QUANTIFIED RISK ANALYSIS OF VENTILATION SYSTEMS IN ROAD TUNNELS: SIMPLE PORTAL-TO-PORTAL LONGITUDINAL VENTILATION VERSUS LOCAL SMOKE EXTRACTION SYSTEMS

Steiger M., Norghauer N., Day J.R.
Pöyry Infra Ltd, Switzerland

ABSTRACT
Road tunnel design guidelines in many European countries require a smoke extraction system be implemented for given tunnel design factors and traffic conditions. However, in some European countries, there are no design guidelines to specify the ventilation system. In those countries, a risk analysis approach based on EU Directive 2004/54/EC (minimum safety requirements for tunnels in the trans-European road network) may be applied to determine whether a simple longitudinal portal-to-portal ventilation system is acceptable. Otherwise, a local smoke extraction needs to be implemented.

A tunnel with unidirectional congested traffic is used as an example to determine, by means of a quantified risk analysis according to the above mentioned EU Directive, whether a simple portal-to-portal longitudinal ventilation with reduced spacing between the emergency exits may provide the same safety level as a local smoke extraction system compliant with the various national road tunnel design guidelines.

The results show that by reducing the distances between emergency exits, the same safety level can be achieved for both systems.

Keywords: EU Directive 2004/54/EC, quantified risk analysis, ventilation design, emergency exits

1. INTRODUCTION
In many European countries (e.g. Austria, Germany, Switzerland) national road tunnel design guidelines are in place to define the tunnel ventilation system concept for given design factors and traffic conditions. The distinction is made between natural longitudinal ventilation, mechanical longitudinal ventilation and ventilation systems with smoke extraction.

When choosing a ventilation system, European countries with no respective guidelines (e.g. Greece) may base their decision on the EU Directive 2004/54/EC [1] which leaves more leeway than offered by existing national tunnel guidelines. According to this Directive, a simple portal-to-portal longitudinal ventilation system can be used for a road tunnel, if a risk analysis proves it to be acceptable.

This paper aims to determine by means of a quantified risk analysis according to the EU Directive whether, for a two-tube tunnel with congested unidirectional traffic, a portal-to-portal longitudinal ventilation system may be used rather than a ventilation system with local smoke extraction as would be required by many national road tunnel design guidelines.

2. EU DIRECTIVE 2004/54/EC

The following two points of the Directive are relevant in choosing the ventilation system:
Point 2.9.3: “In tunnels with bi-directional and/or congested unidirectional traffic, longitudinal ventilation shall be allowed only if a risk analysis according to Article 13 shows it is acceptable and/or specific measures are taken, such as appropriate traffic management, shorter emergency exit distances, smoke exhausts at intervals.”

Point 2.9.4: “Transverse or semi-transverse ventilation systems shall be used in tunnels where a mechanical ventilation system is necessary and longitudinal ventilation is not allowed under point 2.9.3. These systems must be capable of evacuating smoke in the event of a fire.”

For a tunnel with unidirectional traffic as used in this study, the following may be said:

- If the traffic is not congested, a simple portal-to-portal longitudinal ventilation system may be used.
- If the traffic is congested, a simple portal-to-portal longitudinal ventilation system can be used provided that a risk analysis proves it to be acceptable. Otherwise, a local smoke extraction system needs to be implemented.

The EU Directive also specifies that “a mechanical ventilation systems shall be installed in tunnels longer than 1000 m with a traffic volume higher than 2000 vehicles per lane” (Point 2.9.2) and the “distance between two emergency exits shall not exceed 500 m” (Point 2.3.8).

3. VENTILATION SYSTEMS AND DISTANCES BETWEEN EMERGENCY EXITS IN SOME EUROPEAN COUNTRIES

The requirements regarding ventilation systems and emergency exits for tunnels with congested unidirectional traffic for the three German-speaking countries can be found below.

Requirements as to under what circumstances a certain ventilation system needs to be used may vary greatly. Generally, the requirements are much stricter than under the EU Directive.

3.1. Austria

Simple portal-to-portal longitudinal ventilation is only permitted in tunnels up to 1500 m. For tunnels between 1500 m and 3000 m, a longitudinal ventilation system with massive point extraction (maximum distance 750 m) has to be available, and for tunnels of more than 3000 m in length, the ventilation system must be a one with local smoke extraction. [2]

The distance between two emergency exits shall not exceed 500 m. [2]

3.2. Germany

Simple portal-to-portal longitudinal ventilation can be used in tunnels up to 600 m long and possibly up to 1200 m long if verified using a risk analysis. Above 1200 m long the emergency ventilation must be a local smoke extraction system with remotely controlled mechanical dampers. [3]

The distance between two emergency exits shall not exceed 300 m. [3]

3.3. Switzerland

Simple portal-to-portal longitudinal ventilation can be used in tunnels up to 800 m long and possibly up to 1500 m long provided a) the daily traffic flow per lane is lower than 11,000, b) the daily truck flow per lane is less than 800, and c) the gradients in the tunnel are between –1.5% and +1.5%. Above 1500 m long the emergency ventilation must be a local smoke extraction system with remotely controlled mechanical dampers. [4]

In single tube tunnel the distance between two emergency exits is between 300 m and 500 m, depending on the longitudinal gradient whereas in twin-tube tunnels the distance between two emergency exits (cross connections) shall not exceed 300 m. [5]
4. SIMPLE PORTAL-TO-PORTAL LONGITUDINAL VENTILATION VERSUS LOCAL SMOKE EXTRACTION SYSTEMS

The two ventilation systems differ mainly in the following aspects:

Unlike the longitudinal ventilation system, the smoke extraction system requires additional civil construction works: A smoke exhaust duct that directs the exhausted smoke towards the atmosphere. Throughout its entire economic life, the smoke exhaust duct must cope with different loading types (static air pressure, constraints, etc.) and only minor leakage (tunnel construction, closed dampers) may occur, which poses a major challenge to the manufacture of this structural element. Furthermore, ventilation station(s) to host the exhaust fan(s) and chimney(s) to safety disperse the smoke in the atmosphere are required.

The electromechanical equipment for local smoke extraction is substantially more comprehensive than for longitudinal ventilation. While both systems use jet fans, the system with local smoke extraction additionally uses exhaust dampers, exhaust fans, more cabling and a more complex ventilation control system.

The local smoke extraction comprises significantly more components than the longitudinal ventilation system, which is why it is more complex in maintenance as well. Both with regard to civil construction works (ducts/false ceilings, ventilation station, etc.) and electro-mechanical equipment (exhaust fans, exhaust dampers, etc.). Moreover, due to its high level of complexity, the system is naturally more prone to non-function and malfunction than a longitudinal ventilation system. Thus, regular maintenance is inevitable in order to ensure proper functioning of the exhaust ventilation in case of emergency. However, this requires a high degree of expertise, which could be a problem in technologically lesser developed countries.

In summary, it can be stated that the use of a smoke extraction as opposed to a longitudinal ventilation system comes with significant additional costs. Based on experience gained from previous projects, the costs for civil construction and electromechanical equipment are approximately 20% to 35% and 280% to 300% higher, respectively, than for a tunnel with simple longitudinal ventilation. Furthermore, additional costs for maintenance and power/energy throughout the economic life of the system need to be considered as well.

5. QUANTIFIED RISK ASSESSMENT

Article 13 of the EU Directive states that the risk analysis must cover all design factors (tunnel length, tunnel geometry, longitudinal gradient, etc.) and traffic conditions (characteristics, type) that affect the safety level. The Austrian tunnel risk model (TuRisMo) [6], developed by a group of experts in the field of tunnel safety and ventilation and published as an official Austrian guideline (RVS 09.03.11), fulfils this requirement.

The risk analysis used for this study is based on TuRisMo. Since this model considers dangerous goods in a simplistic manner and makes no distinction between different dangerous goods, the quantitative risk assessment model (QRAM) from OECD-PIARC [7] is used for this type of scenario.

TuRisMo follows the Austrian tunnel design guideline [2], thus the calculation of the risk for tunnel users is not possible for certain tunnel design factors. Namely for the consequences (fatalities) of scenarios involving fire, which depend on ventilation system, tunnel length and distances between emergency exits. On this account, additional one-dimensional ventilation simulations and evacuation simulations have been carried out to determine the consequences missing in TuRisMo.
5.1. Approach

Point 2.9.3 of the EU Directive states that a longitudinal ventilation system can be used, if a risk analysis shows that this is acceptable (Section 2). The term "acceptable" is not accurately defined (e.g. fatalities per year) and therefore leaves considerable room for personal assessment. In order to render the term more concrete, the safety level of a tunnel with local smoke extraction system and emergency exits every 500 m is defined as being “acceptable” and shall be quantified by the expected societal risk value in fatalities per year. This safety level is equivalent to the minimum safety requirements set forth by the EU Directive in cases where longitudinal ventilation is not acceptable.

To examine whether a simple longitudinal ventilation system may be used, the following process within the risk analysis (Figure 1) is implemented:

The expected societal risk value for a tunnel with given design and traffic conditions using a local smoke extraction and emergency exits every 500 m has been determined. The very same value must be reached for a tunnel with identical design factors and traffic conditions using a longitudinal ventilation system with reduced distances between emergency exits. The required safety level shall be reached solely by reducing the distances between emergency exits.

The expected societal risk value is the sum of the products of frequency and consequence for all damage scenarios. The ventilation system only affects the damage extent of scenarios involving fire and dangerous goods, thus the risk analysis in this study could theoretically be limited to just those scenarios. However, since the percentage of scenarios with only mechanical effects (i.e. accidents, collisions, etc) constitutes a significantly larger part of the value, those scenarios are also being considered for illustrative purposes.

This approach is being pursued to assess whether, according to the EU Directive, a simple portal-to-portal ventilation system can be used for a tunnel (Section 5.3) when several national road tunnel design guidelines demand a system with smoke extraction (Section 3).

5.2. Damage scenarios

TuRisMo covers 28 damage scenarios with accidents or breakdowns being the initial events. The scenarios can be divided into mechanical effects, fire and dangerous goods scenarios for different vehicle types (passenger cars, heavy goods vehicles (HGV) and buses). Apart from scenarios involving dangerous goods, all scenarios are adopted from TuRisMo. For scenarios involving dangerous goods, QRAM from OECD-PIARC has been used.

Figure 1: Approach of the safety level comparison
Unlike TuRisMo, QRAM differentiates between various types of dangerous goods. The risk analysis covers scenarios involving flammable liquids in bulk, propane in cylinder, propane in bulk and ammonia.

5.2.1. Modelling of frequencies

The frequencies of the different scenarios in TuRisMo and QRAM are based on a statistical assessment of breakdowns and accidents. The ventilation system has no impact on the frequency of each scenario.

5.2.2. Modelling of consequences

The consequences for mechanical effects scenarios are taken from TuRisMo where they are again determined by means of a statistical assessment of accidents in tunnels. The ventilation system has no impact on the consequences of those scenarios.

The consequences for scenarios involving fire are calculated for passenger cars, HGV and buses through ventilation and evacuation simulations. The damage extent (fatalities) is calculated for one fire location (worst case) within in the tunnel and is based on the Fractional Effective Dose (FED) and the visibility.

Based on the duration of exposure, the FED concept [8] determines a person’s incapacitation due to gases (CO, HCN, CO₂) produced by the fire or lack of oxygen (hypoxia). The method calculates the quotient of the dose inhaled in a certain time interval and the dose leading to incapacitation. The quotient is summed up for a series of time intervals, whereby incapacitation is reached when the sum is one. Apart from toxic effects, the FED is also used to calculate heat impacts (convection, radiation) on a person.

The visibility, which in case of fire is limited by soot particles, is of great importance in the self-rescue of people. The smoke from vehicle fires usually causes strong irritation of the eyes, which makes movement below a visibility range of 5 m virtually impossible. It has to be noted that disorientation occurs earlier. [9]

The consequences for scenarios involving dangerous goods are taken from QRAM from OECD-PIARC where they are established by means of different calculation models.

5.3. Example

A 3 km long twin tube tunnel with unidirectional traffic with the likelihood of traffic congestion is being used as an example. If the tunnel were to be built in Austria, Germany or Switzerland, the ventilation system would have to feature a local smoke extraction system. The key parameters of the example are shown in Table 1.
Table 1: Key parameters

<table>
<thead>
<tr>
<th>TUNNEL, TRAFFIC, ACCIDENT AND BREAKDOWN DATA</th>
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<tbody>
<tr>
<td>Tunnel length</td>
</tr>
<tr>
<td>Tunnel cross section (LV / SV)</td>
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<tr>
<td>Longitudinal gradient</td>
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<tr>
<td>Number of lanes</td>
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<tr>
<td>Annual average daily traffic (AADT) per tube</td>
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<td>Traffic jam frequency</td>
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<td>Vehicle proportion</td>
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<td>Breakdown rate</td>
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<td>Accident rate</td>
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VENTILATION AND EVACUATION DATA

| Response time of fire detection system (LV / SV) | 1 min / 1 min                        |
| Response time of the ventilation system (LV / SV) | 3 min / 3 min                      |
| Expected longitudinal velocity (LV / SV)         | 3 m/s; 1.5 m/s; 3 m/s; 0 m/s; 1.5 m/s |
| Visbility                                       | ≥10 m                             |
| Escape speed of a person                        | 1.2 m/s                           |

FIRE DATA

| Fire load (in 5 min with linear increase) | 5 MW (passenger cars) |
|                                          | 30 MW (HGV and buses)   |
| Yield soot                               | 0.13 [kg/kg]            |
| Yield CO₂                                 | 2.07 [kg/kg]            |
| Yield CO                                  | 0.043 [kg/kg]           |
| Yield HCN                                 | 0.01 [kg/kg]            |

* LV: portal-to-portal longitudinal ventilation system
  SV: local smoke extraction system

Notes on some key parameters:
For visibility ranges below 10 m, a drastic reduction of the escape speed can be expected and disorientation will begin. For the calculations it is assumed that people can save themselves, if the visibility range is greater than 10 m, and the escape speed is set to 1.2 m/s. [9]

For longitudinal ventilation systems, the air velocity is set to a minimum of 3 m/s in regular traffic and to a maximum of 1.5 m/s in a traffic jam so as not to destroy the smoke stratification. For local smoke extraction systems, it is set to 3 m/s upstream of the extraction zone and 0 m/s downstream for a fire occurring in regular free-flowing traffic. For a fire occurring in a traffic jam it is set to 1.5 m/s upstream and downstream of the extraction zone.

The yield values are the mean values for different material types (polyurethane foam, polystyrene, mineral oil) and are taken for all vehicle types. [10]

5.4. Results
In this section, the results of the societal risk estimation for both types of ventilation system are shown. The expected societal risk is expressed by mechanical effects, a fire and a dangerous goods component and generated for the different damage scenarios.

5.4.1. Local smoke extraction system
The figure and the table clearly demonstrate that, of the three components, the component mechanical effects has by far the largest influence on the expected value of societal risk.
Considering that the twin tube tunnel can be ventilated with simple portal-to-portal longitudinal ventilation during normal traffic operation and that the smoke extraction is only necessary in emergency cases (i.e. just related to the risk components fire or dangerous goods), a large investment is needed for these rare occurrences.

### 5.4.2. Portal-to-portal longitudinal ventilation system

By means of an iterative approach, a distance between emergency exits of approximately 100 m was found to result in a similar societal risk as with the use of a local smoke extraction system. The results are shown in the following figure.

![Figure 3: Expected societal risk [fatalities per year]](image)

The calculation indicates that the required safety level can be achieved with a longitudinal ventilation system and a reasonable distance between emergency exits. The QRAM from OECD-PIARC features a very conservative evacuation model which does not react very sensitively to changes of the distances between emergency exits. As a result the proportion of risk due to dangerous goods cannot be sufficiently reduced by decreasing the distances between emergency exits and, thus, the risk needs to be offset by just the component fire.

### 6. DISCUSSION

The study shows that – based on the EU Directive – it is possible to replace the local smoke extraction system for the twin tube tunnel with simple portal-to-portal longitudinal ventilation system with reduced distances between the emergency exits while still achieving the same overall level of societal risk.

The determination of distances between emergency exits for simple portal-to-portal longitudinal ventilation systems greatly depend on fire data (fire load, yield values, fire location, reaction time of the ventilation system, etc), tunnel design factors (longitudinal...
gradient, etc.) and evacuation data (escape speed) concerning the escaping person. It is, thus, a very sensitive process. If for example the escape speed is reduced, plausible distances may no longer be calculated.

The study is based on recognised models. For scenarios involving fire and dangerous goods in unidirectional tunnels, TuRisMo calculates damage consequences for traffic jam situations only. The calculation shows that fire scenarios in free-flowing traffic do not cause any consequences, which is not the case for scenarios involving dangerous goods in free-flowing traffic.

Damage scenarios involving dangerous goods are based on QRAM from OECD-PIARC. This model proceeds on the assumption that the traffic in front of the accident can leave freely, whilst the traffic behind is blocked. Due to its low likelihood, the jam situation is not considered in this model. These scenarios are being accounted for very differently by the two models.

Furthermore, the risk assessment demonstrates that the societal risk components considered (mechanical effects, fire, dangerous goods) have different influences. The component mechanical effects has by far the largest impact. The proportion resulting from fire and dangerous goods is very small and depends on the duration of the daily traffic jam. If this value increases, the proportions of the two components in the societal risk are higher.

The safety level of a local smoke extraction system can be achieved more easily by measures which mainly concern the mechanical effects component. Such measures encompass reduction of speed for HGV traffic or a section speed control.

7. CONCLUSIONS

This study illustrates that the local smoke extraction system for the twin tube tunnel can be replaced by a simple portal-to-portal longitudinal ventilation system with reduced distances between emergency exits. Its validity will, however, largely depend on the input values used for the calculation. It needs to be stressed that this study does by no means question the requirements set forth by national ventilation guidelines. It merely wants to draw attention to the fact that considerable resources are being expended on localised smoke extraction systems to mitigate against the minor risks relating to fire and dangerous goods.

8. REFERENCES

[6] "Tunnel, Sicherheit: Tunnel-Riskoanalysemodell“, RVS 09.03.11, Österreichische Forschungsgesellschaft Strasse Schiene Verkehr (FSV), 2009