VENTILATION AND ESCAPE FACILITIES FOR SHORT CUT-AND-COVER URBAN TUNNELS

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ABSTRACT
Cut and cover tunnels or enclosures of existing highways in urban areas are typically rather short (up to 600 m) and have a high number of lanes. Due to high traffic frequency in urban areas such tunnels have a high probability for congested traffic. In case of incident the number of trapped persons in the tunnel is high and the risk for incident with high severity grows. A scenario analysis, investigating self-rescue process and self-rescue conditions due to ventilation in such tunnels has been performed. The results of this scenario analysis reveal that common ventilation and self-rescue strategies, as defined in various normative documents should not be applied to these tunnels. A better safety level can be obtained by increasing the number of emergency exits, which can be built cheaply in cut and cover tunnels, and choosing a passive ventilation strategy in case of congestion.

Keywords: urban road tunnel, egress facilities, ventilation strategy, incident detection

1. INTRODUCTION AND OBJECTIVES
Cut and cover tunnel are frequently built in urban environments for mitigating the negative impacts of traffic, particularly air pollution and noise. Such tunnels are increasingly built also for recuperating or saving valuable surface space. They are frequently short or very short (in the range of 300 to 600 m), have often three or more lanes for every traffic direction and suffer from frequent traffic congestion. In case of fire a large number of persons and vehicles could be trapped in the tunnel due to the high number of lanes. Self-rescue means and strategies need to be adapted to these circumstances. These characteristics are also essential for ventilation design and for selecting the ventilation strategy. An adequate level of smoke management should be provided, while preventing as much as possible smoke destratification. Limited space and large aspect ratios of the tunnel cross section have finally a very large impact on the design of several safety elements, including fire detection and ventilation.

Recent design experience allowed identifying a number of specific issues which require a special treatment and adapted solutions in case of cut and cover tunnels:

- Capacity and layout of egress facilities
- Ventilation design and operation
- Congestion and fire detection
- Protection of the safe tube against smoke penetration (doors and portal smoke recirculation).

While several issues apply also for tunnel with bidirectional traffic, this paper will focus on the more frequent situation, with two tunnel tubes and unidirectional traffic. All examples presented herein are based on recent real-life investigations. Nevertheless, the focus will be on principles and investigation methodology rather than on specific examples and there will be no reference to specific projects.
2. NORMATIVE REQUIREMENTS

The unusual characteristics of cut and cover tunnels in urban environments are not always entirely accounted for at the normative level. This shall be illustrated based on self-rescue facilities. An informal overview of the international state-of-the-art for the maximum distance between emergency exits for twin-tube tunnels shows that there is no clearly defined “international state-of-the-art” for the maximum allowable distance between emergency exits, but the following indications emerge quite clearly:

- Minimum requirement: 500 m (EU’s directive 2004/54/EC)
- “Standard” requirement: about 300 m (CH, DE, FR, IT, AT and USA)
- Maximum requirement: 100 m (NL and UK).

Also concerning applicability of longitudinal ventilation systems, different national and international regulations provide quite heterogeneous prescriptions.

Norms and recommendations are focused mainly on medium and long bored tunnels, as they pose the more relevant safety risks. The concepts and solutions provided are not readily applicable to cut and cover tunnels, for both technical (see e.g. [1]) and economic reasons. The low investment required for additional emergency exits coupled with technical issues related to fire detection and ventilation call for safety concepts which are different from conventional excavated double-bore tunnels.

3. TUNNEL CHARACTERISTICS AND SCENARIOS

The issues are illustrated based on a short urban cut-and-cover tunnel of 580 m length with varying number of lanes and cross-passages. Peak-hour traffic around 2050 vehicles per hour and lane with around 10% HGV are expected. This real-life example is merely used for illustrating general issues and the technical details of this specific tunnel are not relevant. Different tunnel setups with different number of lanes and number of emergency exits are considered for investigating in a systematic manner ventilation and self-rescue. All representative fire scenarios with and without congestion are analyzed in detail in terms of smoke propagation and person movements. The list of scenarios is given in Table 1, which does not include traffic conditions. The number of scenarios is doubled by considering congested and moving traffic.

<table>
<thead>
<tr>
<th>Table 1: Tunnel characteristics of investigated scenarios</th>
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<tbody>
<tr>
<td>Scenario</td>
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<tr>
<td>Number of cross-passages</td>
</tr>
<tr>
<td>Number of lanes</td>
</tr>
<tr>
<td>Tunnel width</td>
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<tr>
<td>Tunnel height</td>
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</table>

The self-rescue distance is varying with the number of cross-passages. In case of one cross-passage a maximum self-rescue distance of 290 m results. In case of three cross-passages the maximum self-rescue distance can be reduced to 145 m. Increasing of cross-passage width has been preliminary judged as no effective mean to reduce self-rescue time. Although the high number of lanes does lead to increased number of persons per meter of tunnel length, the main driving factor for long self-rescue times in wide cut-and-cover tunnels still is the self-rescue distance and not the emergency exit capacity.
The ventilation system for this tunnel consists of two groups of jet fans, installed in a distance of 100 m to the portals. Limited space for jet fans leads to fans with rather small diameter, but high in number (about 8 per group). The rationale between this selection of the ventilation system is related in particular to redundancy requirements (at least two jet-fan groups are needed in every tube for redundancy in case of fire) and for the pressurization of the opposite tube. Moving the jet fan groups to the portals lowers the probability of disturbing smoke layering in case of fire incidents. However, the jet fan groups could be operated only in one direction and thus redundancy is lost and the total number of installed jet fans is slightly increased (group at entrance portal must generate total thrust for incident ventilation and group at exit portal must be sufficiently equipped to ensure over-pressurization).

The scenario analysis is based on a timeline of events. An identical timeline has been assumed for free-flowing traffic and congested traffic (see Table 2). Detection of fire within 1 minute is a requirement of the Swiss guideline for fire detection in road tunnels [4]. Tunnel closure and activation of ventilation would start immediately after fire detection in modern tunnels which are equipped with automatic control system. The slight delay is introduced to consider late detection and special cases where the tunnel reactions do not follow immediately. For the beginning of self-rescue a distinction is made between persons close to the fire and further away in order to account for different perceptions of specific situations.

Based on traffic frequency and time between traffic blockage in the tunnel and tunnel closure a congestion length of about 400 m can be expected in the tunnel in case of free-flowing traffic.

### Table 2: Scenario timeline for free-flowing traffic

<table>
<thead>
<tr>
<th>Time [min]</th>
<th>Event / Description of scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Start of fire and blockage of traffic in whole fire tube</td>
</tr>
<tr>
<td>1</td>
<td>Fire detection</td>
</tr>
<tr>
<td>1.5</td>
<td>Closure of tunnel</td>
</tr>
<tr>
<td>2</td>
<td>Activation of ventilation system and alarming of tunnel users</td>
</tr>
<tr>
<td>2.25</td>
<td>Start of self-rescue for persons close to the fire location (distance up to about 30 m)</td>
</tr>
<tr>
<td>2.75</td>
<td>Start of self-rescue in whole tunnel</td>
</tr>
</tbody>
</table>

The effectiveness of different safety concepts can be evaluated using a scenario-based approach, such as described in [2]:

- Global assessment of evacuation process based on NFPA 130
- Detailed simulation of evacuation process, taking into account individual persons and vehicle locations (with the dedicated software ASERI)
- Investigation of fire development and smoke propagation (CFD).

The results can be compared in terms of visibility conditions and self-rescue time. A fair chance of self-rescue only exists, if sufficient smoke control can be provided during the whole self-rescue phase.
4. VENTILATION AND SMOKE PROPAGATION

4.1. General objectives and design criteria
The general objectives of fire ventilation are as follows:

- Keep escape way free of smoke during the whole self-rescue phase
- Support the selected intervention strategy with a proper smoke-management strategy
- Prevent smoke penetration into the rescue tube
- Prevent smoke recirculation through the tunnel portals.

In case of longitudinal ventilation, the resulting requirements for ventilation design are:

- The ventilation system shall be designed for attaining the critical velocity
- An overpressure shall be maintained in the rescue tube at all emergency exits.

4.2. Ventilation strategy
Ventilation design depends largely on the ventilation strategy to be adopted in case of fire. The optimum ventilation strategy depends on both fire location and traffic conditions:

- In case of fluid traffic the critical air velocity shall be attained in the fire tube, preventing smoke backlayering over the vehicles stopped upstream of the fire
- In case of congestion downstream of the fire flow inversion should be prevented and a moderate longitudinal air velocity (typically 1-1.5 m/s) can be useful for improving self-rescue conditions
- Exceptional conditions with bidirectional traffic are handled analogously to congestion
- Portal smoke expulsion, depending on local conditions, in case of fire in the immediate vicinity of one portal, depending on air velocity.

Smoke penetration into the parallel tube must be prevented. This can be achieved with:

- Same flow direction as in the fire tube, for preventing smoke recirculation at the portals and generating similar pressure distributions in both tunnel tubes
- Overpressure generated by using part of the jet fans opposite to the flow direction.

In case of congestion downstream of the fire or bidirectional traffic, no jet fans shall be used in smoke-filled areas, where they would instantly destroy smoke stratification. During self-rescue this requirements is generally far more important than a proper control of smoke propagation since escape is impossible without adequate visibility. As shown in the section below, for short tunnels the use of jet fans should generally be prevented in case of congestion.

4.3. Scenario analysis
Congested traffic is coupled with low longitudinal air flow velocities, as there is no piston effect and meteorological effects for short, urban tunnels can in most cases be neglected. Assumption for the scenario analysis is a longitudinal velocity of 0 m/s at the start of the fire incident. Smoke propagation will evolve on both sides of the fire, at the beginning in a stratified manner. If the stratified smoke layer propagates into the influence area of jet fans, stratification will be destroyed and destratified smoke propagation will occur along the tunnel. The self-rescue conditions are worse than without ventilation (example is given in Figure 2).
In the analysis, the smoke-propagation distance till fire detection (2 minutes according to scenario timeline), has been evaluated by 3D simulation. This allows to evaluate the fire locations for which the ventilation system can be activated without destroying a stratified smoke layer. The result is illustrated in Figure 3. Tunnel sections around jet fan groups are marked red. Activation of jet fans for fire locations in the red sections will certainly lead to destratified smoke propagation, as smoke is conveyed through jet fans or the turbulent jet impinges on the smoke layer. Yellow marked sections indicate fire locations from where smoke propagates into the influence areas of jet fans (red section), which will lead to destratified smoke propagation. The length of the yellow marked sections is dependent on time between start of fire and activation of jet fans.

Figure 3 shows that for short urban tunnels activation of jet fans is problematic for about 85% of the fire locations in case of congested traffic. If activation of jet fans is delayed (2.5 minutes after start of fire), activation of jet fans will cause destratification for all fire locations.
Jet fan location can be optimized. Moving them closer to the portal increases the tunnel sections which are not problematic for longitudinal ventilation. Figure 4 illustrates the situation with optimized jet fan location. Still 60% of fire locations are problematic concerning destratification of smoke layer by activation of jet fans.

![Figure 4: Jet fan location optimized](image)

**Figure 4:** CFD results for fire situation with optimized jet fan location

Activation of jet fans in short urban tunnels leads with a high probability to destruction of stratified smoke layer and worsens self-rescue conditions. The CFD-analysis shows, that if no longitudinal ventilation is used in case of congested traffic, smoke propagates symmetrically, in a stratified manner along the tunnel ceiling (see Figure 5). The analysis shows additionally, that acceptable conditions for self-rescue can be expected for a duration of about 5 minutes, if no jet fan is activated. After 5 minutes, stratification is gradually lost and areas with a visibility range below 20 m may occur.

Instead of installation of comprehensive ventilation equipment, the means for self-rescue must allow for a fast rescue (within 5 minutes from start of fire) of the incident tube. This allows for safe and reliable operation also in case of congested traffic.

4.4. **Means for detection**

Detection of congestion in case of wide tunnels with a high number of lanes has to be more sensitive than in common two lane tunnels. The number of vehicles and persons involved in congestion grows fast to a considerable number (50 m of congestion on 5 lanes correspond to 60 persons). The spatial resolution of detection equipment for congestion and fire should allow for accurate detection in the order of at least +/-50 m. Additionally, fire detection must account for the high aspect ratio of wide and comparatively low tunnels, which in most cases requires an increased sensor density. The author’s recommendations are as follows:

- The use of CCTV for detection and localization of congested areas
- The use of CCTV for fire detection is not widely accepted due to comparable high number of false alarms. Using common means for fire detection (smoke sensor, heat detector), CCTV data could be used for a more exact localization of fire incidents after alarm of a common sensor. Such an approach would combine the strengths of the different systems.

![Figure 5: CFD results for fire situation with congested traffic and natural ventilation](image)
5. ESCAPE FACILITIES

The general requirement for escape facilities according to analysis of smoke propagation is to enable self-rescue within 5 minutes after start of fire. Egress calculations have been conducted for different constellations of escape facilities (1, 3 and 4 cross-passages) and vehicle occupancies. The egress calculations have been performed using the simple approach described by NFPA 130. Validation of some specific cases with the well-established software ASERI has shown excellent agreement (deviations in total egress time of 1% to 3%).

Relevant for the egress time is the person density (number of persons per tunnel length), or the vehicle occupancy respectively. A low person density means that only the distance to the next emergency exit determines the egress time. For high person densities the capacity of means of egress becomes relevant. The limit value for door widths of 1.25 m is 0.853 Persons/s. The mean occupancy for private vehicles in Switzerland is about 1.6 Persons / PCU [5]. This results in following person densities:

- 3 lanes (1.6 Pers/PCU): 0.720 Pers / m
- 5 lanes (1.6 Pers/PCU): 1.200 Pers / m

Higher person densities are of course possible, either because of an higher general occupancy of cars or owing to the presence of busses. Both have not been considered in the analysis, but would increase the egress time. Buses with up to 55 persons would lead to a capacity-determined egress process and extend the egress time by maximum 35 s.

![Figure 6: Total egress times as a function of fire location](image)

Figure 6 illustrates egress times for a fully congested tunnel tube in dependence of fire location. Assumption is that fire blocks the tunnel and the fire location cannot be passed. Only the time required to leave the tunnel is accounted for. Time lost through alarming and perception of tunnel users is not included in the illustrated egress time. Egress time peaks occur for fire locations in the proximity of cross-passages and portals as either the nearest cross passage or the path to the close portal is blocked. The egress times for three and five lanes differ little. Larger differences become visible for higher person densities.

According to chapter 3, 2.25 minutes (135 s) for alarming and perception have to be added to the “walking” time in order to get the total egress time from start of the fire incident. The maximum total egress time is presented in Table 3. The main impact on egress time arises from self-rescue distance. Door capacity (width of 1.25 m) is not an issue for common car occupancies, as the self-rescue time for 3 lanes and 5 lanes is almost identical.
Table 3: Total maximum egress times

<table>
<thead>
<tr>
<th>Variant</th>
<th>3 - Lanes</th>
<th>5 - Lanes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Cross-passage</td>
<td>$4.8 + 2.25 = 7.05$ min</td>
<td>$5.1 + 2.25 = 7.35$ min</td>
</tr>
<tr>
<td>3 Cross-passage</td>
<td>$2.4 + 2.25 = 4.65$ min</td>
<td>$2.5 + 2.25 = 4.75$ min</td>
</tr>
<tr>
<td>4 Cross-passage</td>
<td>$1.9 + 2.25 = 4.15$ min</td>
<td>$2.0 + 2.25 = 4.25$ min</td>
</tr>
</tbody>
</table>

The design of emergency exits require some attention. Users could reach the emergency exits before the traffic in the safe tube is blocked. In a few European countries, emergency exits are locked under these conditions. This is in the author’s opinion unacceptable. As stated by PIARC [3] “emergency exit doors should not be locked”.

6. CONCLUSIONS AND RECOMMENDATIONS

This paper showed that normative requirements for road tunnels are not always applicable in a straightforward manner to cut and cover tunnels in urban environments. These are usually characterized by high traffic loads and frequent congestion. A scenario-based approach was presented for analyzing the requirements in terms of ventilation and emergency exits for any specific configuration. The results and conclusions are case dependent, but a few general indications clearly emerge from the analysis of several cases:

- A distance of 300 m between emergency exits is likely to be insufficient in case of short tunnels with natural or longitudinal ventilation
- A door width of about 1.2 m is likely to be sufficient for tunnels with high number of lanes, as egress time is mainly determined by self-rescue distances
- In case of congestion and short tunnels the risk of smoke destratification is high and the best possible ventilation strategy is likely to be natural ventilation (no activation of the jet fans in the fire tube) complemented by providing short self-rescue distances
- Ventilation design must take into account smoke recirculation and over-pressurizing the opposite tube (used for self-rescue)
- Congestion detection must be fast and accurate and thus needs a dense net of point sensors or support from CCTV
- Fire detection needs special attention in case of large numbers of lanes and high tunnel aspect ratios.

7. REFERENCES


