SMOKE CONTROL IN ROAD TUNNELS

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ABSTRACT

The philosophy of fire ventilation in road tunnels has been improved in the past years. The goal of fire ventilation for smoke control is the handling of the longitudinal airflow. This is important for tunnels with smoke extraction as well as for short tunnels with only longitudinal ventilation. In order to control the longitudinal airflow, jet fans are required. In special cases, for example in case of a powerful transversal ventilation with several ventilation sections, the airflow can be controlled without jet fans. The best method to control the longitudinal airflow is by means of a closed-loop control. The control routines must be based on a physical model of the tunnel. Furthermore, the measurement of airflow in the traffic space becomes essential. Nevertheless, the application of the new fire-ventilation philosophy in practice is not simple.

1. INTRODUCTION

A fire hazard in a tunnel often produces smoke, which is dangerous to the tunnel users, as the visibility is reduced and it may be toxic.

Fig. 1 Smoke in a road tunnel

In a one-dimensional system, such as a road tunnel, the smoke may spread very fast in one or two directions, threatening the persons situated there. Ideally, the smoke is extracted or directed towards the direction, where no persons are endangered.

Smoke control means essentially the control of the longitudinal airflow in the tunnel, either on its own or in combination with a smoke extraction system. Smoke control is primarily in order to ensure the escape of tunnel users from the dangerous area. Secondly, the fire brigade has to be supported by ensuring a smoke-free access to the fire site.

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2. REQUIREMENTS TO THE VENTILATION

From the point of view of smoke control, there are two basic concepts. In both cases, the control of the airflow in the tunnel is essential.

In tunnels with pure longitudinal ventilation, the only way for the smoke is through the traffic space itself. In this case, the smoke control system only influences the direction and velocity of smoke movement.

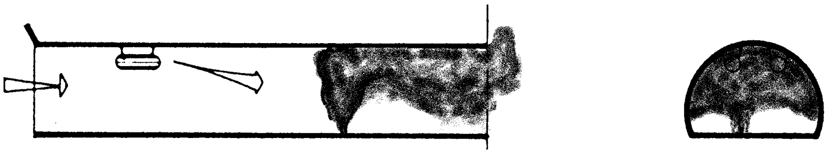

Fig. 2 Longitudinal ventilation in case of fire

Using longitudinal ventilation for example in a tunnel with unidirectional traffic, the typical design objective is to prevent smoke from backlayering i.e. to ensure that all smoke is driven in one direction. In that case, the longitudinal velocity must reach at least the so called "critical velocity". It is inherently assumed that there are no persons downstream of the fire.

The situation is quite different in a tunnel with bi-directional or congested traffic. Tunnel users may be situated on both sides of the fire. With high air velocities, a possible stratified smoke layer underneath the tunnel ceiling would be dispersed over the whole tunnel cross section. Therefore, with a longitudinal ventilation, the intention of the smoke control is to stabilise the airflow at a low air velocity. The goal is to prevent changes in the flow direction and to keep the air velocity low in order to minimise turbulence or large eddy flow.

In longer tunnels, there should be a smoke extraction from the tunnel tube using a separate airduct. Ideally, the smoke is extracted at the point of the smoke source, e.g. at the fire site.

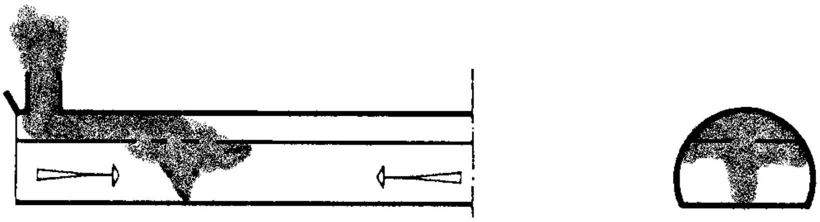

Fig. 3 Local smoke extraction system

In the one-dimensional point analysis, the demand for an efficient smoke control means that the airflow in the tunnel tube must be from both sides of the fire towards the extraction point. Wind, meteorological and thermodynamic forces may lead to high air velocities in the tunnel. Even with a powerful smoke extraction, the smoke may pass the extraction point.

The new Swiss [2] and German [1] guidelines require that the flow from both sides of the fire reaches a velocity of at least 1.5 m/s towards the extraction point. This has to be complied with under the worst foreseeable conditions. Usually, the indicative case for the dimensioning is the extraction near a tunnel portal, with an adverse natural airflow caused by wind and thermodynamic effects.

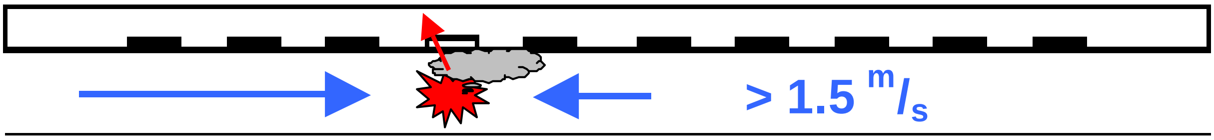

Fig. 4 Design for smoke control with smoke extraction

In order to fulfil the requirements for the support of the smoke extraction, jet fans are demanded to control the longitudinal airflow in the tunnel. The higher the smoke extraction capacity, the less jet fans are required. When laying out a ventilation system for smoke extraction, an optimisation between extraction rate and number of jet fans is carried out.

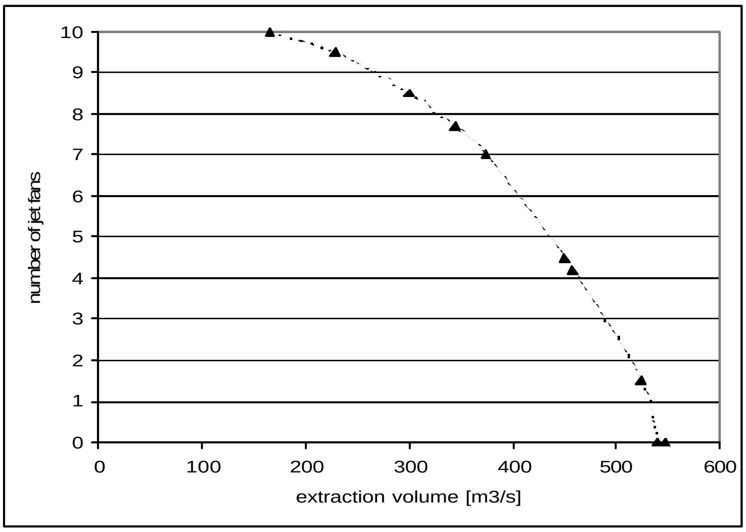

Fig. 5 Smoke extraction volume versus number of jet fans (example)

The first installation of jet fans for the automatic control of the longitudinal velocity, which has been proven in practice, was first realised 1999 in the Vue-des-Alpes tunnel in Switzerland. Other examples are the refurbished Mont-Blanc tunnel between France and Italy and the refurbished San Bernardino tunnel in Switzerland.

By now, all long Swiss road tunnels that are planned or under construction are equipped with smoke extraction and jet fans for the control of the longitudinal airflow. An example is the Gotschna tunnel in the Swiss mountains with a length of 4.2 km and a slope of 4.8 %. Due to thermodynamic effects, forces of more than 200 Pa act on the flow and have to be catered for. Even with a high extraction capacity of 220 m^3/s, additionally 24 jet fans must be installed in order to ensure adequate control of the airflow in the case of fire. The inauguration of the Gotschna tunnel is in 2005.

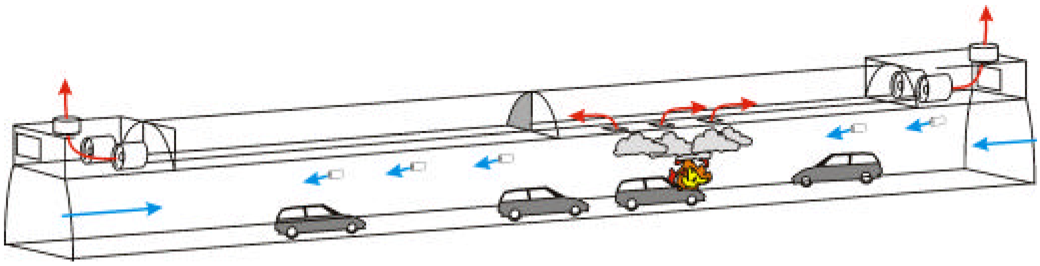

Fig. 6 Ventilation system of the Gotschna tunnel

In special cases, instead of controlling the longitudinal airflow by jet fans, the air velocity can be ceased by means of a powerful transversal or semi-transversal ventilation, which is common in older tunnels. Examples are the Gotthard road tunnel in Switzerland, the Elbe tunnel in Hamburg / Germany and the Branisko tunnel in Slovakia.

In the Branisko tunnel, the smoke extraction can be supported using the semi-transversal ventilation in the opposite branch of the tunnel. It has been tested successfully during the smoke tests prior to the tunnel opening.

3. CONTROL ROUTINE

The forces driving the airflow in the tunnel are not determined and may vary rapidly. As long as the airflow in the tunnel is driven by the traffic, it cannot be controlled. The effect of the traffic decreases because in the case of an incident, the vehicles stop or leave the tunnel. The tunnel portals must be closed, so no further cars enter the tunnel.

Other driving forces become more influential. Buoyancy may be caused by temperature differences between the tunnel and the ambient air and by the heat of the fire. Wind pressure on the portals has an additional influence. The smoke control, with or without smoke extraction, has to compensate these forces as well as possible. In order to achieve this, a closed-loop control using the average air velocity in the tunnel as a target value must be applied. In special cases, the temperature measurements inside and outside the tunnel may be used as additional input for the control routine.

The control routine must use a mathematical model of the tunnel to calculate the number and direction of jet that has to be switched on and off in order to reach the target value. Alternatively, standard P-controllers could be applied, but in practice such controllers have not proved to be satisfactory.

$$F_{soll1} = \begin{pmatrix} F_{istW} + F_{istO} + (C_E + C_{RF} \cdot x_W) \cdot (C_{TA}^2 \cdot Q_A^2 - u_W^2) - (C_E + C_{RF} \cdot x_O) \cdot (C_{TA}^2 \cdot Q_A^2 - u_O^2) + (u_W^2 - u_O^2) + \ldots \\ \ldots + C_D \cdot \frac{C_{TL}}{\Delta t} \cdot \left(C_{TA} - 2 \cdot u_W(t) + u_W(t - \Delta t)\right) \end{pmatrix}$$

Fig. 7 Example for control algorithm

In case of a smoke extraction at bi-directional traffic, the target value is to have zero flow at the location of the fire. Then the airflow in the two branches should be symmetric towards the extraction point. In case of longitudinal ventilation with congested or bi-directional traffic, the target value may rather be 1 to 1.5 m/s, with the main objective to prevent a flow inversion.

The control cycle must take the inertia of the tunnel air into account. For most applications, cycles of about 1 minute or more may be useful.

Without a reliable, precise air-velocity measurement, a smoke control is impossible. Therefore, the measurement of the direction and value of the average air velocity in the tunnel is of utmost importance. Controlling the longitudinal airflow using wrong values may have catastrophic consequences in a real fire incident, , as was seen for example in a fire test in the Plabutsch tunnel in Austria [3]. The value must be determined using at least three independent measurements in such a way that faulty values are filtered out by a plausibility check. No obstructions must disturb the airflow in the vicinity of the anemometers.

In practice, only devices measuring the air velocity over the cross sections by means of an ultrasonic ray have been proven to work satisfactory.

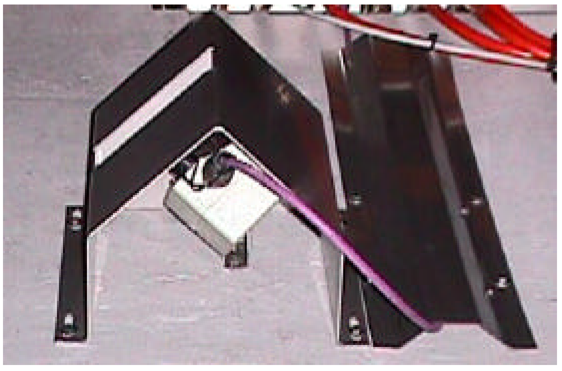

Fig. 8 Ultrasonic anemometer in road tunnel

Another important aspect is that jet fans or fresh-air supply may be only applied in a smoke-free zone. Smoke must be detected, usually by the existing opacity-meters. The detection is used to switch off jet fans in the smoke area.

This leads to the demand for small distances between the opacity-meters for smoke detection, for example 150 m according to the new German guidelines (RABT [1]).

4. RESTRICTIONS IN PRACTICE

In practice, the smoke control is possible only within limited circumstances. The restrictions are caused mainly by the following uncertainties

- The time between the start and the detection of the fire is unknown.
  Usually, a fire respectively smoke cannot be detected until several minutes after the fire has started. At the moment of detection and start of the fire ventilation regime, the tunnel may be full of smoke over several 100 m. That is the reason why an automatic fire ventilation is difficult to apply for short tunnels.
- The smoke zone cannot be determined exactly, especially in older tunnels with large distances between smoke detection devices. Smoke detection by opacity-meters has a time delay that is necessary in order to prevent false alarms. Therefore, it cannot completely be prevented that jet fans would work in the smoke zone, dispersing the smoke over the whole cross section.
- The measurement of the airflow is not always precise and reliable, even when the commissioning and maintenance of the measuring devices have been worked out carefully. Especially in short tunnels, due to the lower inertia of the tunnel air, fluctuations may occur, which cannot be controlled

5. CONCLUSIONS

The control of the longitudinal airflow during a fire in a tunnel is the key for an effective fire ventilation with or without smoke extraction.

In theory, the control of the longitudinal velocity may be rather simple. However, in practice the application of an automatic control routine sets new demands to the reliability of the control routines and instrumentation. It cannot simply be assumed that the anemometers give adequately reading to permit an automatic control. Consequently, it is paramount firstly to calibrate the measurement instruments and secondly to conduct plausibility tests prior to each iteration of the automatic control. Otherwise, a rather good smoke extraction can be destroyed and the survival conditions for the tunnel users deteriorate.

6. LITERATURE

[1] RABT-2003 - German Design Code -
Richtlinien für die Ausstattung und den Betrieb von Strassentunneln, 2003

[2] ASTRA - Bundesamt für Strassen, Swiss Design Code -
Richtlinie Lüftung der Strassentunnel, Draft version 19. December 2003

[3] A. Waltl, Safety Measures for Road Tunnels – Newest Developments for the Plabutschtunnel, Austria
2nd Symposium on Tunnel Safety and Ventilation, Graz April 2004