USE OF MOBILE TUNNEL VENTILATION DEVICES TO ASSIST EMERGENCY SERVICES DURING FIRES IN UNDERGROUND ROAD SYSTEMS

Stefan Hofbauer, Hubert Heissl  
Rosenbauer International AG, Paschinger Str. 96, A-4060 Leonding, Austria

ABSTRACT

Constantly rising volumes of traffic mean that the risk of accidents on open roads and in tunnels is also steadily on the increase. The danger of vehicles catching fire in underground road systems is exacerbated by the fact that the smoke and toxic gases emitted soon reach dangerous levels. This often prevents emergency services from reaching the scene of the accident fast enough to rescue people and fight the fire, and also hampers them during clean-up operations. Mobile ventilation devices can be of considerable assistance to the emergency services by affecting the natural air currents in the desired way or boosting the capacity of the stationary ventilation systems in place.

Having evaluated the operational conditions required, mobile tunnel fans were designed and their efficiency validated using CFD calculations. In many field tests, some under emergency conditions, the results of the theoretical considerations were examined and the handling checked. It was therefore proved that if these ventilation devices are taken into consideration in operation procedures, they can be a great help to the emergency services and enable them to reach the scene of the accident much faster.

Key words: tunnel safety, fire, positive pressure ventilation, PPV, fan, mobile

1 CURRENT SITUATION

The volume of traffic in Europe has risen dramatically over the past few decades and in view of the current situation with globalisation, EU enlargement to the east and the expiry of existing transit agreements, it would appear that it will continue to rise, above all national and transnational freight traffic. Although the EU Commission is committed to stepping up rail transport, the majority of passenger and freight traffic will also go by road in the future.

Fig. 1: Traffic volume in Europe [VDA 2001]
At the same time the percentage of underground traffic routes is growing. In Alpine regions, such as Austria, Switzerland and Italy, tunnels are often the only possible or at least the shortest link, while in less mountainous countries, such as Germany, they are usually built for reasons of noise abatement (city bypasses). Of the 250km of road tunnels in Austria, around 190km are in the main road network (motorways and dual carriageways). As the main network is approx. 2000km in length, the tunnels represent roughly ten per cent of the total [OEAMTC]. The percentage is equally high in Switzerland where there are 170 tunnel kilometres out of a total of 1640 motorway kilometres. Switzerland is currently planning on building a further 218 motorway kilometres, 110 of which will be underground, thus raising the tunnel share to 15 per cent over the next few years [ASTRA 2000]. Table 1 and Fig. 1 show the Austrian motorway and dual carriageway tunnels broken down into groups in lengths of under 1km, 1 to 5km, 5 to 10km and over 10km.

### Table 1: Tunnels in Austria

<table>
<thead>
<tr>
<th>Lenght [km]</th>
<th>One-way traffic</th>
<th>Two-way traffic</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number</td>
<td>Total length [km]</td>
<td>Number</td>
</tr>
<tr>
<td>&lt; 1 km</td>
<td>4</td>
<td>2</td>
<td>99</td>
</tr>
<tr>
<td>1 to 5 km</td>
<td>8</td>
<td>17</td>
<td>16</td>
</tr>
<tr>
<td>5 to 10 km</td>
<td>8</td>
<td>55</td>
<td>0</td>
</tr>
<tr>
<td>10 km</td>
<td>1</td>
<td>14</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>88</td>
<td>115</td>
</tr>
</tbody>
</table>

By far the largest number of tunnels is to be found in the group under 1km long. Even if the kilometres of the individual groups are added together, almost two thirds are still in tunnels less than 5km long. The majority of these sections are two bore, i.e. each with one-way traffic. The groups longer than 5km represent the typical Alpine tunnels. They are generally single bore, but some of them will be upgraded to two bores for reasons of safety and capacity.

### Fig. 2: Tunnels in Austria

If the tunnels in the federal and provincial roads are included in these figures, the focus is still on shorter tunnels to an even greater extent.
In the tunnels various types of stationary ventilation systems are used [Pucher 1999].

**Fig. 3: Ventilation designs**

**Longitudinal ventilation**: primarily used in tunnels up to 3km long. The air is replaced by axial flow in the tunnel that is either caused by the thrust from the vehicles (one-way traffic) or assisted by high volume fans.

**Semi-cross ventilation**

**Extract air**: the supply air is sucked in through the tunnel mouths, and the extract air removed through a separate duct and blown outside.

**Fresh air**: fresh air is blown into the tunnel through a duct, and the extract air dissipates through the tunnel mouths.

**Full cross ventilation**: fresh air and extract air are moved in and out of the tunnel through separate ducts. This ventilation design does not therefore require axial flow in the tunnel.

**2 FIRES IN UNDERGROUND TRAFFIC SYSTEMS**

Road accidents in tunnels are particularly critical situations. In statistical terms, the probability of having an accident in underground sections is less than on the open road. If however the risk is examined as the product of accident probability x accident consequences, it soon becomes clear why safety in tunnels has become such an issue [Knoflacher]. When a vehicle in a tunnel catches fire and cannot be kept under control, the consequences can prove catastrophic, as many examples in the past have shown. In addition to the injuries sustained by the people involved, there is the damage to the tunnel itself and the costs of closure.

The greatest problem in the case of fires in tunnels is definitely the enormous heat and smoke that develops and often cannot be expelled properly. If a fire gets out of hand, the only way people can save their lives is to try and escape. An additional danger lies in the fact that the smoke initially forms layers, i.e. the fumes rise up to the roof and the fresh air remains near the ground. The people are lulled into a false sense of security while the toxic gases spread above their heads. After a few minutes, however, the layers start to mix and the people are trapped in the middle of asphyxiating smoke.

Smoke and heat are also what prevent the emergency services from reaching the scene of an accident quickly. Conventional compressed air devices (twin packs) are designed for 30 to 45 minutes maximum. If the services have to proceed on foot, it does not give them much time to rescue the people and fight the fire. Fire brigades at the tunnel mouth are therefore equipped with breathing apparatus that permits longer periods in action. In addition, the smoke obstructs vision, reducing the speed of advance and making it virtually impossible to find the injured (without heat image cameras). Finally, heat that cannot be dissipated also
prevents services from reaching the scene of the accident or spending longer time in the tunnel [Vries 2002].

These scenarios show how important smoke-free escape and access routes are in the case of tunnel fires. Extraction dampers that suck out high concentrations of fumes are definitely useful both for protecting the people affected and also for assisting the emergency services on the spot [Lucas 2001]. In Austria for example planning specifications RVS 9.261 require such extraction dampers for ventilation systems in tunnels with cross ventilation, and they are currently being retrofitted in a number of road tunnels [BMVIT 2001], [BMVIT 2002], [OEAMTC], [OESAG]. As discussed above using Austria as an example, the majority of underground traffic systems are shorter than 5km, and have simple axial flow systems at the most. It is not therefore to be expected that these tunnels will be equipped with full cross ventilation and extraction dampers in the foreseeable future. The next section shows that the positive pressure ventilation (PPV) principle represents a sensible option, especially in such cases.

3 PRINCIPLE OF POSITIVE PRESSURE VENTILATION – USE IN TUNNELS

Fire brigades have successfully been applying the principle of PPV for fighting fires in enclosed spaces for many years. It is based on the fact that air in higher pressure environments escapes to areas of lower pressure. The pressure is built up by fans sited in front of the door ensuring that the air cone completely covers the opening. At the same time air outlets are made through which the smoke and heat can escape. This creates a flow, and the fire fighters can work with the “wind” in their backs.

Traffic tunnels are enclosed spaces with openings at the mouths and, in the case of cross ventilation, also at the fresh and extract air dampers. The positive pressure fans are placed in front of the tunnel mouth, ensuring that the air stream seals the opening completely. This enables the pressure to build up inside the tunnel. The air can either escape through the mouth at the other end or through the extract bore.
3.1 One-way traffic tunnel without stationary ventilation or with longitudinal ventilation

As mentioned above, the majority of Austrian motorway tunnels are under 1km in length. These tunnels are almost all operated with one-way traffic, and are generally equipped with longitudinal ventilation systems. In the group up to 5km there are also many tunnels with one-way traffic and longitudinal ventilation. When the stationary ventilation systems are not adequately dimensioned for larger fires or there are not any stationary systems in place, axial flow can be generated, existing natural currents increased or even reversed with the help of positive pressure fans. This keeps the area in front of the accident smoke-free where the people involved and those following are located, and from where the emergency services arrive.

3.2 Two-way tunnel without stationary ventilation or with longitudinal ventilation

If a tunnel is operated with two-way traffic, great care has to be taken when generating axial flow. Those responsible have to ensure that nobody is behind the accident, as they would be put at risk from the gases and heat set in motion. Only once they have established that the area is clear can the positive pressure fans be used to assist the firefighting and clean-up work.
3.3 Tunnel with cross ventilation

In tunnels with cross ventilation the smoke primarily has to be extracted at the scene of the accident. To achieve this, the axial flow in the tunnel has to be less than 1.5 m/s. Mobile fans can be used in such cases to halt natural axial currents. Natural axial flow can for example occur due to weather conditions or the chimney effect. In addition, mobile positive pressure fans can be used at both tunnel mouths to boost the stationary ventilation system’s extraction capacity.

4 MOBILE TUNNEL FANS: THEORETICAL DESIGN AND PRACTICAL TESTS

The aim of using positive pressure fans is to build up, stop or reverse axial flow in the tunnel. To obtain a detailed picture of the flow characteristics, computational fluid dynamics (CFD) simulations were carried out in cooperation with the Institute of Internal Combustion Engines and Thermodynamics at Graz Technical University. The spread of heat and fumes in a fire in a tunnel without a stationary ventilation system was examined, as well as the effect of PPV on the flow characteristics in the tunnel.
An extract of the calculation results is shown below:

**Tunnel**
- Tunnel length: 1,500m
- Cross section: 50m²

**Fire**
- Capacity: 20MW (lorry)
- Distance from fan: 1,000m

**Initial conditions**
- Natural flow: 1m/s
- No stationary ventilation

**Fan**
- Thrust: 2,500N
- Velocity: 37m/s

Due to the natural currents, the entire tunnel was filled with smoke from the mouth to the scene of the accident after 15 minutes. The fan was then started. After another ten minutes the natural flow was successfully reversed and both the smoke and the heat expelled through the mouth at the other end of the tunnel.

These simulations served as the basis for the fan design. In addition, various factors had to be observed, such as maximum fan diameter to ensure that the fan could be transported and would comply with the highway code. The fan also has to be manoeuvrable to enable it to be positioned in front of the tunnel mouth without obstructing entry and exit to any great extent. Finally, the fan also has to be fundable, i.e. all the components, such as drive (internal combustion motor), blower, and power transmission have to be utilised to the full in terms of efficiency, weight, space requirements and cost-benefit ratio. Extensive practical trials proved the theoretical findings and the capability of the fans even in hot fire tests [Sturm 2001], [Knittel 2000], [Oberhollenzer 2001].

Table 2 and Fig. 10 show examples of firefighting exercises where mobile fans were used to support the emergency services.

### Table 2: Practical testing of the tunnel fans

<table>
<thead>
<tr>
<th>Ventilator</th>
<th>Total thrust [N]</th>
<th>Country</th>
<th>Tunnel</th>
<th>Length [m]</th>
<th>Stationary ventilation in use</th>
<th>Natural flow</th>
<th>Ventilation with / toward natural flow</th>
<th>Flow velocity with ventilator</th>
</tr>
</thead>
<tbody>
<tr>
<td>TL2500</td>
<td>2500</td>
<td>Österreich</td>
<td>Selzthaler</td>
<td>1000</td>
<td>NONE</td>
<td>NO</td>
<td>toward</td>
<td>4</td>
</tr>
<tr>
<td>2 x TL2500</td>
<td>5000</td>
<td>Österreich</td>
<td>BildsteinTaubertunnel</td>
<td>9400</td>
<td>NONE</td>
<td>NO</td>
<td>toward</td>
<td>1</td>
</tr>
<tr>
<td>TL1500</td>
<td>1500</td>
<td>Italien</td>
<td>Frangenfeste</td>
<td>750</td>
<td>longitudinal</td>
<td>NO</td>
<td>with</td>
<td>3.75</td>
</tr>
<tr>
<td>TL2500</td>
<td>2500</td>
<td>Österreich</td>
<td>Ambergtunnel</td>
<td>3000</td>
<td>cross</td>
<td>NO</td>
<td>with</td>
<td>3</td>
</tr>
</tbody>
</table>

Fig. 9: CFD simulation of a tunnel fire [Pischinger 2000]
During all the exercises the fire brigade approach route was kept smoke free, which greatly facilitated the emergency services’ work. In addition, it is extremely reassuring for the people involved when the escape route remains “open”.

5 ONE-DIMENSIONAL CALCULATION FOR ESTIMATING FAN EFFICIENCY

When simulating emergency situations in particular, it is vital to be able to predict the effect of a tunnel fan in advance. In addition to the extensive CFD simulations, a program was therefore developed together with the Institute of Internal Combustion Engines and Thermodynamics for quickly estimating the flow characteristics. It is based on a one-dimensional consideration of the stationary flow, taking the following into account:

- power input (fan thrust),
- force due to the pressure differentials at the mouths (weather),
- buoyant forces due to the difference in temperature inside and outside the tunnel (if there is a slope in the tunnel),
- forces due to buoyancy in the event of a fire,
- wall friction and resistance forces due to vehicles in the tunnel [Pischinger 2002].

The program is very easy to use thanks to simple parameter input, and the extremely short calculation times enable online evaluation of the results. Fig. 11 shows the dialog box for the parameters and Fig. 12 the results of the relevant calculations.

In the diagram the flow velocities are shown in relation to the pressure difference between the two tunnel mouths. The broken line corresponds to the natural currents from the prevailing weather conditions and the grey highlighted area up to the continuous line shows the extent to which the natural flow can be affected by the use of fans. For example, if there is no natural flow in the tunnel, the fan can achieve a maximum wind velocity of nearly 5m/s. If the weather conditions cause air turbulence in the tunnel of 3.75m/s, the fan can reverse the flow maintaining the strength, but moving it in the opposite direction.
6 SUMMARY

Unless counteractive steps are taken, the risk of accidents in tunnels with serious consequences will continue to rise in future firstly due to the steady increase in traffic volume, and secondly due to the constantly growing percentage of underground road sections.

A critical factor for improving the situation of all the people involved in an accident is dispelling the heat and smoke. One option is certainly to upgrade the stationary ventilation systems. There are however large numbers of shorter tunnels that cannot be equipped with full cross ventilation and extraction dampers in the foreseeable future. Positive pressure ventilation can constitute a rational supplement to the stationary systems for this group in particular, especially when the tunnel is for one-way traffic. Controlling the airflow
conditions substantially improves the situation both for the people escaping, and also for the approaching emergency services.

Calculations and field tests have shown that mobile fans can generate, increase, or even reverse the airflow. Use under realistic conditions during fire fighting exercises has also proved their capability and importance for the emergency services.

To ensure successful use, it is imperative to draw up plans of action for various scenarios. Here the calculations and estimates of fan capacity are a valuable complement to the exercises.

REFERENCES
ASTRA 2000 Bundesamt für Straßen Tunnel Task Force Schlußbericht Mai 2000; Schweiz
BMVIT 2001 Bundesministerium für Verkehr, Innovation und Technologie; Projektierungsrichtlinien RVS 9.261; Österreich
BMVIT 2002 Bundesministerium für Verkehr, Innovation und Technologie; Generalverkehrsplan 2002; Österreich
Knittel A 2000; Lüftungsuntersuchungen Tauerntunnel 24.10.2000; Planungs-gemeinschaft Böckstein – Tauerntunnel ILF beratender Ingenieure ZT GmbH; Österreich
Knoflacher H; Tunnelsicherheit: Gefahrengut und Transportgefahren in Alpentunnels; Institut für Verkehrsplanung und Verkehrstechnik Technische Universität Wien, Österreich
Lucas J P 2001; What do you want Tunnel Fire Dampers to do?; Tunnel Fires and Escape from Tunnels; Third International Conference 9-11 October 2001, Washington DC, USA
OEAMTC http://www.oeamtc.at
OESAG; http://www.oesag.at
Oberhollenzer C 2001; Realistische Brandübungen im Autobahn tunnel; Die Freiwillige Feuerwehr – 2/2001, Italien
Pischinger R 2000, Pretterhofer G, Pucher K, Sturm P; Einsatz eines mobilen Ventilators zur Steuerung der Rauchgasströmungen bei einem Tunnelbrand; Institut für Verbrennungskraftmaschinen und Thermodynamik Technische Universität Graz, Österreich
Pischinger R 2002, Öttl D, Lechner B; Dokumentation des Programmes „Schub“; Eindimensionales Modell zur Strömungsberechnung in Tunnelanlagen; Institut für Verbrennungskraftmaschinen und Thermodynamik Technische Universität Graz, Österreich
Sturm P 2001, Pucher K, Öttl D, Pretterhofer G, Braunias S, Muhlenbruch G; Combined use of water spray and mobile ventilation to increase chances in case of fire in tunnels field measurements and numerical simulation; Tunnel Fires and Escape from Tunnels; Third International Conference 9-11 October 2001, Washington DC, USA
VDA, 2001 Verband der Automobilindustrie; Auto Jahresbericht 2001; Frankfurt am Main, Deutschland
Vries H 2002 Fire Chief Mining for Answers; IndustryClick Articel, University of Wuppertal, Germany