PROBLEMS ON VENTILATION IN COMPLEX CITY TUNNELS

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ABSTRACT

In most cases city tunnels are characterised by heavy traffic and involve complex connections to adjoining surface roads. This results in many cases in on and off ramps inside the tunnel. Such ramps, together with traffic guiding installations increase the problems in both ventilation design and in ventilation control in the case of a fire. Based on the case of a city tunnel in Austria which carrying some 60,000 veh/day and involving a complex connections to the surface roads, the experience gained during the installation and testing phase of ventilation systems are discussed.

Keywords: ventilation design, city tunnels, incident ventilation

1. INTRODUCTION

National and international guidelines require the installation of ventilation even in short tunnels as soon as the traffic volume exceeds a certain threshold value. As soon as mechanical ventilation is necessary the design has to be appropriate for normal operation as well as for incident ventilation. Normal ventilation does not play a significant role as most of the city tunnels are twin tube tunnels with unidirectional traffic, and as long as traffic is free flowing, the piston effect results in self ventilation. This is not the case in incident ventilation, where parameters like design fire load, road gradient and cross section play a decisive role.

Many tunnels in cities carry heavy traffic. In addition they may have on and off ramps in the tunnel, which have an almost unpredictable influence on the ventilation behaviour in incident cases. However, it is necessary to adapt the ventilation design and the procedure for ventilation control in such as to come as near as possible to the goals proposed in the respective guidelines.

In many cases the benefits of ventilation design are counteracted by various other factors, e.g. construction constraints on tunnel height which might result in small fans being mounted in the corners of the cross section, or the sitting of road signs in combination with on and off ramps inside the tunnel. A prerequisite for well functioning ventilation control in incident cases is high quality information about the air speed inside the tunnel. This implies that the sensors have to be mounted at locations not influenced by running fans, road signs or other installations which might disturb the flow field.

2. VENTILATION DESIGN GUIDELINES

In Austria, ventilation design is based on the guidelines RVS 9.261/9.262. These guidelines state the requirements for normal and incident ventilation. Normal ventilation control can be based either on in-tunnel air quality (visibility or CO concentration) or the number of vehicles passing through the tunnel. Correct incident ventilation involves the provision of a predefined air flow with a defined velocity of the smoke/air mass at the incident location.

In the current version the requirements are stated as follows:
• Mechanical ventilation is required for tunnels with a length of more than 500 m and more than 10,000 veh/day/lane or more than 700m and a traffic density of more than 5,000 veh/day/lane.
• Design fire load: 30 MW
• Unidirectional traffic: max. air velocity 2 m/s in the direction of the traffic flow
• Bidirectional traffic: max. air velocity 1 – 1.5 m/s in the direction of the air flow just before the incident. Reversal of the air flow is possible at special locations (e.g. near portals) when it enhances the self-rescue possibilities of tunnel users.

These simple requirements concerning air velocity and direction can cause big problems as soon as complex tunnels have to be considered.

3. COMPLEX CITY TUNNEL

The problems which can occur shall be demonstrated by taking the Bindermichl tunnel in the city of Linz/Austria as example. This tunnel is part of the A7 highway which leads traffic through the city in a north-south direction (see Figure 1). The Bindermichl tunnel is connected to the Niedernhart tunnel, having the connections to the city center between them. Both of the tunnels carry some 60,000 veh/day and are important for commuter traffic as well as for transit traffic from Austria to the Czech Republic.

![Figure 1: Location of the Bindermichl and Niedernhart tunnels at the A7 highway in Linz/Austria](image)

3.1. Technical details of the Bindermichl tunnel

The Bindermichl tunnel has a length of 1 km and was built in cut and cover. The on- and off ramps “Mudenstrasse” are located roughly in the middle of each of the two bores. While the east bore (south to north) has two on- and off ramps, the west bore has only one on- and one off ramp. The gradient is roughly 1% from south to north with the exception of the most northern 400 m, where the gradient reaches 4%. The on- and off ramps have a gradient of 4%. Although the tunnel was designed to be used in unidirectional mode, bidirectional traffic was to be taken into account as during the first year only the east bore was in operation.
The cross sections vary throughout the whole length, and reach up to 120 m² (180 m² at one portal). Figure 2 shows a sketch of the east tube. The west tube is similar, with the exception that the Muldenstraße ramp is only on one side. Figure 3 depicts the south portal section (section A-B in Figure 2).

Ventilation design came up with a necessary thrust of some 7300 N to be produced by 18 fully reversible jet fans (408 N each). These were grouped into 2 fans per cross section.

Figure 2: Sketch of the Bindermichl East tube

The Muldenstraße ramps split the tunnel more or less into three sections. The entrance section between the portal south and the Muldenstraße off-ramps (zones A – D in Figure 2) with three lanes plus pull off lane (hard shoulder), the central section between the off- and on ramps (zones E-H in Figure 2), two lanes plus pull off lane, and the exit section from the on-ramps to the exit portal (zones I – J in Figure 2), with up to 6 lanes.

Figure 3: View of the south portal section (zone A and B in Figure 2)
3.2. Fan positioning

The positioning of the fans was restricted by the following facts:

- No more than two fans per cross section were possible due to problems with ceiling fixed fans.
- The fans had to be wall mounted wherever possible. The direction signs for the traffic had to be placed exactly above the respective lanes.
- The minimum distance between two cross sections with fans should be at least 80 – 100 m.
- Any loss of thrust due to interference with the traffic signs has to be avoided.
- Fans have to be mounted such that the thrust is not lost through the on- and off ramps.

Due to the short length of the tunnel and the huge number of fans it was almost impossible to keep the minimum distance of 80 to 100 m between the fans without running into problems either with the ramps or the position of the traffic signs or lights.

After a first installation of the fans and some flow field measurements throughout the whole tunnel a very inhomogeneous flow field was observed. While in the sections close to the wall the wind speed was relatively high, the air flow in the centre was much slower. In some cases recirculation was even observed in the sections between portals and ramps. Only in the middle part of the tunnel (between the ramps) was a more or less uniform wind profile achieved. As it was not possible to change the position of the fans, the fans were upgraded by installing bent entrance and exit parts (so called banana jets). With this type of fan the negative flow field effects of having only two wall mounted fans per cross section were reduced (but not fully resolved).

The ramps are more or less open holes in the tunnel. The length of the 4 ramps is some 100 m each with a road gradient of 4% (exit positive, entrance negative). If fans are mounted too close to the ramps, the ramps impair the performance of the fans and each fan downstream of a ramp pushes a large part of the air out of the tunnel instead of providing the required thrust for in-tunnel air movement. In addition, each position between the on-ramps and the exit portal mainly results in introducing new air into that part of the tunnel instead of moving the air inside the main part of the tunnel. Figure 4 and Figure 5 show the main features of the air flow inside the tunnel, as dependent on the location of the activated fans. The influence of wind pressure from outside the tunnel is not taken into account in these sketches.

![Figure 4: Sketch of the air flow as dependent on the active fans (section south and centre)](image-url)
The negative effects of the ramps on the air flow have to be taken into account when designing ventilation procedure for cases of fire. Despite having all the power (thrust) available for controlling the air flow inside the tunnel in practise “false” air from the ramps or air leaving over the ramps has an almost unpredictable influence on the in-tunnel situation.

3.3. Positioning of air velocity sensors

The ventilation procedures for incident cases are based in many countries on achieving and retaining a certain air velocity during the incident case in order to support rescue operations. Hence, the exact knowledge of the air flow inside the tunnel is imperative in cases of fire inside the tunnel. The air velocity sensors are a very important part in the ventilation procedure in incident cases. Without proper working sensors a useful ventilation strategy is almost impossible. The Austrian guidelines require proof of the accuracy of the sensors. In the case of point measurements it has to be proved that the results given by the sensors are representative of the average air velocity over the respective cross section of tunnel.

When looking at the outline of the Bindermichl tunnel (Figure 2) there is almost no appropriate place for an unbiased measurement of the average air velocity over a cross section. First, the cross section is too big to work with single point measurements. Second, most locations at which a positioning of sensors might be possible are either influenced by the jet fans (when in operation) or in some way influenced by air flows over the ramps.

In the end, the tunnel was equipped with sensors in four different locations. All of them are in the same cross section as the fans, but this was the only position where the influence of the jet from the fans could be eliminated. The location of the sensors is depicted in Figure 2. In order to have a picture of the average velocity within the cross section a sonic measurement system was chosen. While in the middle part of the tunnel the distance between the two walls of the tunnel did not exceed the maximum distance between sender and receiver, this was not the case for the sensors in the north and south sections. At these locations it was necessary to have a special installation for the receiver on the ceiling of the tunnel, while the sender had to be mounted on the wall.

Data collected by the velocity sensors are mainly used for ventilation control during specific incidents. If the incident is located near a velocity sensor these data can not be used as they may be biased either by the hot temperature or by turbulence generated by the fire. Thus, data from a different measurement section have to be taken. In the case of the Bindermichl tunnel the measurements in the south and north sections are not as reliable as those in the middle section. The reason for this is the unpredictable influence from airflows over the ramps. Therefore, for most incident cases the velocity information is taken from the sensors mounted in the middle section (LG1, LG2, see Figure 2). However, these data are taken at a location with a totally different cross section compared to the sections south and north. Hence,
correction factors have to be applied when these data are used for the ventilation control in the other sections. The correction factors are mainly based on the relative proportions of the tunnel cross sections at the incident and the measurement location, and adapted by on site measurements in order to include influences caused by the ramps.

3.4. Incident ventilation

In tunnels with dense traffic and a high risk of congestion the probability of having an accident is higher than that expected in tunnels in rural areas. In the case of the two A7 tunnels the ramps inside the tunnel as well, as the complex traffic situation outside, further increase this probability. A big effort was made to take this complex situation into account during the planning stage.

3.4.1 Simulation

Intensive numerical simulations were already performed during the design phase in order to take the influence of the incoming/outgoing air into account. These simulations were made using a CFD code which allows the coupling of tunnel and ramps (Almbauer et al. 2004). They showed clearly that due to the influences from the Muldenstraße ramps the requirements for ventilation in incident cases can not be achieved at all possible locations inside the tunnel. The only solution to this problem would be to separate hydraulically the Muldenstraße ramps from the main tunnel during fire incidents. In such cases the main tube could be considered as a simple tunnel and the ventilation goals could be achieved without any major problem. Measures to implement such a hydraulic separation have not been applied for several reasons (see section 3.4.3).

The incident ventilation procedure was developed on basis of the results of numerical simulations. This procedure was later tested in the tunnel in order to improve the ventilation performance and to adapt the scheme wherever necessary.

3.4.2 Ventilation tests

The Austrian guidelines for tunnel ventilation require a hot smoke test in each tunnel before the tunnel goes into operation. As the situation in the Bindermichl tunnel – especially in the east bore – is very complex an intensive test phase was applied. Hot and cold smoke tests were performed at different locations and for different ventilation schemes (uni- and bi directional traffic). The incident ventilation procedures were tested for all of the 10 fire detection sections, as all of them apply different activation levels of the fans and they use the air flow information from different velocity sensors. The test of all of the sections (A-J) was performed without smoke, with manual triggering of the incident and monitoring of the response of the system (fans) and the air velocities inside the tunnel.

Special emphasis was put on tests in the ventilation sections I and J, as these sections are in the region with the highest gradient, have a very big cross section and are influenced most by the airflows over the Muldenstraße ramps. As almost no time was available for tests in the west bore of the Bindermichl tunnel, the ventilation situation for the west bore was also simulated in the east bore. The west bore north portal site, is the most critical location, as in this section the Austrian guidelines require an airflow in the direction of the traffic, i.e. downwards the 4% gradient. This results in the highest power requirement for ventilation.

The hot smoke tests were performed in the zones D and I. The simulation for the west bore entailed physically closing Muldenstraße the on and off ramps at the east side of the tunnel. In accordance with the Austrian guidelines 40 l diesel and 10 l gasoline were burned in a pool with an area of 2 m². Such a fire results in a heat release of some 3 MW. In order to simulate
the buoyancy generated by a higher fire load, a mobile fan with a maximum thrust of 3000 N was employed. The position of the test fire and the mobile fan is depicted in Figure 6.

**Figure 7** shows the test performed at the location in zone I with one Muldenstraße on- and one off ramp open. This test served to simulate unidirectional traffic in the west bore. The ventilation goal was smoke movement from the north to the south portal (which is the driving direction in the west bore) with a velocity between 1.5 and 2 m/s. In such a case the ventilation system has to overcome the buoyancy forces caused by the fire and to blow the smoke against the updraft in the tunnel. The picture was taken shortly after ignition. The large cross section allowed the smoke to rise. Although a wind velocity in driving direction was present, back-layering built up quickly.

![Figure 6: Location of the hot smoke tests](image)

**Figure 6: Location of the hot smoke tests**

![Figure 7: Test fire section I (north) with the open Muldenstraße ramp (right hand side)](image)

**Figure 7: Test fire section I (north) with the open Muldenstraße ramp (right hand side)**

**Figure 8** shows the results for the test. The black solid line represents the velocity in the fire region. A target velocity of -1.5 m/s needs to be achieved. The value at sensor LG1 was the
control value for the ventilation. This sensor was located in the central part of the tunnel (see Figure 2). As the ratio between the cross-section in the central and north part of the tunnel has to be taken into account, the wind velocity at that location had to be in the range of 3 m/s (shaded range in Figure 8). Back-layering cannot be prevented. In order to minimise the risk of a down mixing of smoke in the region between entrance portal (north) and fire location, the fans in section I and J were not activated. The main work was done by the fans in the middle part of the tunnel (sections E-G). This resulted in an overpressure in the region downstream of the fire. Hence, a positive pressure drop between tunnel and outside existed and smoke polluted air was pressed out also through the Muldenstraße south ramp. This can be seen in the broken and dotted line in Figure 8. During this phase the ventilation power was insufficient and the target velocity at LG1 was not reached. The control system reacted by activating the fans in the south section (A-D), inducing in an inflow of air through the Muldenstraße on ramp (south). The opposite effect occurred at the Muldenstraße north ramp. At the beginning, air with some smoke was moving out (positive values). The increased ventilation power resulted in a reversal of the flow and an inflow occurred (20:20 in Figure 8). The increasing ventilation power resulted mainly in an increased air inflow over the Muldenstraße north ramp instead of pulling the smoke from the fire location downwards through the tunnel. In order to simulate higher heat releases the mobile fan positioned north of the fire location was turned on (20:26). This even resulted in a reversal of the flow direction in the incident region. The region between incident and entrance portal, i.e. the region where people might be trapped and the rescue operations are expected, was fully covered with smoke. After a few minutes the mobile fan was stopped (20:31) and the flow and smoke turned back in the right direction.

Although all available fans were running at that time (except those at the incident location) and the target velocity was reached at the control sensor LG1, the available thrust was mainly used to bring in air from the Muldenstraße north ramp where the wind speed went up to 4 m/s. The main results of this test were:

- For small fire loads the target velocity in the incident zone was reached
- The back-layering at that time was already massive, but due to the unusual height of the tunnel in that region (more than 7m) there was no risk for people.
- An increase in fire load resulted in a reversal of the flow in the incident region and a fully smoke filled zone between incident location and entrance portal. The ventilation system was not able to provide the conditions required by the guidelines.
- Any increase in ventilation power would not help as a big part of the air enters the tunnel through the north ramp Muldenstraße. There is no positive effect for the fire zone, but there is a negative effect for the remaining part of the tunnel.
- In such cases, additional, non ventilation related measures have to be taken to improve the self-rescue possibilities for persons captured in the region between tunnel entrance and fire.

For all other locations the ventilation system performed well.
3.4.3 Separation of the ramps in incident cases

As mentioned above the Muldenstraße ramps have a negative impact on the performance of the ventilation in incident cases. The only way to overcome the problems caused by the air movements over the ramps would be to separate them from the main tube. In such a case a simple hydraulic system would result and ventilation control would not be biased.

There are two principal possibilities to establish such separation:

a) Separation by mechanical installations

b) Separation by extra ventilation inside the on and off ramps

When looking at mechanical installations, either a fixed installation using solid doors or a flexible installation using movable curtains are both possible. Solid doors have been rejected due to the expense required in their installation, and due to specific maintenance and material constraints (e.g. the need for stainless steel and temperature resistance). The installation of flexible curtains (Öttl at al. 2002) has been discussed in detail as it would allow separation without cutting off any of the escape routes. The tunnel operator has rejected the latter option on grounds of lack of existing experience with such systems.

From the tunnel operator’s point of view option b) is the preferred one, as any malfunction of the system would not cause any problem for the tunnel users and fan maintenance is not considered a problem. However, the drawback of additional fans on the ramps is that this would include a further unknown influence on the ventilation control. The control system would become unmanageable as the flow in the regions where the ramps enter the main tunnel would be almost unpredictable. Thus option b) was rejected too.

It was decided to work with uncontrolled air flows over the ramps and to compensate for lack of conformity to guidelines by introducing other safety increasing measures such as additional escape routes.

Figure 8: Results of test with open Muldenstraße on- and off ramp and activation of mobile fan.

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4. CONCLUSIONS

City tunnels are often characterised by complex situations involving high traffic loads, complex links to adjoining surface roads, on- and off ramps inside the tunnel, etc. This complexity in construction and traffic situation is a challenge for ventilation design. Very often the ventilation requirements conflict with other requirements e.g. for traffic management. High traffic loads and high gradients inside the tunnel result in a high demand in ventilation power. In many cases city tunnels are quite short (up to 1 km), often making it difficult to find enough space for fans, velocity sensors etc. Ramps inside the tunnel complicate the flow situation. Hence, the official requirements for ventilation control are not easy to comply with. In order to meet requirements as closely as possible, proper ventilation strategies have to be developed. Simulation techniques are a prerequisite; however final adjustment has to be based on tunnel tests. Despite all the care taken, situations can still occur where ventilation capability is not sufficient, and where additional measures have to be taken to support rescue possibilities and to increase safety for tunnel users.

REFERENCES

