ABSTRACT

Great importance is attached to the ventilation in the event of an incident in a road tunnel. Appropriate operation of the tunnel ventilation system should first and foremost allow users to find their way to the next accessible emergency exit. Despite optimal operation of modern detection, traffic management and ventilation control systems, a rapidly spreading fire can cause smoke to stretch over several hundred metres. Today, the distance between the emergency exits does not generally depend on the length of the tunnel: in the event of an incident, users escaping a 400 m tunnel may have to travel the same distance to reach the emergency exit as users of a 10 km tunnel. In short tunnels it is important to remember that due to the required effective length, ventilation systems can cause serious disturbance in the primary incident zone. The authors believe that in such cases the ventilation system should not be operated in automatic mode, as this cannot adequately register the current and rapidly changing situation in most circumstances. Manual operation of the ventilation system is possible; however, this requires the deployment of experienced staff in a control room or on site at a later stage.

The considerations in this paper are based on the requirements valid in Switzerland for tunnel ventilation systems and the distances between emergency exits. The specifications regarding the areas of application of the ventilation systems are reasonable. However, in the case of short tunnels it is important to assess the effect of the ventilation system and its operation, particularly in relation to the gradient of the tunnel.

Key words: short tunnels, ventilation, emergency exit, safety

1. INTRODUCTION

Prompted by several horrific fires in road tunnels, there has been a great effort to increase safety for tunnel users over the last number of years. Many countries are already tending to enforce more stringent requirements for systems and their operation. Some of these requirements, for example, adding a second tube to single tunnels or even equipping new and refitting existing tunnels with state-of-the-art systems – particularly ventilation systems – are extremely costly. In addition to the prickly cost-benefit issues in the field of safety (this is addressed in [1] with regard to various safety systems) the advantages of a mechanical ventilation system in short tunnels are open to debate. Experience has shown that operating a ventilation system can further endanger tunnel users.

In Switzerland the generally applicable regulations governing the design of tunnel ventilation systems of 1983 were superseded by those of the FEDRO directive of 2004 [2]. In the event of an incident in a tunnel, the primary objectives in the first stage of self-rescue are to alert the tunnel users so that they can leave the tunnel via the emergency exits. In some cases, however, those involved in an accident may not be able to leave the scene, neither by themselves nor with the help of the other tunnel users. These people are dependent on the help of the emergency services with special equipment. Generally speaking, the emergency services only arrive at the scene 5 to 30 minutes after the alarm is raised.
The fundamental concepts for alerting the tunnel users and the emergency services, switching on the lighting, the signalling and the traffic management are well known. The basic ideas and objectives with regard to operating the ventilation system are very simple: gases which are harmful and which reduce visibility must be kept away from the tunnel users. There are two different approaches here, depending on whether there are people on one side of the incident or people on both sides. In the first case, which is more straightforward, the problem can be solved by longitudinal ventilation. In the second case, the smoke has to be directed through a separate duct. This ventilation system is expensive, especially in shorter tunnels.

**Figure 1: Basic ventilation strategies**

This paper looks at some of the issues that arise in the ventilation of short tunnels and proposes some possible solutions.

2. **BASIC REQUIREMENTS**

2.1. **General note**

The following considerations focus on the relevance of ventilation in the self-rescue stage. Other safety devices may be just as important as ventilation, or possibly even more so, in short tunnels. The need for and the usefulness of ventilation at a later stage of an incident are mentioned briefly.

Not least because of the requirement in the EU directive [3], much effort is put into developing risk assessment methods. There is, however, no widely recognised means of selecting individual safety features in tunnels as yet. In Switzerland, these decisions are currently taken jointly by the consenting and the operating authorities on recommendation of the design engineer. Different countries have different policies regarding responsibility. It is essential to note that the safety benefits of complex ventilation systems in short tunnels are small and in certain cases can pose additional risks.

2.2. **Escape routes**

The spacing between the emergency exits out of the tunnel determines the maximum distance the tunnel user has to travel by foot in an emergency in the primary danger zone. The exits must be clearly visible and – obviously - it must be possible to open the doors of the emergency exits. Often the pressure distribution in the tunnel during an incident is not taken into account during the design of the doors.

In Switzerland emergency exits in new double tunnels must be at 300 m intervals. This spacing is generally a fixed distance as opposed to a maximum distance. Reasons against shorter distances, for example in cut-and-cover tunnels or in tunnels with a parallel escape gallery or a second tube, include non-requirement, costs or problems with exits at the surface. According to SIA 197/2 [4, Section 8.8.2.3] and on the basis of the EU directive [3], tunnels without a second tube and tunnels without an escape gallery can have up to 500 m between the emergency exits depending on their gradient. The dependency on the gradient was determined using a simple approach which takes into account the tunnel user’s escape speed and the time available for escape. The information contained in SIA197/2 is limited to gradients of up to 5%.
Figure 2: Escape route distances in SIA 197/2 [4] and the range of the primary model specification [5]. SIA 197/2 specifies gradients in the range of up to 5%.

The longer distances between escape routes in single tunnels without parallel tubes or escape galleries is solely due to the increased costs; after all, the ventilation requirements for tunnels with two-way traffic are much stricter (Figure 3). In Switzerland it was assumed until 1998, on the basis of the knowledge of the effect of tunnel ventilation at that time that no emergency exits at all were required in tunnels with transverse ventilation.

2.3. Ventilation

The basic objective of operating the tunnel ventilation system in the event of an incident is to minimise the spread and concentration of the harmful substances produced in the tunnel and escape routes. This is intended to aid the self-rescue of tunnel users, keep the access paths of the emergency services free from smoke and extract smoke from the tunnel after a fire. In case of an incident without a vehicle fire, the ventilation system should in the same way help to keep any volatile, toxic substances away from tunnel users.

The Swiss guideline has stipulated a standard in this respect which must also be applied when refurbishing existing tunnels. Deviations from these specifications are permitted provided they are adequately justified on the basis of special project-specific circumstances.

Figure 3: Area of application for ventilation systems as per guideline [2] valid for gradients up to 5%. NV: natural ventilation, LV: longitudinal ventilation without extraction, SE: with extraction. Classification into areas A, B or C is based on the volume and composition of traffic as well as the relevant gradient.

Below is a discussion of the issues raised when changing the basic ventilation systems natural ventilation (NV) to longitudinal ventilation (LV) and longitudinal ventilation to extraction (SE). The transitional areas illustrated in figure 3 are based on general risk considerations. It is not possible to provide a quantified explanation in this general form.
2.4. Supplementary measures and systems

As a matter of principle the systems are to be operated automatically in the event of an incident according to the situation. This is conditional upon the incident being quickly and accurately detected and the status being adequately monitored. A special guideline [6] has been formulated for detecting smoke very quickly. The sensors at intervals of 100 m should be able to automatically trigger the emergency ventilation programme within one minute. This system should be used in addition to a linear temperature detector and event detection via traffic video monitoring.

Manual override of the automatic ventilation response must be possible at any time. Experience has, however, shown that this can only be expected from highly experienced staff.

Figure 3 illustrates the marked difference in requirements concerning the system choice for tunnels with one-way traffic depending on whether situations with full congestion are likely. This specification is based on the PIARC publication [7]. The operation of the system depends strongly on the traffic condition at the time of the incident. It is difficult to continuously and reliably detect the traffic status. The intention is to perform this by means of event detection via traffic video monitoring.

Some fire brigades are already equipped with mobile fans which are designed for use in tunnel fires. In short tunnels without ventilation a mobile fan can be useful for fighting the fire. In tunnels with a fixed and adequate ventilation system the use of mobile fans is not generally recommended due to the risk of adverse interaction with the tunnel ventilation.

The Swiss guideline [2, Section 7.2.6] requires that structural measures be taken in twin tube tunnels to prevent harmful gases from being recirculated from the tunnel in which the incident occurred into the opposite tube, which is mostly used as an escape and access route. Generally a 30 m long inflow zone must be separated from a 100 m long exhaust zone with a portal offset or a high partition wall.

![Figure 4: Structural separation of portals in tunnels with two parallel tubes](image)

This may even be of relevance in short tunnels without mechanical ventilation (see case study 4).

3. VENTILATION CONSIDERATIONS

3.1. General

The longitudinal ventilation system is appropriate for tunnels with one-way traffic without congestion. If, however, there is the possibility of people on either side of the incident scene, the situation can no longer be fully controlled with longitudinal ventilation alone. The following looks at the suitability of the systems from the point of view of ventilation under various constraints.

3.2. Systems without extraction

There is no linear correlation between the length of the tunnel and the sum of the pressures contribution by buoyancy, tunnel friction, traffic and meteorology. Calculated according to the respective tunnel length, short tunnels require higher values.
In short tunnels the arrangement of jet fans is problematic. To ensure that an adequate thrust is generated, the jet fans should be at about 80 m intervals. Generally speaking there should be more than one group of jet fans (except in case study 6) and, in order to reduce the number of groups endangered by the fire, there must be at least 100 m between the groups.

In tunnels with one-way traffic, where congestion does not need to be taken into account for operating the ventilation in the event of an incident due to the volume of traffic, the flow measurement is of no great consequence - unlike in tunnels with two-way traffic where the jet fans have to be controlled in accordance with the current flow measurements. In this case it is essential to ensure that the flow measurement can adequately represent the effective volume flow at the measuring section. Readings from appliances which can be distorted by the jets of the fans or the effect of the fire must be eliminated. The target low longitudinal flow is extremely difficult to achieve. It must be noted that in short tunnels it is virtually impossible to prevent smoke from spreading throughout the whole tunnel section with jet fans. Consequently, this is highly likely to further endanger tunnel users.

### 3.3. Systems with extraction

The Swiss guideline demands the smoke extraction system with controllable exhaust air dampers to be designed depending on the tunnel cross section. Other countries use smoke production values derived from the design fire load as their basis. To control the situation in accordance with today’s assessment, the extraction rate at the place of the fire generally needs to be between 120 and 220 m$^3$/s. The length of the tunnel is irrelevant in this respect. This means that the cost efficiency of the mechanical ventilation equipment is small for short tunnels.

In tunnels with a gradient in particular, an extremely one-sided pressure can build up, even in a stationary state. In order to generate the desired symmetrical flow to the extraction point, this pressure must be compensated by using jet fans with the inevitable result of de-stratifying the flow in the tunnel. The problems with regard to controlling the air flow in the system are discussed in 3.2.
4. CASE STUDIES

4.1. Tunnel 1

Tunnel description
- Planned tunnel in suburban centre
- Length 580 m, varying gradient averaging 2.3%
- Two lanes, two-way traffic, with short separate tubes at each end
- High average traffic volume with low heavy traffic ratio
- Longitudinal ventilation with jet fans
- Two escape routes to the open

Problem
The project intends to equip the tunnel with six groups of two jet fans and to control the system according to the flow measurements taken in between. The layout of the flow sensors is problematic. Automatic operation of the longitudinal ventilation system can jeopardise the safety of tunnel users. It is not possible to separate the traffic flow in opposite directions due to lack of space.

Proposed solution
The ventilation system is exclusively designed for manual use following the instructions of the emergency services on site or by an operator via TVM. Two emergency exits should be planned at approx. 200 m intervals: this is already below the minimum requirement of 500 m.

Conclusion
When defining the operation scenarios it is important to take into account non-ideal operation of the longitudinal ventilation system due to the variety of possible sources of error. The short distance between the emergency exits considerably increases safety in the event of an incident.

4.2. Tunnel 2

Tunnel description
- Existing tunnel at Alpine crossing
- Length 1,000 m, gradient 6%
- Two lanes, two-way traffic
- Low average traffic volume but high ratio of heavy traffic, high peak values due to holiday traffic
- Longitudinal ventilation with jet fans
- No escape routes to the open

Problem
The longitudinal ventilation system cannot guarantee the safety of tunnel users in two-way traffic. Given the steep gradient in the relatively short tunnel it is not worth installing an extraction system because there is still the problem of controllability.

Proposed solution
To solve the problem, a second tube needs to be built. The situation could then be brought under sufficient control using a longitudinal ventilation system. Alternatively, consideration should be given to installing emergency exits at short intervals - say 200 m.

Conclusion
Tunnels with two-way traffic and a gradient greater than 5% should not be built, otherwise the distance between the emergency exits must be reduced.
4.3. Tunnel 3

Tunnel description:

- Planned tunnel at Alpine pass road at 2,000 m above sea level
- Length 800 m, gradient 8%
- Two lanes, two-way traffic
- Low average traffic volume with high peak values due to holiday traffic
- Longitudinal ventilation with jet fans
- No escape routes to the open

Problem

The longitudinal ventilation system cannot support the safety of tunnel users in two-way traffic. Given the steep gradient it is not worth installing an extraction system because there is still the problem of controllability.

Proposed solution

It is not considered worthwhile building a second tunnel due to the overall low traffic volume. The route needs to be revised. If the tunnel were to be built as planned, emergency exits would have to be installed at short intervals (Figure 2: 150 m).

Conclusion same as for case study 2

Tunnels with two-way traffic and a gradient greater than 5% must not be built.

4.4. Tunnel 4

Tunnel description:

- Tunnel under construction
- Length 600 m, gradient <1 %
- One-way traffic, two parallel tubes
- Medium traffic volume
- Natural ventilation
- One crossway in the centre of the tunnel (opposite tube is escape and rescue route)

Problem

The portals are directly beside each other. The tunnel opens directly to a bridge and heavy structural precautions to prevent smoke recirculation at the portals are complicated.

Proposed solution

Instead of a partition wall, it was considered installing low-powered jet fans in the opposite tunnel. Since the effect of such an installation would be too late this measure is not worthwhile.

Conclusion

Incorporate structural measures to prevent smoke transfer right from the early planning stages. A light construction (noise protection) wall can do the purpose as well.
4.5. Tunnel 5

Tunnel description:
- Planned underpass in urban area reserved for development
- Length 700 m, U-shaped length profile with gradients up to 3%
- Two lanes, two-way traffic
- High average traffic volume with high peak values due to rush-hour traffic
- Longitudinal ventilation with jet fans
- Two escape routes leading outside

Problem
The longitudinal ventilation system is only of minimal benefit to the safety of tunnel users. Automatic operation is therefore not recommended.

Proposed solution
In the middle section the underpass could be opened to a length of 150 m and equipped with noise protection. A central emergency exit should be constructed in each of the two tunnels. An escape stairway to the surface is to be installed in the open section.

Conclusion
If possible the length of the short tunnel should be reduced to such an extent that a ventilation system is not required. There should be adequate space between the tunnels.

4.6. Tunnel 6

Tunnel description:
- Existing cut-and-cover tunnel
- One-way traffic in two tubes of three lanes
- Tube lengths of 800 m and 1,000 m respectively, gradient 1.5%
- Very heavy rush-hour and through traffic
- Longitudinal ventilation with jet fans
- Escape routes to the open or to an escape gallery (not into opposite tunnel) at short intervals

Problem
The tunnel currently features a spot extraction system in the middle of the tunnel. In the foreseeable future frequent congestion is expected in the tunnel. It is planned to keep congestion in the tunnel to a minimum by implementing traffic management measures. Jet fans cannot be accommodated in the tunnel due to lack of space.

Proposed solution
The tunnel will firstly be extended at the entrances in order to accommodate a group of powerful jet fans. These are to be fitted directly at the entrance and can only function in the direction of traffic. Together with the traffic management measures a ventilation system which conforms to the guidelines for a tunnel with low frequency of congestion is to be developed. Smoke is to be prevented from being transmitted to the opposite tunnel at the entrances by way of an additional partition.

If the congestion frequency cannot be reduced to a suitable level, the installation of an extraction system with controllable dampers and inwardly blowing jet fans at the exits should be considered.

Conclusion
In tunnels with one-way traffic and low frequency of congestion jet fans can be positioned directly at the entrance without redundancy. In the event of a fire in close proximity, the ventilation system does not need to be operated. In the above case the fact that the escape routes do not lead into the opposite tube alleviates the problem.
4.7. Tunnel 7

Tunnel description:
- Existing tunnel at Alpine pass at 1500 m above sea level
- Length 870 m, gradient 11%
- Two lanes, two-way traffic
- Open six months per year, on good weekends heavy tourist traffic for short periods
- Longitudinal ventilation with jet fans (low installed thrust)
- No escape routes

Problem
Even with low thermal power, the longitudinal flow is greater than the speed of escape. The advantages of a ventilation system are limited to a few scenarios. On the other hand, a ventilation system could further jeopardise tunnel users in many situations. It would take the emergency services at least 30 minutes to be deployed.

Proposed solution
The ventilation system should not be operated in the event of an incident. As a lesser priority, the tunnel should be fitted with emergency exits 100 m apart.

Conclusion
The ventilation in this system does not increase safety in case of an incident. The focus should be placed on rapid detection, alerting and short escape routes.

5. CONCLUSIONS

Ventilation aspects must be taken into account right from when the route is being planned. The required jet fan thrust depends strongly on the length profile of the tunnel. The design fire load plays an important role here. In tunnels with two-way traffic the spread of smoke becomes difficult to control with high gradients. Tunnels with two-way traffic and gradients over 5% should therefore not be built.

The general requirements for ventilation systems contained in guidelines must be verified according to the specific tunnel. Possible negative consequences of the ventilation must be assessed and included in the operating specifications. The non-ideal and often difficult to simulate interfering factors are fundamental here. If the proposed solution diverges from the general specifications, detailed documentation about the factors that led to the decision is imperative for legal reasons.

In borderline cases regarding the suitability of a ventilation system it may be necessary to refrain from automatic operation. It can be assumed that there is room for improvement in the control algorithms used today, but especially in short tunnels the acquisition of accurate data is difficult.

Passive, structural measures such as partition walls or sufficient distance between the portals can prevent the recirculation of harmful gases.

In addition to the usual measures such as a fast detection, a clear alarm and signalling steep tunnels should have short distances between emergency exits. In any case, short distances are intended to complement other measures and should not be regarded as a substitute. All technical measures can only support the primary important self-rescue. This presupposes that the tunnel users are informed about the possible emergency situations in tunnels in order to act correctly.
LITERATURE

[4] Swiss Association of Engineers and Architects Norm SIA 197/2, Projektierung Tunnel, Strassentunnel, 2004
[7] PIARC: Fire control in Road Tunnels, Report 05.05B, 1999