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Tunnel ventilation in practice – Insights from testing

P. Pospisil[1], L. Ilg[2]

[1]*tunnelventilation.Pro, Münchenstein, Switzerland*

[2]*tunnelventilation.Pro, Horgen, Switzerland*

ABSTRACT: Ventilation is one of the most important systems that enhances the safety of a tunnel. Most ventilation systems are designed in first order for the emergency case, i.e. the fire ventilation, and many are hardly ever used in normal operation. Only by rigorous testing, the practical functionality of equipment and the whole system can be proven. Besides the usual factory and site acceptance tests of equipment, the focus is on the proper control algorithms and integral functionality of the whole system. The control of the longitudinal airflow is essential to confine the spread of smoke. Realistic smoke tests prove the proper function of the automatic smoke detection and show the performance of the fire ventilation. Practical experience from those tests leads to findings that should be considered in the concept and design process. This is particularly important where requirements in actual design guidelines were based mostly on mere theoretical considerations. In this article, the safety goals, testing procedures and findings are presented on examples for different tunnel types: long alpine tunnels with bidirectional traffic and a short two-tube city tunnel with unidirectional traffic.

1 Introduction

Tunnel ventilation systems serve to improve the safety of the tunnel users. In first order, they can ensure a sufficient visibility in the tunnel for safe traffic, and prevent concentrations of noxious gases from reaching critical values. However, the natural ventilation, mainly caused by the piston effect of the vehicles and by meteorological forces, is sufficient to ventilate most road tunnels. Therefore, the majority of ventilation systems is designed and used mainly to control the smoke movement in case of a tunnel fire.

Since tunnel fires fortunately are not frequent, the ventilation system will be used only occasionally or even not at all. If systems are not tested regularly and thoroughly there is a good chance that they will not work properly when they are needed. Without a clear definition of safety goals and rigorous testing procedures to prove that those goals are achieved, the usefulness of the whole fire ventilation system must be questioned. The effect of improper fire ventilation systems was tragically visible on the tunnel fires in 1999 and 2001.

Equipment performance tests in factories and on site are important means of quality assurance. However, they do not prove that the ventilation system works, just that the equipment meets the design criteria. The ventilation systems for the tunnel and for the escape routes are embedded in a complex system of incident detection, other safety equipment and control systems.

2 Safety goals and acceptance criteria

The safety goals for the fire ventilation system are in first order supporting the escape of tunnel users and in second order supporting the emergency services, i.e. the fire brigade, to access the incident site. Those safety goals lead to the following requirements for the fire ventilation systems:

- Control and confine the spread of smoke.
- Inhibit the spread of smoke to the escape routes.

Guidelines usually provide design requirements for steady states. In practice, the dynamic process of an incident has to be considered. Testing procedures and acceptance criteria should be defined to answer the following questions:

- The design case for the fire ventilation is usually a hot fire (e.g. a burning truck with a heat release rate of 30 MW as in the Swiss guideline ASTRA 13 001). How can the functionality of the fire ventilation for the design case be proven taking into account that the tests are worked out at ambient temperature without heating up the air?
- What boundary conditions have to be taken into account (and eventually simulated) for the acceptance tests?
- Does the automatic fire / smoke detection work reliably for different initial and boundary conditions?
- After detection of the fire and the start of fire ventilation procedures, how long does it take to achieve the required state (according to the design criteria) for different initial and boundary conditions?
- How long does it take to stabilize the airflow in the tunnel?
- For systems with smoke extraction, how long does it take for the smoke (which has spread previously along the tunnel) to be confided within the extraction zone?
- Is the smoke confinement sufficient to guarantee for the safety of affected tunnel users?
- Can the escape doors be opened under all conditions?
- Does the smoke possibly spread into unaffected compartments (second tube, technical rooms etc.)
- What happens in case of failures of equipment or the power supply?

3 Integral tests

The proof of safety has to comprehend the complex system. The focus is on the proper control algorithms and integral functionality of the whole fire ventilation system, which includes detection and measuring instruments, ventilation equipment, the control system, power supply, and not to forget the man-machine-interfaces (MMI) and operators. Very important is also the traffic management system, since the traffic can be the strongest force acting on the airflow in the tunnel and therefore influences strongly the spread of smoke.

Because the control of longitudinal airflow is essential, a reliable and precise measurement of the air velocity in the tunnel must be ensured. For long tunnels, the air temperatures must be taken into account to calculate the mass flow, which is constant in tunnel segments with longitudinal flow. Anemometers must be calibrated, e.g. by applying a 5 x 5 point measuring grid as described in the standard ISO 5802.

Figure 1. Flow measuring grid in tunnel

Initial and developing boundary conditions, i.e. meteorological pressures and possibly the dynamic traffic behaviour have to be simulated independently from the tunnel ventilation system. This can practically very well be achieved by using mobile jet fans.

Figure 2. Mobile jet fan for simulations of meteorological pressures

Implementing a suitable testing program, many realistic and also critical scenarios are run through by varying the relevant parameters like fire location, initial and boundary conditions. All those scenarios can be simulated and the air velocities recorded. By analysing the test data, the achievement of the goals can be assessed.

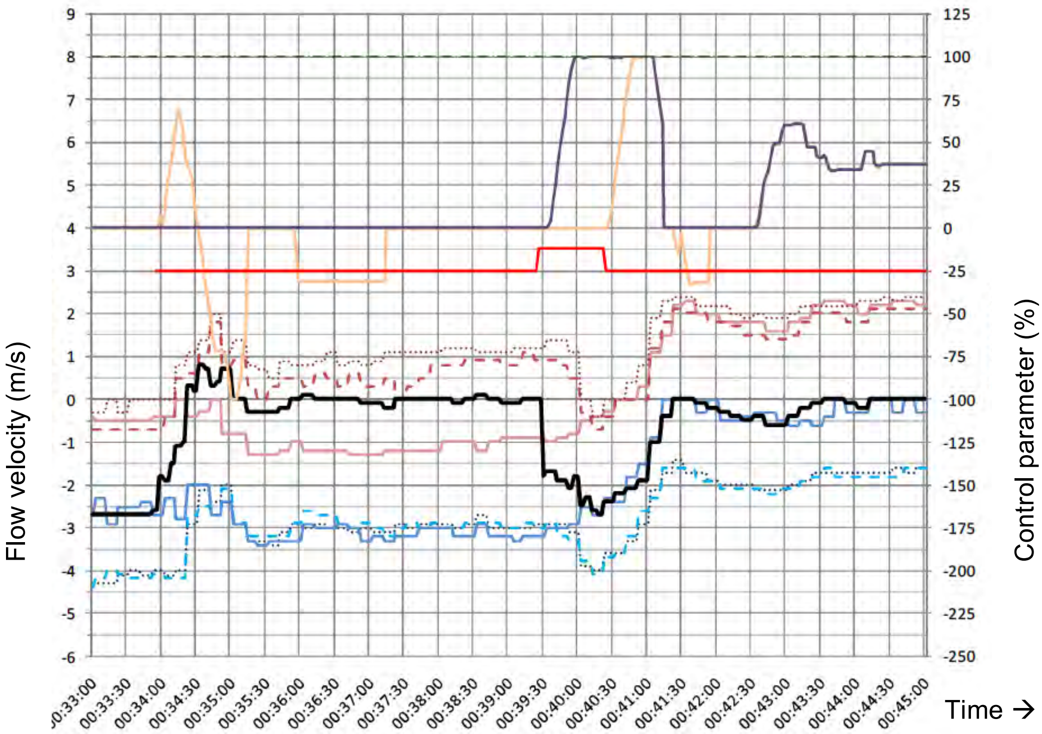

Figure 3. Example of a record of flow velocities and control parameters during a test

During testing, possible failures must be discovered and optimisations would be evaluated. If there are no faults, you have not tested thoroughly enough. Many tests must be repeated after troubleshooting and adjustments of parameters. For that, a sufficient time reserve has to be planned.

While the flow velocities and equipment data are usually monitored by the control system respectively the SCADA, some acceptance parameters have to be measured and recorded manually on site, e.g. the force that is required to open the escape doors while the fire ventilation is in operation.

4 Smoke tests

Smoke tests serve to prove the functionality of the automatic smoke detection, and demonstrate the efficiency of the fire ventilation for some specific scenarios.

The fire ventilation design case, which might be e.g. a 30 MW heat release rate fire, would damage the tunnel structure and equipment; therefore it is normally not feasible to arrange an acceptance test for the real design case. The fire and smoke behaviour should be simulated as realistic as possible but without negative impacts.

A suitable test smoke should feature the following characteristics:

- Its physical properties, particularly the optical density, should be similar to real vehicle fires,
- The heat release should be large enough to enable smoke stratification (under appropriate flow conditions), but not as large as to cause any damage to the equipment in the tunnel,
- The smoke must be harmless to human health, and should not leave any deposits on tunnel equipment (i.e. cameras and measuring instruments)
- The handling of testing equipment should be simple and fast. It should also allow for simulations of moving burning cars by a mobile smoke source.

Figure 4. Simulation of a moving burning car

5 Practical examples

5.1 Alpine tunnels with bidirectional traffic and smoke extraction system

As examples, we would like to present some test results from two similar tunnels in the Canton Graubünden in Switzerland. The Isla Bella tunnel on the A13 was opened in 1983 and refurbished with a new ventilation system until 2009. The Saaser tunnel was opened in 2011.

Both are approximately 2.5 km long with bidirectional traffic. They are equipped with modern tunnel ventilation systems, using exhaust fans in a portal station and a duct with controllable dampers for extraction and jet fans in the tunnel for the control of longitudinal airflow.

The Isla Bella tunnel has no escape ways besides the tunnel portals, whereas the Saaser tunnel is equipped with a parallel escape tunnel and cross passages in distances of approx. 230 m.

The airflow control in the Saaser tunnel uses a discrete controller with steps according to the number of jet fans operating at nominal speed. Such a control algorithm takes several minutes to establish the desired state of flow. It is standard in most modern Swiss tunnels with a smoke extraction, and fulfils its purpose.

The ventilation system of the Isla Bella tunnel is equipped with a state-of-the-art closed loop control of the longitudinal airflow, using a continuous controller and frequency converters for the supply of the jet fans. By that, the airflow in the tunnel can be adjusted to the desired state within approx. one minute from any initial and boundary conditions, even under traffic, and the fire ventilation achieves its maximum efficiency almost immediately after start-up.

This sophisticated airflow control in the tunnel Isla Bella can be seen as a compensation for the lack of escape routes. Its efficiency was proven in comprehensive integral tests (see Figure 3).

The smoke tests in the Isla Bella tunnel were accomplished after the implementation of smoke detectors in 2010. Valuable findings of those tests served to improve the algorithm for smoke detection, particularly for moving smoke sources. The performance of the fire ventilation was demonstrated in an impressive way.

Figure 5. Smoke test in the Isla Bella tunnel

In the Saaser tunnel, the smoke tests took place before tunnel opening in autumn 2011. They showed the robustness of the fire ventilation system, even when some minor failures of equipment occurred. Those were fixed immediately.

However, reality caught up the tests soon. In the first months after opening of the tunnel, three fire incidents occurred, with a burning car, bus and truck. In all cases, the fire ventilation worked satisfactorily as it was tested before. The fire fighters were able to control all the fires, and nobody was harmed.

The following conclusions and findings were derived from the smoke tests in the tunnels with smoke extraction:

- Smoke tests provide precious information for the optimisation of fire ventilation control algorithms and reveal hidden faults, which normally appear in any technical system
- By opening less exhaust dampers than originally designed, the smoke confinement is significantly improved, even when the exhausted volume is slightly reduced.
- Between two open dampers, the smoke is standing still and cannot be removed without changing the flow situation.
- The smoke confinement achieved by an extraction system is especially helpful for the access of fire fighters.
- The smoke may spread into the surroundings of the tunnel portals or the exhaust shaft and can affect the visibility on adjacent roads.
- Ambient air inlets must be equipped with smoke detectors to prevent smoke from being aspirated.
- With a continuous closed-loop control, the intended flow situation and by that the smoke confinement can be achieved much faster than with a discrete controller.

Figure 6. Smoke test in the Saaser tunnel

5.2 Short urban tunnel with unidirectional traffic

The Husovický tunnel in Brno (Czech republic) is presented as an example for a short urban tunnel with two tubes. The approx. 600 m long tunnel was opened in 1998, and its safety became a public issue after a tunnel fire with a casualty in 2008. In 2012, the ventilation system has been refurbished and the tunnel was equipped with additional cross passages as well as with new escape doors

In this case, the main purpose of the ventilation system is to prevent smoke entering the non-incident tube, which serves as escape route in case of a fire. Therefore, it must generate an overpressure at the cross passages as well as at the portals. In the incident tube, the ventilation must be able to push the smoke in traffic direction to prevent smoke endangering the blocked persons upstream of the fire site. That is the common fire ventilation philosophy for tunnels with unidirectional traffic.

Because the first cross passages are situated in distances of approx. 75 m from the portals, jet fan groups are placed directly at the portals.

The smoke tests demonstrated that the goals were achieved. Through all open cross passage doors, an airflow towards the incident tube prevented any smoke from spreading. Even when the jet fans at the portal in the non-incident tube were ingesting air directly from outside, no smoke could pass over.

Figure 7. Portal of the Husovický tunnel during smoke test

As an additional remark, it has to be pointed out that only by the proper operation of the tunnel ventilation in both tubes, the passing of smoke to the non-incident tube at the portal can be prevented.

Dividing walls between tunnel tubes do not inhibit spread of smoke to the non-incident tube under all circumstances. This was demonstrated e.g. in an earlier smoke test in a Swiss highway tunnel.

Figure 8. Spread of smoke over a dividing wall between tunnel tubes

6 Conclusion

Fire ventilation is the design case for most tunnel ventilation systems.

Testing of equipment and control systems is crucial for tunnel safety.

Though very expensive, safety systems, particularly the tunnel ventilation, are practically worthless if they are not tested properly.

After completion of all acceptance tests, a series of integral tests and smoke tests should be worked out. Smoke tests should be as realistic as possible, but must be feasible without extraordinary effort. A series of smoke tests with different boundary and initial conditions is more valuable than a single fire test with a high heat release rate. The latter are useful as basic research, to be realised in test tunnels, but not as acceptance tests for safety systems.

Tests lead to practical findings about safety issues that were not addressed during the design process. A detailed testing program must be taken into account already from the first stages of project scheduling with adequate time reserves for fault correction.

The impact of smoke on the environment during the tests, particularly on traffic on adjacent roads, may not be neglected.

The design criteria according to the actual guidelines should be adjusted to findings and conclusions obtained from practical experience.

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