundary conditions always differ from design assumptions. The boundary conditions actually experienced are typically better than the 'worst case' design scenario, but they could also be worse – hopefully, a very low probability.

The easiest and most often practiced way to operate a ventilation system is to simply switch it on to the operating modes defined by the design, without considering the real boundary conditions. In fact, there are many ventilation systems where airflow is not even measured. In such cases, the tunnel will be overventilated when the boundary conditions are better than the 'worst' design case, which by definition will be almost always.

Overventilation in normal operating conditions increases energy consumption, considering the drive power of a fan increases with the third power of the flow velocity. During a tunnel fire, overventilation may accelerate the spread of smoke, fan the fire and deteriorate escape conditions. In fact, most fatalities in tunnel fires are caused by the spread of toxic smoke resulting from overventilation.

To avoid overventilation, the airflow must be controlled based on feedback from measured flow velocity. This paper focuses on the practical aspects of how this flow control can be achieved.

FIRE VENTILATION

Fire ventilation is often understood as simply driving the smoke away from a fire's 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. Applicable standards in the US, namely NFPA 130 (for rail) and NFPA 502 (for road) tunnels, focus on forced smoke spread towards one side without back layering. However, according to NFPA 502 chapter 11.2.4, preventing back layering only applies to tunnels with unidirectional traffic where motorists are likely to be located upstream of the fire site. That only works when there are no people downstream, for instance fires at tunnel portals or rural unidirectional highway tunnels with little traffic, but a residual risk always remains. According to NFPA 502 chapter 11.2.3, where motorists can be on both sides of the fire site, longitudinal air velocity shall be kept at low magnitudes.

Source: Authors archive

Figure 1. Back layering of smoke at controlled flow conditions

In practice, that applies to most road tunnels with unidirectional traffic, especially in urban areas. In rail tunnels, there is always the likelihood that patrons may be situated on both sides of an on-train fire. Given the narrow space around a train carriage, that imposes a safety problem in principle.

Unfortunately, in the NFPA standards there is no definition of what 'low magnitudes' means, and boundary conditions are not specified. In contrast, most European road tunnel ventilation standards focus on target in-tunnel flow velocities under defined boundary conditions such as wind, buoyancy, barometric pressure difference and fire effects. European rail standards follow rather a risk-oriented approach.

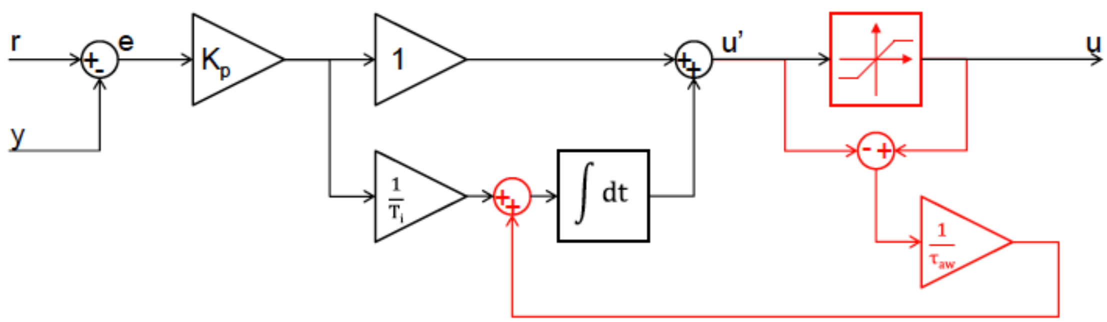
As self-rescue has to be instigated quickly following the occurrence of an incident, it is essential to achieve the desired state of flow with minimal delay. NFPA standard 502 requires that the emergency ventilation system shall be capable of reaching full operational mode within a maximum of 180 seconds of activation. However, the system operational mode does not directly refer to the conditions in the tunnel, especially for impulse fans.

The desired in-tunnel flow velocity may depend on the specific situation. For instance, according to the Austrian and Slovak guidelines, when people are assumed to be situated on both sides of a fire, the target value is approx. 1 – 1.5 m/s. For tunnels with a lower probability of people being blocked downstream, the target value is around approx. 1.5 – 2 m/s, still lower than the critical velocity. Most importantly, the target value must be achieved within a short time frame following the fire alarm sounding. In the Slovak guidelines, the allowable delay is 120 seconds. That value has been derived feasible for existing tunnel ventilation systems in Switzerland and Slovakia. This goal cannot be achieved without sophisticated flow control.

Such requirements have a direct consequence for the design process. The ventilation system must not be designed simply for a steady state, but on the basis of dynamic simulations for many different scenarios, taking into account the inertia of the moving air, wind fluctuations, traffic movement and assumptions on fire dynamics and smoke buoyancy. For that, realistic controllers, as implemented in the ventilation programmable logical control (PLC), must be simulated with an appropriate design software tool.

FEEDBACK CONTROL

The closed-loop feedback control, based on precise and reliable flow measurement and sophisticated control algorithms, has become the proven standard in most European tunnel ventilation systems, regardless of whether the ventilation system is purely longitudinal or with a concentrated exhaust. Basic principles of flow control are described in Swiss investigation reports (Pospisil et al. 2010, Altenburger et al. 2013).



Source: Altenburger et al. 2013

Figure 2. Controller schematic

To successfully implement reliable flow control in a tunnel is a challenging task. Precise, reliable flow measurement in the tunnel is very important. Unfortunately, flow measurement within a large tunnel cross section is neither precise nor reliable. Local effects may also superimpose vortices on the directional flow and moving traffic can generate strong fluctuations.

For most tunnel applications, ultrasonic anemometers, measuring in a line over the tunnel cross section, have been established as the standard to measure airflow. However, to allow for a plausibility check, at least three independent instruments in different cross sections are required to take into account varying local flow conditions. Such may be caused for instance by tunnel geometry, or standing vehicles. Adequate positioning of the anemometers should include avoiding disturbances from portals, branches, obstacles and operating impulse fans. Calibration of anemometers using a precise reference measurement is essential. From that, calibration factors are derived that take into account local geometrical conditions.

Source: Authors archive

Figure 3. Cross ultrasonic line measurement for calibration of anemometers

EXPERIENCE FROM EUROPE

One of the first projects to use a reliably functioning closed-loop flow control system in a road tunnel was the 1.2km long, longitudinally ventilated, Balmenraintunnel in Switzerland (2003). The number of jet fans to be switched on (or off), depends on the actual measured in-tunnel flow and is determined by matrices based on previous tunnel model calculations. This represented a primitive form of Model-based Predictive Control (MPC).

$$F_{solll} = \begin{pmatrix} F_{istW} + F_{istO} + (C_E + C_{RF} \cdot x_W) \cdot (C_{TA}^2 \cdot Q_A^2 - u_W^2) - (C_E + C_{RF} \cdot x_O) \cdot (C_{TA}^2 \cdot Q_A^2 - u_O^2) + (u_W^2 - u_O^2) + \dots \\ \dots + C_D \cdot \frac{C_{TL}}{\Delta t} \cdot \left(C_{TA} - 2 \cdot u_W(t) + u_W(t - \Delta t)\right) \end{pmatrix}$$

Source: Pospisil 2020

Figure 4. Simple model of thrust determination

Subsequently, tunnels with concentrated exhaust and superimposed flow control have been designed, commissioned and operated. The use of proportional-integral-derivative (PID) controllers have also become common as they are available as standardized software (SW) modules in industrial PLCs.

By simply switching single jet fans on and off, target conditions cannot be achieved rapidly enough, and often only very roughly. Successive switching operations may lead to fan failure due to the overheating of motors. This can be avoided by using Variable Frequency Drives (VFD), which also present advantages for the startup and reversal of motors. A continuous flow control using VFD, and PID-Controllers was implemented in the 2.5 km long Isla Bella tunnel on the A13 highway, in Switzerland, in 2008. During extensive testing, it was demonstrated that the desired state of flow could be achieved in less than two minutes from different initial conditions. Over the following decade, this became the state-of-the art standard for many European tunnel projects.

An integrated, decentralized flow control system with increased redundancy and system reliability was applied in the 1km long bidirectional Polana tunnel, in Slovakia, in 2017, and has been operating reliably since. A key component of such systems is a control unit, where the VFD, PLC with controller, switchgear and communication terminals are integrated in a housing (suitable for the highly corrosive tunnel environment) that can be installed close to the jet fans, such as in niches, cross passages or in the tunnel ceiling.

Source: Authors archive

Figure 5. Jet fans with in-tunnel control units

SITUATION IN THE US

Flow control has not generally been implemented in tunnel ventilation systems in the US yet. It requires three main elements:

- Modulation of fan output
- A means of measuring the process (or controlled variable)
- Equipment capable of performing closed loop control

In the process control systems found in wastewater treatment, for example, centrifugal multi-stage blowers are used to provide varying levels of oxygen to aeration basins. This is most commonly achieved with closed-loop control of pressure in a header that serves several aeration basins and closed-loop control of dissolved oxygen levels in the basins, which modulates an inlet valve to each basin. For header pressure control, the system has the required components:

- Modulation of fan output – achieved through modulation of an inlet damper
- A means of measuring the process (or controlled variable) – a pressure instrument on the header
- Equipment capable of performing closed loop control – a PLC

For in-tunnel fan applications within the United States, the most popular design is an open-loop configuration. However, two of the three components required to achieve flow control are typically installed and only a small addition is required to achieve closed-loop flow control.

- Modulation of fan output – Variable Frequency Drive
- A means of measuring the process (or controlled variable) – not usually present
- Closed loop control equipment – PLCs

In the name of robustness and simplicity, fans are selected to deliver the required flows at full speed and are started in emergency situations. As each fan is started, it is ramped up to operating speed using a variable frequency drive (VFD) or electronic soft start. Ramping is used primarily to cushion the electrical system, especially when fans are being powered by a local backup generator, as the additional load on the generator must be added gradually. Modern soft starters are generally comprised of power electronics (roughly equivalent to a VFD) with a full speed contactor allowing efficient and reliable full speed operation but are limited in terms of available torque. The VFD provides the means to start motors quickly from varying operational conditions, vary fan output and achieve flow control.

Measuring the controlled variable can be achieved in one of two ways. First, flow measurements after construction can be used to develop a flow curve based on fan speed for the completed tunnel. The programming then can be simplified to open loop control by programming the system to respond using the pre-determined operating curves. While this is crude, it is often used as a backup to more sophisticated systems that rely on an on-line instrument for operation that needs maintenance and periodic testing. This is very similar to what was previously described as being implemented in Europe.

Another method for measuring flow is to install a flow metering system. Several types of tunnel flow monitors are now available. One example uses multi-path transit time measurement. This technique has been used in large pipe and large air flow monitoring applications for over 30 years and is well developed, stable, and has a known reliability. Any instrumentation is only as good as the program carried out by the system owner to maintain and periodically test the equipment. Unlike large wastewater treatment facilities, transportation authorities and tunnel operators do not typically have instrumentation and control technicians on staff.

Evolution of the systems used for firefighting such as water, communications, intelligent traffic systems, and other tunnel systems will eventually require this type of person on staff, making instrumentation of this type more practical.

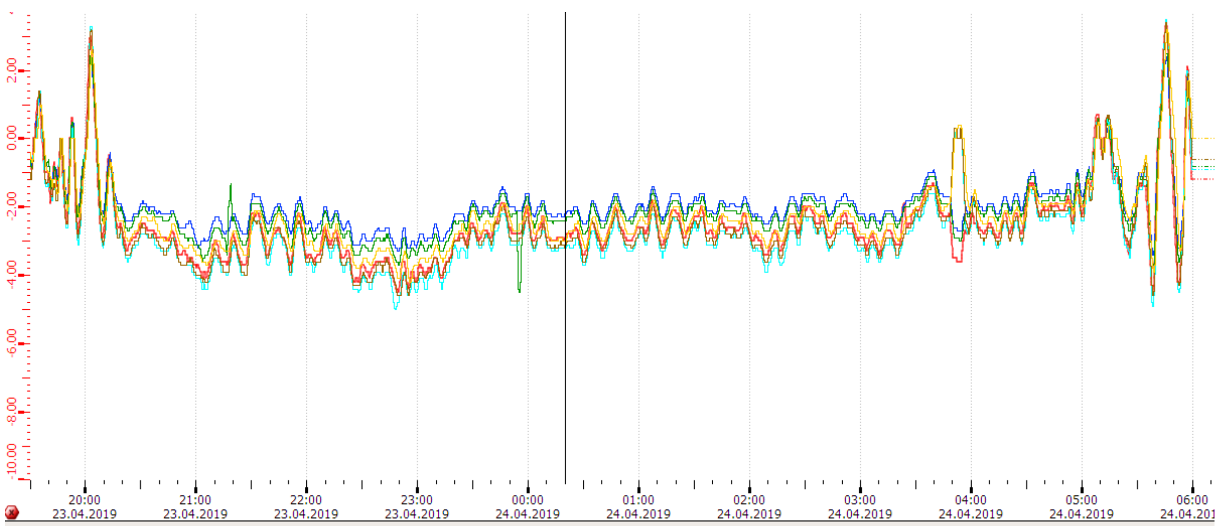
In modern tunnel construction there are many systems to be monitored and controlled. A Supervisory Control and Data Acquisition system (SCADA system) is usually installed on new projects providing several functions: integrated operator's computer control station, remote control and visualization of controls and equipment status, off-hours alarm monitoring and delivery to off-site operations staff, and automation of systems including fire pumps and fire suppression foam additive systems.

The SCADA system is comprised of several PLCs located strategically in the tunnel and in equipment rooms to provide automation and control. PLCs are used in the process control industry for sophisticated closed-loop control of many types of industrial processes. PLCs include factory standard algorithms for open-loop and closed-loop control and are highly programmable. Backup scenarios and control modes can be programmed in PLCs allowing automatic shifting to open-loop modes if the process variable monitoring equipment goes offline or out of range. This equipment is well suited to achieving closed loop control for tunnel ventilation systems and is already considered included in new tunnel designs.

PRACTICAL ASPECTS

A flow control system does have some disadvantages. A common problem is Electromagnetic Compatibility (EMC) issues, due to long shielded cables between VFDs and Fans. Reliability of VFDs, error proneness of a centralized control and SCADA system, and communication lines are other aspects that must be considered.

In order to be able to precisely regulate the jet fans and central fans (depending on the tunnel's length and shape), reliable measurements are required, as described above. These measurements must be used to transfer the flow speed and direction to the controls.



Source: Pospisil 2020 / canton Uri highway administration

Figure 6. Measured longitudinal in-tunnel flow velocities

In addition, smoke detectors / visibility measurements are installed in many European tunnels at short regular intervals. These detect smoke emitted by burning vehicles within the tunnel. Moving burning objects can also be detected, including changes in direction, and the tunnel ventilation can react accordingly.

Signal error of flow measurements may impose a key problem for flow control. Usually, the sensors in the tunnel are connected to decentralized PLCs, which may be installed in a service tunnel or technical room. These controllers must be linked together in a communication ring. It is important that the control intelligence is also as decentral as possible so that a failure of a subsystem does not have a negative effect on the entire tunnel. This means the tunnel should be divided into control sectors with each sector responsible for its part. Sensors and actuators from one sector must also be connected to the assigned controller and the software logic must be programmed for autonomous operation.

Of course, there is a higher-level data exchange between the controllers, as fallback levels can be established if sensors fail. The assigned sensors of a sector are continuously monitored for plausibility by the assigned controller. If a sensor delivers measured values that are outside the logical and expected values, the measured values of the other instruments connected to the sector are automatically compared. If these are OK, these values are automatically used as a measured variable and an alarm is sent to the maintenance service. If these values are also incorrect or not available, the network connection can be used to temporarily adopt the values from adjacent sectors in front or behind as a fallback level.

Today’s controls, including intelligently developed software, may even be able to use assumptions based on past measurement values as the last fallback level in the event of a total failure of all sensors (artificial intelligence). However, this should be seen as a last resort, as the conditions in the tunnel can change very quickly. A total failure up to the last fallback level is almost impossible with the control design described above. A data connection via the fiber optic cables is also required for the control of central actuators such as higher-level exhaust fans and dampers, as well as for the connection to the central SCADA system, which monitors the entire tunnel, records data and sends alarms to the maintenance service.

Source: Authors archive

Figure 7. Screenshot of highway tunnel ventilation operation display on SCADA

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 functionality of the flow control. Even when the complete communication fails, a reduced autonomous operation is guaranteed as long as the power supply works.

The basic problem of flow control, compared to simple switching, is that increasing complexity leads to more possible failures and therefore additional expenses for implementation and testing. In this respect, the integrated control system has a big advantage: It can be preassembled and tested before installation in the tunnel. The flow control can be checked in advance and optimized by the application of a ‘Hardware in the Loop’ Tunnel Simulator via an OPC interface to the PLC. In this way, precious time and cost for implementation, commissioning and testing in the tunnel can be saved.

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 sensors (e.g. smoke detectors), and a redundant communication ring that connects all the components and provides the interface to the SCADA system and the fire alarm system.

High redundancy of critical elements, quality control at all stages of implementation and thorough testing on site under different conditions are key to achieving reliable operational safety.

FUTURE DEVELOPMENT

The performance of standardized PID controllers is limited, especially for complex systems where energy saving during normal operating conditions is the primary goal. The use of fully programmable PLCs or MPC controllers should allow such solutions in the future. Controller programming and tuning can be directly derived from aerodynamic models that have been used for the design.

Deployment of tunnel ventilation closed-loop control using PLCs will make standardized approaches and even programming available to be used elsewhere making this approach simpler and less difficult to implement.

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