TUNNEL SAFETY BY VENTILATION – AN ILLUSION?

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ABSTRACT

The ventilation is considered to be a vital component of road tunnel safety plans. Accordingly, substantial amounts have been invested for this purpose. However, though the installation and operation concepts have been discussed, decided and implemented by specialists, weaknesses continue to appear in routine operation, tests and emergencies. While work to eliminate these weaknesses is an ongoing process, it must not lead us into the error of increasing the complexity of the systems and thus creating new weaknesses. The problem is to find the golden mean.

Key words: tunnel ventilation, safety, smoke detection, safety gallery, escape door

1. INTRODUCTION

The safety of tunnel users is ensured by a whole range of interconnected individual components and subsystems. The systems are mainly designed for the first phase of a vehicle fire in which the persons trapped inside the tunnel have to reach safety on their own. To this end, there are various systems of optical and acoustic signals which provide tunnel users with the information and indications needed to make the appropriate decisions for themselves. In addition, there are also systems intended to ensure that the escape routes can be found and reached even in the case of a fire.

The primary purpose of tunnel ventilation in the event of an incident is simple, namely to give the persons concerned in the tunnel sufficient opportunity to identify and reach a way out of the danger zone. In modern tunnels, this purpose is usually achieved by means of a longitudinal ventilation system, with or without smoke extraction, depending on the type of traffic. After the rapid detection of an incident, the next priority is the measurement and control of the longitudinal air flow in the traffic space.

Other objectives include support for the specialised emergency services during the rescue phase and, during later phases, the protection of the structure.

Experience has shown that various causes may contribute to a situation getting out of control. For example, the scale or course of an incident may exceed the design limits of the system, individual components may not function properly or the concepts may not be appropriate.

From the reports by emergency services on major incidents, we know that, within 10 to 20 minutes – i.e. just as the rescue specialists are arriving – the situation may have escalated to such an extent that the fire brigade can no longer rely on the tunnel-related concepts. The commander on the spot must be prepared for surprises since there are limits as to what the systems can do.

The following critical comments relate mainly to tunnel ventilation systems and, in this regard, we set out a number of experiences concerning ideal concepts, real-life behaviours, erroneous assumptions, lack of knowledge and promising approaches.
2. WISH AND REALITY

The following ten topics serve to illustrate the difficulties and the approaches to solutions.

2.1. Ventilation concepts

In the past, tunnels were equipped with distributed exhaust extraction systems. At the time, the extraction process was homogeneous over the length of a whole section. People were so confident in the concept that the smoke layer should be extracted under the ceiling that, in general, little provision was made for escape doors in such tunnels. Distances of 3 km and more between exits were considered sufficient. Although some critical spirits expressed doubts during the 1990s as to whether this method of ventilation with fixed openings at intervals of around 10 m in the false ceiling would prove effective in the event of fire. However, despite the positive experiences already available at the time (e.g. from Austria), it took a great deal of persuading to bring about the change to extraction by means of controllable dampers. In December 1998, the Federal Roads Office (FEDRO) began drawing up the Road Tunnel Ventilation Directive (the directives and the technical manual for the equipment for operation and safety EOS can be downloaded from www.astra.admin.ch).

Since the year 2000, the directive has served as the binding basis for ventilation conception and design. The changeover was hastened by the fatal tunnel incidents at the turn of the century, which revealed that the earlier concept of efficient smoke extraction was an illusion.

All of the foregoing is now familiar and has come to be seen as self-evident in the meantime. However, there is at least one argument against the ‘mechanisation of the false ceiling’ which cannot simply be brushed aside. It has to be recognised (i) that the clearly improved extraction at the scene of the incident depends on a means of detection that is both rapid and precise, plus extremely reliable maintenance of the damper system and (ii) that if wrong dampers open in the event of an incident, there can be fatal consequences, with the smoke being actively carried over sections with tunnel users. The problem is not a trivial one and it must not be underestimated, particularly in the case of concepts with dampers that remain open in normal operation which again demands perfect maintenance.

2.2. Detection

Nowadays, heat detection with linear sensors under the tunnel ceiling is a widely accepted standard. In the past, the adequate response time of this system was called in question and different proposals were made as to how improvements might be achieved with complementary systems.

There is no denying that, in the past—for example in the Gotthard road tunnel—fires were almost invariably first detected by the opacity sensors despite the fact that there is an interval of more than 1 km between these measuring points. Together with the reaction of the mechanical system—the mass of air in the Gotthard tunnel amounting to around 1,000 tonnes—a stationary condition was not established until after around 15 minutes.

In order to permit the expensive ventilation systems to fulfil their appropriate function in good time, FEDRO decided to equip all of the mechanically ventilated tunnels with additional systems capable of detecting cold smoke within one minute. The measurement principle is not defined in the Fire Detection Directive. In the Gotthard road tunnel, such devices have recently been installed at intervals of around 100 m at every exhaust damper. The sensors have exceeded expectations in respect of function security, false alarm rate, maintenance intervals and, not least, cost.

However, a decision to dispense with the thermal line sensors seems unjustifiable because, in an initial phase, it still has to be expected that there will be a long smoke zone. In such an eventuality, a thermal signal can provide a reliable detection of the seat of the fire and the basis for manual intervention and control.

In any event, the evaluation of the smoke sensor signals raises considerable new control requirements. Before a concentrated extraction can be initialised, it is first necessary to ensure
that the smoke source is no longer in motion (Figure 1). Moving smoke sources are particularly frequent in the Gotthard as it is a summit tunnel. A method for processing the smoke sensor signals is proposed in the EOS technical manual published by FEDRO.

![Figure 1: Time-location diagram of opacity from a driving smoke source in the Gotthard tunnel. Δx between rows: 96 m, Δt between lines: 5 s](image)

The cost of installing smoke sensors—usually at intervals of 100 m (up to a maximum of 300 m)—is considerable and, without adequate maintenance, the functionality of the system is limited. In any event, if ventilation is initiated too late, the hazard for the tunnel users could be even worse than with no ventilation at all.

2.3. Air flow measurement

The measurement of an airstream with a velocity of ± 0.2 m/s represents no great challenge under laboratory conditions. However, it is an illusion to assume that the results can simply be transposed directly to a tunnel, where the issue in question is the mean velocity in the traffic space. The difficulties of achieving a reliable air flow measurement are numerous, ranging from the problems of the positioning of the sensors in the traffic space, through electronic difficulties, to problems of the concept.

In most incidents, the ventilation has to be adjusted in accordance with the values measured in the traffic space at the time. As a consequence, in Switzerland the plausibility of the air flow data has to be tested on the basis of three independent measurements. As a fallback, it is possible to make use of the less precise measurement of the pressure measurement at the exhaust fans.

2.4. Fire size

As indicated in the introduction, it is in the self-rescue phase that the effectiveness of the safety systems is the focus of attention. However, the discussion and determination of fire size is also important as the basis for the principles for the design of the structure and the equipment for operation and safety. At the present time, there are wide differences between countries in terms of limits, ranging from 30 MW (as in Switzerland) up to 200 MW. However, we need to differentiate and must be careful not to be misled into thinking that a higher requirement in terms of fire size signifies greater safety. If operated inappropriately, powerful jet fans can create additional hazards for tunnel users. In any event, it must not be forgotten that even a smoke source that does not generate heat has to be brought under control.

It is our opinion that the interpretation of fire size—the real art in this domain—must be contained in the design specifications. Even a slight longitudinal gradient in a tunnel sets the temperature distribution and the resulting buoyancy effect as a function of time to a focus of interest. The undifferentiated use of a fire size in any ventilation software can lead to illusory results.
2.5. Interference effects in the aerodynamic system

The design and operation of ventilation systems for tunnels with a small longitudinal gradient and fluid traffic might be considered a simple matter. However, attempts to transpose the design to very long tunnels, to short tunnels or to tunnels with a gradient of over 1.5 % must be treated with special caution.

In the case of long tunnels, the continuous and rapidly changing interference effect resulting mainly from exiting traffic leads to conditions that cannot be controlled in the short-term. A reduction of the indicated speed limit from 80 to 60 km/h would theoretically reduce the interference pressure but it would then last longer. In the case of short tunnels, the length may be insufficient to accommodate the necessary thrust and in addition to maintain interference-free zones. It is an established fact that the consequences to be feared of a fire are not proportional to the tunnel length. In both cases, it is necessary to acknowledge the limits to the effectiveness and, under certain circumstances, even the applicability of mechanical ventilation. In addition to the imperative need for rapid detection to raise the alarm for tunnel users and the reliable control of a ventilation system, there are other possible approaches to solutions, including escape doors at short intervals, or even alternative track routing in the case of a planned tunnel.

2.6. Safety galleries and escape doors

About ten years ago, it became evident that the effect of ventilation systems cannot substitute emergency exits. Hence, the necessity arose to build single-tube tunnels with safety galleries and existing tunnels to be retrofitted. The resulting investment cost is considerable. The FEDRO Directive Ventilation of Safety Galleries requires a low-level permanent operation for the ventilation of safety galleries and, in the event of an incident, an adequate air flow through up to three open escape doors. This gives rise to an over-pressure of around 350 Pa in the safety gallery. The specific fan power to be installed for operation during an incident is about 15 kW/km. The energy consumption for permanent normal operation is very low.

As a result of the decision to put the safety galleries to an over-pressure in order to preclude smoke intrusion and of the requirement that the opening of the escape doors should not be mechanically assisted, it was necessary to make provision for sliding doors.

![Figure 2: Sliding escape door - view from the side of the safety gallery](image)

Sliding doors with an opening force of only 60 N at operating pressure have already been produced. In Switzerland, the maximum force is stipulated to be 120 N. Since the Gotthard tunnel was opened 30 years ago, it has been equipped with sliding doors in the traffic space. Today there are certainly escape doors in some tunnels that could not be opened in the event of an incident, due to pressure differences generated by fans and the residual traffic. The tests for the necessary opening force can be carried out properly only under real operating conditions.
2.7. Recirculation of smoke

From exhaust opening to the portal

Ventilation systems using single-point extraction without a mechanical air supply draw in air from the outside through the portals.

It has been shown that the positioning of portals and exhaust openings can be a tricky matter. If smoke in the tunnel suddenly comes from the direction in which the user has been expecting fresh air, the effect can be, to say the least, unsettling.

Figure 3: Left: South portal of Gotthard tunnel during the 2001 fire. The distance between portal and stack is 70 m. Right: Test with cold smoke at Islisberg tunnel, jet speed of 20 m/s

Between portals

In longitudinally ventilated tunnel systems, the smoke is expelled through the exit portal. To ensure that a second tube and thus the escape routes remain smoke-free, the air flow is reversed into this second tube. However, the process can take a few minutes. For this phase, structural measures are indispensable to prevent any recirculation between the portals, an arrangement that is also favourable for normal operation.

From portal or exhaust opening to safety gallery

The air intakes for the ventilation of the safety galleries are located at the two exits. The exits are equipped with locks for a permanent over-pressure. The safety gallery exits and, in general, the traffic space ventilation station are situated close to the portals of the single-tube tunnel. It is necessary to ensure that smoke is not drawn into the safety gallery, which can be achieved by a favourable positioning of the air intakes of the safety gallery or by means of smoke detection in the area of the suction intake and subsequent adequate ventilation reaction.

2.8. Exhaust duct leakage

In the past, there was hardly ever any question about the leakage, e.g. between supply and exhaust air duct or between traffic space and exhaust duct. With the deployment of controllable exhaust dampers the sufficient seal between the exhaust duct and the traffic space became important. Recent measurements have demonstrated the relevance for new tunnels of the indications concerning duct leakages contained in the Road Tunnel Ventilation Directive.
Considerable importance attaches to the often underestimated supplementary requirement that the maximum under-pressure in the exhaust duct as compared with the traffic space must remain restricted to 2.5 kPa. Technically, it would be feasible to achieve under-pressures of up to 5 kPa but this would considerably increase the leakage flow and thus lead to an undesired difference in longitudinal air flow in the traffic space.

2.9. Complexity of ventilation control

A major difficulty in the design of ventilation control systems lies in harmonising the automatic responses of the system to the multitude of possible incident scenarios. Designers of control processes often try to cover a vast number of eventualities. However, the increased complexity of the system is paralleled by an increased risk that an incident will be accompanied by unanticipated conditions and system failure. What we need to avoid is system reactions that could place tunnel users at risk.

We must follow the principle that the only acceptable system is one that the technical specialists consider transparent and testable and that offers an appropriate service life.

2.10. Cost savings

As financial resources are restricted, we are under an obligation to keep expenses down. The main method used in this regard is currently risk analysis but the theoretical and pragmatic approaches have yet to be standardised. At the same time, attempts are being made to define requirements and to rationalise processes. The essential aspect here is that field personnel responsible for operation are involved so that the terms of reference do not simply appear from someone's desk. In Switzerland, the national road network is on the point of completion. Thus, for the future, the crucial task will be to ensure that the infrastructures provided continue to be properly maintained and to function perfectly. In the event of any incident, danger could arise if active components like exhaust dampers or ventilation controls have not been appropriately serviced and integrally tested.

For the future, maintenance costs are expected to rise considerably. In today's world, it is a badge of distinction for the manager if he is able to obtain a certain performance for the lowest possible price. With a price weighting of 50% and more, contracts are hardly going to be awarded on the basis of quality criteria. Moreover, once the work has begun, it is extremely difficult if not impossible to exert pressure for changes or to make corrections.

3. CONCLUSION

There have been great changes in the tunnel ventilation field over the last ten years. For those who have to deal with these tasks daily, the new requirements quickly become self-evident. Today, facilities are planned and constructed on the basis that the structure concerned will have a service life of 50 years or more. Nevertheless, it is only to be expected that, with changing parameters and new knowledge, we may well look back and, with hindsight, call in question some of the things that presently appear to be self-evident.

Since predicting the future is an uncertain science, our best approach is to be critical of the requirements and objectives that are set; to be self-critical with the specific solutions that we propose as engineers; to be consistent with the concepts for solutions; and to be communicative in order to allow and, where applicable, to accept outside criticism. If we can do all of this, we will be able to get rid of illusions and to increase the safety of tunnel users.