VENTILATION OF ROAD TUNNELS
THE NEW SWISS DIRECTIVE

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1. ABSTRACT

Due to the tunnel fires on the one hand and the reduction of vehicle emissions on the other hand the design of tunnel ventilation systems is nowadays determined by safety reasons. Several new features of the new Swiss directive have led to changes in conception and design of the ventilation systems of planned tunnels, tunnels under construction and existing tunnels.

Main novelties in ventilation design in Switzerland are

- Ventilation system definition: Transverse and reversible semi-transverse systems as formerly used will not be recommended any longer.
- Standardisation of system choice: The ventilation system has to be determined according to traffic type and volume, tunnel length and gradient and in some cases secondary influence factors have to be checked.
- Design fires: The buoyancy effect of the design fires is defined.
- Remote control dampers: In the case of fire controllable dampers are used to concentrate the extraction capacity to the location of the incident. Indications for position, shape and dimensions of the dampers are given.
- Redundancy: The redundancy of primary safety elements is defined.
- Escape routes: The maximal distance of escape routes for different tunnel types is defined.

The higher complexity of the new systems requires primary attention to the maintenance of the most important elements such as dampers, incident detection and measuring systems.

2. INTRODUCTION

The work for the new Swiss directive for the choice of system, design and operation of road tunnel ventilation started in December 1998. The document replacing the report FEDRO (1983) will be released this year by the Swiss Federal Roads Authority. The fundamental ideas of the new directive must be applied today already. Due to the fatal tunnel fires on the one hand and the reduction of vehicle emissions on the other hand today safety reasons determine the design of tunnel. Several new features of the directive have led to changes in conception and design of the ventilation systems of planned tunnels, tunnels under construction and existing tunnels.

3. AIM

The aim of the directive is to standardise the design process of tunnel ventilations and consequently standardise the systems and equipment of the road tunnels. The directive is primarily designed for

- the tunnel owner offering an easy to use instrument for rough estimates
- the ventilation specialist to give him clear indications for the system choice and design
- the engineers of other domains indicating the necessary facts in the early conceptual stages
The requirements of the directive are mandatory for the design of all tunnels that are subsidised by the Swiss Federation. If possible and practical it should be applied also for all other tunnels in Switzerland. When renovating an existing tunnel, the standard defined in the directive has to be reached. Deviations from the requirements of the directive are admissible if they can be justified by project specific features.

4. CLASSIFICATION OF VENTILATION SYSTEMS
On a first level the ventilation systems are classified into three groups:
1. Natural ventilation
2. Ventilation systems without a smoke extraction duct and
3. Ventilation systems with a smoke extraction duct.
On a second level the systems with a mechanic ventilation are subdivided in
2a. Longitudinal ventilation with jet fans and
2b. Longitudinal ventilation with point extraction with or without jet fans
3a. Systems without fresh air duct
3b. Systems without fresh air duct
Furthermore combinations of the above mentioned systems are possible.

5. GENERAL CONCEPTUAL RULES
In general the following rules must be observed:
The extraction capacity must be concentrated onto the tunnel section near the incident by means of controllable dampers usually situated in the intermediate ceiling. If needed the openings for fresh air supply must be placed near the road surface. Reversible fresh air/exhaust air duct are no longer possible. The reason for this is the possible de-stratification of smoke by the fresh air blown in from the ceiling and the loss of time during the reversing process of the air in the duct and possibly of the ventilator or the dampers. Dampers for air extraction should only be used in the positions closed or fully open. Continuous air extraction through slightly opened dampers is not recommended.

6. CHOICE OF THE VENTILATION SYSTEM
The directive uses the classification of traffic according to PIARC (1999a) distinguishing
RV 1 uni-directional traffic with low frequency of congestion,
RV 2 uni-directional traffic with high frequency of congestion and
GV bi-directional traffic
(RV stands for 'Richtungsverkehr', GV for 'Gegenverkehr')
High frequency of traffic congestion is given if it occurs more often than once a week.
Together with the tunnel length the main group of ventilation system can be determined with Figure 1. If necessary influence factors of first or second order have to be applied to determine the relevant system. The indications are valid up to a slope of 5 %.
While for tunnel X (figure 1) with a length of 2.5 km a refined investigation has to be made to judge the necessity of a smoke extraction duct, Figure 1 indicates that for Tunnel Y and Z the smoke extraction duct is mandatory. To allocate a tunnel in the subdivision A, B or C the main influence criteria are used: the traffic volume per day and lane number, the number of HDV per day and lane number and the slope of the tunnel (extreme mean values over 800 m).
If the main group is still not clear, further influence factors are proposed among them the length of escape routes. This indicates a weak interdependence between the choice ventilation system and the escape route length. In fact the authors of the directive regard ventilation and escape routes not as compensatory.

7. DESIGN OF THE VENTILATION SYSTEM

The directive defines the requirements and describes the design of the chosen ventilation system for normal traffic situations, incidents including fires and protection of the environment.

7.1 Design for normal traffic situations

For normal traffic situations, e.g. freely flowing traffic, congested traffic, blocked traffic and exceptionally bi-directional traffic, the approach described in PIARC (1995) is used. Some special features are:

- The end of the design period is 10 years after putting the tunnel into normal operation.
- Congested traffic is only to be considered if congestion is expected during more than 50 hours per year.
- A prognosis of such a value is usually very difficult. Therefore the directive in appendix 2 offers an estimation method on the basis of traffic character and traffic volume per day and lane.
- According to measurements of the driving speed of heavy duty vehicles on the San Bernardino route in 2001 the maximal speed values for HDV in slopes have been defined as:

<table>
<thead>
<tr>
<th>Slope [%]</th>
<th>-6</th>
<th>-4</th>
<th>-2</th>
<th>0</th>
<th>2</th>
<th>4</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>V\text{max,HDV} [km/h]</td>
<td>60</td>
<td>80</td>
<td>90</td>
<td>90</td>
<td>80</td>
<td>65</td>
<td>50</td>
</tr>
</tbody>
</table>

It is mentioned that on routes with a high percentage of trucks the values are lower.
For the calculation of the fresh air requirement the limit values of 100 ppm CO and 0.005 m⁻¹ for turbidity are given. These values are used for all kind of traffic schemes. Higher requirements as e.g. in PIARC (1995) are not regarded as necessary, since in the future all tunnels should be equipped with a traffic control system to prevent long exposition times in tunnels. For tunnels below an altitude of 800 m measuring devices for CO are no longer necessary.

The directive quotes the NO₂ limit value of 1 ppm at an oxidation rate of 10 % according to PIARC (1999b). With the given limit values for CO and turbidity the NO₂ value will always be fulfilled and a special calculation for NO₂ is not regarded as necessary.

In Appendix 3 of the directive the necessary values for the emission calculation of CO and turbidity are given in detailed form. Those values include contributions from surface friction and resuspension to the turbidity emission.

To get a controllable system the minimum fresh air requirement in m³/s is defined as 1.5 m/s times the tunnel cross section in m².

7.2 Design for a truck fire

7.2.1 Design fire

As is in several European countries the directive uses a fire load of 30 MW for the main design fire. This value refers to a loaded truck as cited in the Eureka trials (1998). A second design fire with 5 MW relating to a private car fire is a reminder for the ventilation designer to give attention to the fire scenarios with lower heat development but possibly high smoke production. For tunnels with high gradients the air flow and thus the smoke propagation can be fundamentally different. Even down-drafts of smoke are possible due to temperature differences between tunnel and environment.

An analysis of the detailed data of the Memorial trials (1995) led to the necessary interpretation of the label ‘30 MW’ in order to calculate buoyancy forces by the fire:

\[ \Delta T_{\text{fire}} = 65 \, \text{K} \] 
\[ L_{\text{heat}} = 800 \, \text{m} \] 
\[ \Delta \text{time}_{\text{heat}} = 10 \, \text{min} \] 
\[ \eta_{\text{fire}} = 0.75 \] 

For non-homogenous slopes a refined temperature curve within \( L_{\text{heat}} \) can be necessary. The duration of the temperature rise is used for checking the instationary behaviour of the system. The buoyancy effectiveness is an empirical factor derived from the Memorial trials. An realistic combination of unfavourable meteorological conditions has to be regarded. It is the coincidence of a natural temperature difference between tunnel and environment of at least 5 K and the local 95 %-value of the pressure differences between portals due to barometric reasons and wind pressure.

7.2.2 Longitudinal ventilation systems

For the thrust of the jet fans in tunnels with longitudinal ventilation the following flow requirements are set:
Traffic mode (RV 1)

<table>
<thead>
<tr>
<th>direction of traffic flow</th>
<th>downhill</th>
<th>uphill</th>
</tr>
</thead>
<tbody>
<tr>
<td>buoyancy of fire</td>
<td>30 MW</td>
<td>no fire heat</td>
</tr>
<tr>
<td>requested minimal air flow</td>
<td>3 m/s downhill</td>
<td>3 m/s uphill</td>
</tr>
</tbody>
</table>

Traffic mode (RV 2)

<table>
<thead>
<tr>
<th>direction of traffic flow</th>
<th>downhill</th>
<th>uphill</th>
<th>uphill</th>
</tr>
</thead>
<tbody>
<tr>
<td>buoyancy of fire</td>
<td>30 MW</td>
<td>30 MW</td>
<td>no fire heat</td>
</tr>
<tr>
<td>requested minimal air flow</td>
<td>3 m/s downhill</td>
<td>1.5 m/s downhill</td>
<td>3 m/s uphill</td>
</tr>
</tbody>
</table>

Traffic mode (GV)

<table>
<thead>
<tr>
<th>direction of traffic flow</th>
<th>uphill and downhill</th>
</tr>
</thead>
<tbody>
<tr>
<td>buoyancy of fire</td>
<td>30 MW</td>
</tr>
<tr>
<td>requested minimal air flow</td>
<td>1.5 m/s downhill</td>
</tr>
</tbody>
</table>

The design should cover at least a reaction time of 3 minutes between the incident and the start of the jet fans and the traffic control respectively. The consequences of longer reaction times must be declared in the design report.

7.2.3 Ventilation systems with duct for smoke extraction

The report FEDRO (1983), which was the basis for the former ventilation design, started from the assumption that the smoke from a large fire remains stratified for a certain distance and time from the incident. The observations of the Ofenegg trials had led to such a conclusion. As a consequence most tunnels with smoke extraction were equipped with an intermediate ceiling with fixed openings over the whole length of the extraction segment. In newer tunnels the fixed size slot in the ceiling was throttled with a heat sensitive polymer enlarging the slot opening in the case of a near fire.

In the meantime experience from real tunnel fires and from the Memorial trials (1995) has shown that rarely a lasting stratification of smoke can be assumed. Taking into account a reaction time of detection and inertia of the system the new design for extracting smoke is no longer based on the idea of a fully transverse ventilation (fresh-air in on road level, smoke out from the roof) but mainly on the idea of influencing the longitudinal flow in the tunnel towards the fire. To that end controllable dampers between traffic space and smoke duct are necessary.

The main design demands to respect are:

- Smoke extraction must be performed with remotely controllable dampers.
- The dampers are to be placed in a distance of 100 m between each other. Since an erroneously open damper can cause grave consequences, maintenance of their function is a primary need. The given distance had been chosen under the aspects of maximal length between incident and damper, i.e. 50 m and the necessary size of damper (see below).
- At the incident 3 or 4 dampers must be opened, i.e. over a distance of 200 m to 300 m. This requirement results from a compromise between redundancy of dampers and exactness of the detection of the incident location. It is also taken into account that in real tunnel fires a certain length of the tunnel will be filled with smoke before the ventilation is effective.
- The outmost dampers should be installed 200 m to 300 m from the portals. Extraction close to portals is usually very inefficient. In addition this allows to place jet fans in this section.
The free area of the fully open damper should result in a mean vertical speed of about 15 m/s with respect to air of ambient temperature. If the volume flow of extraction is higher than the requested minimum, the vertical flow component can be increased up to 20 m/s. The limit of the vertical speed is set for the case of a stratified smoke layer under the ceiling. With very high local speeds the percentage of fresh air in the extracted gas is higher.

The minimal extraction flow rate $V_{\text{extraction}}$ for a tunnel with cross section $A_T$ over the distance of the opened dampers and related to ambient air is

$$V_{\text{extraction}} = A_T \cdot 3 + V_{\text{fresh, air}}$$

Decisive for the value was that in most tunnel geometries the so-called critical air velocity to force the smoke to one side of the incident is about 2.5 m/s. Applied to bi-directional tunnels the smoke spreading can not be avoided. The fresh air flow from either side might allows though a stratification at the initial phase of a fire.

The requirements for the longitudinal flow on either side of the incident are as follows:

<table>
<thead>
<tr>
<th>Traffic mode</th>
<th>Traffic situation at time of incident</th>
<th>airflow toward location of incident</th>
<th>tunnel section</th>
</tr>
</thead>
<tbody>
<tr>
<td>RV 1</td>
<td>Freely flowing</td>
<td>$\geq 3$ m/s</td>
<td>congested branch</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\geq 0$ m/s</td>
<td>emptied branch</td>
</tr>
<tr>
<td>RV 2</td>
<td>Freely flowing</td>
<td>$\geq 3$ m/s</td>
<td>congested branch</td>
</tr>
<tr>
<td></td>
<td>Congestion</td>
<td>$\geq 0$ m/s</td>
<td>emptied branch</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\geq 1.5$ m/s</td>
<td>both sides of incident</td>
</tr>
<tr>
<td>GV</td>
<td>Freely flowing or congestion</td>
<td>$\geq 1.5$ m/s</td>
<td>both sides of incident</td>
</tr>
</tbody>
</table>

To meet these requirements for all possible incident locations in a tunnel, either a high extraction volume flow or a combination with jet fans is necessary. The thrust of the jet fans balances the pressures in the two tunnel branches on either side of the incident.

In a double tube tunnel, the above stated requirements are valid for both tubes individually and it must be possible to operate the extraction in both tubes simultaneously and independently. The practice has been adopted that the ducts of the two tubes are connectable to get an even higher extraction volume flow at the incident.

The design should cover at least a reaction time of 4 minutes between the incident and the full function of the smoke extraction and the traffic control respectively. The consequences of longer reaction times must be declared in the design report.

### 7.3 Behaviour of the system

For the relevant scenarios, the behaviour of the tunnel system within the first 20 minutes from the incident must be estimated. The result can be decisive for increasing the capacity of the ventilation system.

### 7.4 Redundancy requirements

For the main ventilation components of safety, redundancy requirements are set:

- **Jet fans** After the failure of a group of jet fans the thrust remaining must be at least 90% of the required value.
- **Extraction ventilators** After the failure of a ventilator the remaining extraction flow rate must be at least 65% of the required value.

The directive contains further redundancy requirements for dampers, flow measurements, incident detection and plausibility of automated function checks.
7.5 Environmental aspects

The necessity to design the ventilation system to reduce the outflow of tunnel air through the portals must be determined by a separate environmental study according to Swiss law. Since first design assumptions are usually performed long before those studies are accomplished, the directive names values for the NO\textsubscript{x} portal load over which such systems usually are necessary.

<table>
<thead>
<tr>
<th>Environmental situation</th>
<th>NO\textsubscript{x} portal loads usually asking for measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>city centre</td>
<td>&gt; 10 t/year</td>
</tr>
<tr>
<td>residential</td>
<td>&gt; 20 t/year</td>
</tr>
<tr>
<td>industrial</td>
<td>&gt; 30 t/year</td>
</tr>
<tr>
<td>rural</td>
<td>&gt; 40 t/year</td>
</tr>
</tbody>
</table>

8. ESCAPE ROUTES

Only routes directly to the open are regarded as escape routes. Safety rooms without connection to the open are no alternative to escape routes. The escape routes should be placed equidistantly.

For uni-directional tunnel with two parallel tubes the following requirements are set:

- The distance between cross-connections is defined as 300 m.
- Every third cross-connection must be dimensioned for the vehicles of safety personnel.

For bi-directional tunnels and uni-directional tunnels without a second parallel tube the minimal requirements are still under discussion. Main factors for the definition of the escape route length are tunnel slope, tunnel length and traffic volume specified as number of cars and heavy goods vehicles per time. In certain cases a parallel safety tunnel or a passable duct below the road could represent the most economic solution. Presently the 6.6 km long San Bernardino tunnel is equipped with a safety tunnel below the road.

9. EXEMPLES

At present a large number of ventilations of tunnels in operation, in construction or in the planning stage are checked and brought to the level of the new requirement.

**Gotthard road tunnel** (bi-directional, 16.6 km)

About 18 months ago, the project to replace the fixed openings in the intermediate ceiling with controllable dampers was started. At the time of the tunnel fire in October 2001, a damper prototype had been installed. Today all 180 dampers are mounted and an intermediate ventilation system is in operation. Among all checked road tunnels in Switzerland, including San Bernardino, Gotthard is the only tunnel that has to be operated in fully transverse mode during normal traffic situation. In this mode the dampers have to be put into an intermediate position with very small opening angles (4° to 8°).

The tunnel passes the main alpine ridge, and barometric pressure differences between the portals up to 200 Pa must be considered. Due to the tunnel length and the very large installed fresh air capacity, jet fans to stop the longitudinal flow are not necessary.

**Aeschertunnel** (uni-directional, 2.2 km)

The Aeschertunnel as part of the new highway circle around Zurich is under construction. About half of the tunnel length is already excavated. Due to the fact that the risk of congestion is clearly in the range RV2 (figure 1), the tunnel ventilation system had to be changed lately. In the originally longitudinally ventilated double-tube tunnel, intermediate ceilings were added with two cross-connections between the ducts. With a slope up to 3 %, it was necessary to increase the jet fan thrust.
**Gotschnatunnel** (bi-directional, 4.2 km)

With an average slope of almost 5% the buoyancy by a natural temperature difference of 10 K is about the same as the buoyancy developed by a 30 MW fire. To meet the requirements of the directive (see above chapter 7.2.3), the fully transverse ventilation system with a minimal extraction capacity of 210 m³/s had to be completed with controllable dampers and jet fans. Due to the given tunnel width, 20 jet fans of rotor size 630 mm will be mounted pairwise toward the upper end of the tunnel.

10. CONCLUSIONS

The Swiss directive sets a new national standard for the ventilation of road tunnels. While a few years ago the demand during normal traffic situations dominated the design, today the requirements for the fire case is determining the size of the systems. Extensive trials in the past years in the scale 1:1 led to new findings that were included in the design principles. With the higher quality of ventilations in an emergency case the systems became more complex and maintenance of the systems will require highest priority in order to avoid malfunction with possibly fatal consequences.

11. LITERATURE


Swiss Federal Roads Authority FEDRO, (2001) Lüftung der Strassentunnel (draft, in German and French)


Studiengesellschaft Stahlanwendung e.V. (1998), Projekt 145.2, Brände in Verkehrstunneln, Bericht über Versuch im Maßstab 1:1, "Eureka trials"


World Road Association PIARC, (1999a) Fire and Smoke Control in Road Tunnels, report of C5/WG6

World Road Association PIARC, (1999b) Pollution by Nitrogen Dioxide and Ventilation Control Based on Traffic in Road Tunnels activity report of C5/WG 2