QUANTIFICATION OF THE LEAKAGES INTO EXHAUST DUCTS IN ROAD TUNNELS BASED ON IN-SITU MEASUREMENTS

Reto Buchmann
Project Leader, Pöyry Infra Ltd, Zurich, Switzerland

ABSTRACT
In recent years many countries have changed their requirements for ventilating road tunnels in an emergency. Traditional linear exhaust systems are no longer permitted; the smoke has to be exhausted from the tunnel close to the fire. The design of this new ventilation system requires different treatment in many ways. One aspect is the leakages flow into the exhaust duct away from the exhaust point, which can have a significant impact on the required ventilation power and must be considered in the design.

Nowadays only a very few established basis to quantify leakages are available. For this reason a Swiss research project has been set up to extensively investigate leakages into exhaust ducts in road tunnels. A main element of this research covers in-situ leakage measurements using the tracer-gas method.

The paper gives a general overview of the research project, covering aspects like theoretical background, choice of tunnels, construction and sealing methods, measurement method as well as data analysis to define a dimensionless leakage numbers for easy use in the practical application.

Furthermore the results and experience of the first measurements are presented and discussed. Although at the time of writing just four measurements are available, these results are already informative.

Keywords: Road tunnels, Tunnel ventilation, Smoke extraction, Leakage, Leakage measurement, Ventilation design, Design tool

1. INTRODUCTION
The ventilation system was and still is a major part of the road tunnel’s safety system, however, the design case for the system has completely changed. The principle aim of the ventilation was to maintain the required air quality during normal operation, whereas today it is the smoke extraction in the emergency case. In longer tunnels a mechanical ventilation system to locally extract the smoke at the fire site is required by the guidelines in a number of countries.

The goal of such a system is to help the passenger escape out of the tunnel by preventing smoke spreading over the trapped vehicles. To avoid smoke spreading, an air flow towards the extraction zone from one side (one way traffic) or both sides (bidirectional traffic) with a velocity of 2 – 3 m/s is normally required. With typical tunnel cross sections of 50 – 60 m² the exhaust flow can easily become 150 – 250 m³/s. With such an air flow the underpressure in the exhaust duct rises rapidly to values of 1’000 – 3’000 Pa.

The underpressure in the exhaust duct causes a leakage flow through the closed dampers and through the structure. This additional flow can have a significant impact on the efficiency of the ventilation system and therefore must be considered in the design. The main difficulty today is to quantify the expected leakage because very few established bases are available.

Underestimating the leakage flow means the required exhaust flow cannot be achieved. Providing additional exhaust capacity can become very complicated and expensive.
In case of overestimating the leakage flow, the installed ventilation power is much too high. A further problem is less obvious, but can cause serious problems. Because of the fact that a lower leakage results in a steeper system characteristic, the operation point travels towards the stall region (Figure 1). Fans without variable blade angles are at risk of stalling.

![Figure 1: System characteristics regarding leakage](image-url)

Established data to quantify leakages is required for a more accurate design of appropriate ventilation systems. Leakages into or out of ducts are a general issue in many other technical fields (e.g. air ducts, HVAC systems). A lot of work on air flow with leakages in tubes can be found in the literature. These approaches can in part also be applied for road tunnel ducts. The main difference is the way to calculate the relevant parameters, particularly the ones relating to the leakage. Unlike the leakage into air ducts with well defined vents, the leakage into road tunnel exhaust ducts is somehow random, temporal and special inhomogeneous and difficult to determine. Relevant parameters are very numerous and can for example be the geometry, the construction method as well as the age of the duct. Very few references can be found covering this part.

In 2007 the Swiss Federal Road Authority ASTRA initiated a research project with the title “Quantification of the leakages into exhaust ducts in road tunnels with concentrated exhaust systems”. The project is planned to be complete by 2009.

The research work aims to extensively investigate leakages into exhaust ducts in road tunnels. The results should be used in the future as a basis for the design of tunnel ventilation systems. The main part of the research covers in-situ leakage measurements in several road tunnels and the analysis of data. The measurements will be carried out by an accredited laboratory using the tracer gas method. With a careful choice of the tunnels (type, age, refurbished/new) a maximum coverage can be achieved. The analysis of the measurement data should end up with dimensionless numbers for easy use in the practical application. Furthermore a “Best Practice Guide” will be prepared covering recommendations regarding prevention (e.g. reduction of leakages) and intervention (e.g. increasing ventilation capacity).

This paper focuses on the leakage measurements, the analysis and first results. Although the research is in full progress, the first results are already very informative.
2. LEAKAGE MEASUREMENTS

For the evaluation of the leakages in exhaust ducts the volume flow and the underpressure in the exhaust duct must be identified at different locations. The measurement of the underpressures in the exhaust duct is done with standard pressure measurement devices. The leakage measurements are more complex. The method needs to be accurate and well-proven for volume flow measurements. Furthermore the duration of the measurement procedure must not exceed one night, as some tunnels could not be closed for longer time.

With the tracer gas method the requirements could be achieved and it was chosen for the research project to measure the volume flow. The concept of this method is to inject a constant mass flow of SF6 (sulphur hexafluoride) into the exhaust air at the open dampers. After about 60 duct hydraulic diameters downstream the tracer gas is well mixed with the exhaust air. With the measurement of the concentration of the tracer gas the volume flow can be calculated. A sketch of a typical set-up in a tunnel is shown in Figure 2. At every measurement point (Nr. 1 to 4) the volume flow and the static underpressure in the duct are measured.

![Figure 2: Sketch of the tracer gas measurement set up](image)

The main advantages of the tracer gas method over a velocity based method (e.g. system measurement) are:

- no undisturbed incident flow required (no problems with installed equipment, e.g. dampers)
- no dependency of the duct geometry and the duct cross section area
- easier and simpler in the set up (just 1 – 3 extraction points per measurement section compared to about 36 anemometers for a system measurement)
- very low impact on the pressure losses in the duct
- accurate, especially in complex and arbitrary ducts

As shown in Figure 2 a small sample of the exhaust air is removed from the exhaust duct and pumped to the measurement units (based on photo acoustic infrared spectroscopy) located at the road level. To route the necessary cables and tubes from the exhaust duct to the road level no extra leakage should be created.

All the measurements are carried out by an accredited laboratory. At the time of writing the leakage flows in four tunnels have been measured (Table 1). For every tunnel the measurements were carried out for different fan operating points (normally four). For the Flimsenstein and Raimeux tunnels the volume flow in the dead branch (exhaust duct side with closed dampers) was measured as well.
### Table 1: Description of the measured tunnels

<table>
<thead>
<tr>
<th>Tunnel</th>
<th>Flimserstein</th>
<th>San Bernardino</th>
<th>Giswil</th>
<th>Raimeux</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exhaust duct type</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>Tunnel age</td>
<td>&lt; 1 year</td>
<td>app. 30 years</td>
<td>app. 3 years</td>
<td>&lt; 1 year</td>
</tr>
<tr>
<td>Exhaust duct length</td>
<td>2'300 m</td>
<td>2'200 m</td>
<td>1'550 m</td>
<td>2'658 m</td>
</tr>
<tr>
<td>Exhaust duct area</td>
<td>11.45 m²</td>
<td>11 m²</td>
<td>11.2 m²</td>
<td>9.91 m²</td>
</tr>
<tr>
<td>Q_{max} from exhaust point</td>
<td>180 m³/s</td>
<td>210 m³/s</td>
<td>155 m³/s</td>
<td>140 m³/s</td>
</tr>
<tr>
<td>Δp_{max} (end of duct)</td>
<td>1'600 Pa</td>
<td>450 Pa</td>
<td>1'650 Pa</td>
<td>2'300</td>
</tr>
<tr>
<td>Dampers distance / Area</td>
<td>100m / 4 m²</td>
<td>96m / 4.8 m²</td>
<td>75m / 2 m²</td>
<td>50 m / 2 m²</td>
</tr>
<tr>
<td>Visible duct tightness</td>
<td>good</td>
<td>poor</td>
<td>very good, (nothing could be found)</td>
<td>moderate (drainage holes every 50m)</td>
</tr>
</tbody>
</table>

### 3. ANALYSIS

Basically the absolute leakage value of an exhaust duct or duct section is not very meaningful due to the fact that it is dependent on many parameters. The impact of some parameters are known and predictable (e.g. underpressure, length). The impact of other parameters are rather random and unpredictable (age, sealing method). The goal of the analysis is to find a method considering the known parameters as they are, combining all the others with dimensionless values and quantifying the leakages to enable their comparison and extrapolation.

The approach used is to describe the behaviour of the flow in a mathematical way and define the unknown parameters via the measurement results. The concept thereby is to consider the leakage flow in a macroscopic way, accounting for no detail, as numerous attempts to calculate the leakage in a detailed manner failed.

The results for the relevant parameters come out of a limited number of measurements. Hence they must be considered as orders of magnitude and used as bandwidth. Even though the present method is not suited for a precise prediction of the leakages, it can be used during the design process.

For the exhaust duct the pressure and the volume flow can be described theoretically. The approach used is well known and described in several papers (SIA 196, 1998 or ISETH Mitteilung Nr.19, 1978). With $f^*$ as the effective leakage area the pressure [Eq. 1] and the volume flow [Eq. 2] are given by two differential equations:

\[
\frac{d(\Delta p)}{dx} = \lambda \cdot \frac{1}{D_{hyd}} \cdot \frac{\rho u^2}{2} \quad \text{Eq. 1}
\]

\[
\frac{du}{dx} = \frac{P \cdot f^*}{A} \left( \frac{\rho}{2 \cdot (2 \cdot \Delta p)^{\frac{n}{2}}} \right) \quad \text{Eq. 2}
\]

where:

- $A$: Cross-section area [m²]
- $P$: Perimeter [m]
- $D_{hyd}$: Hydraulic diameter [m]
- $\lambda$: Wall friction factor [-]
- $\Delta p$: Pressure difference [Pa]
- $\zeta$: Pressure loss coefficient [-]
- $n$: Exponent
- $x$: Coordinate in exhaust duct direction [m]
- $\rho$: Air density [kg/m³]
- $u$: Exhaust air velocity [m s⁻¹]
- $f^*$: Effective leakage area [m²/m²]
- $f' = f^* / (1 + \zeta^{0.5})$
- $f'$: Leakage area ratio [m²/m²]

(geometric ratio of the leakage area compared with duct surface area)
The known variables in Eq. 1 and Eq. 2 are the geometric variables \((D_{hyd}, P, A)\) and the change in underpressure and change in air velocity. The geometric variables are defined by the tunnel itself; the other two through the measurements. The unknown variables are \(\lambda, f^*\) and \(n\). \(n\) is dependant on the leakage flow type (per definition \(n = 2\) for turbulent flow and \(1\) for laminar flow). The Reynolds Number of the leakage flow can vary from very low (small cracks) to high (big holes), thus the flow type cannot be defined a priori.

The three unknowns must be solved for each tunnel for every segment and operating point. In contrast to the three unknowns one can just write two equations (Eq. 1 and Eq. 2). The missing equation must come from another measurement of the same segment.

After solving the defined equation system for every segment and operating point one gets several results for the unknowns for each tunnel.

4. RESULTS / DISCUSSION

This section presents the results and the conclusions up to the time of writing this paper. More measurements will follow shortly and may change or refine some statements.

In Figure 3 the results for \(f^*\) and \(\lambda\) for all measurements are shown. Furthermore the leakage value according the Swiss Guideline (ASTRA, 2004) and damper manufacturers have been expressed as \(f^*\) and added in the plot. To divide the leakages into groups a break down with 5 levels is suggested.

The \(f^*\) value includes all leakages (dampers and construction) and the \(\lambda\) value expresses the wall friction including all the pressure losses due to installed equipment like damper actuators and illumination.

The results show a dependency on the age of the tunnel. For new tunnels the \(\lambda\) value varies between 0.013 and 0.020 and the majority of the \(f^*\)-values are in the group “low” or “moderate”. Interesting are the results for “Raimeux Sued”. They are significantly higher compared with other new tunnels and with the north branch of the Raimeux tunnel.

Although the San Bernardino tunnel has been recently refurbished the \(f^*\)- and the \(\lambda\)- values are significantly higher than for a new tunnel. The majority of the \(f^*\)-values are in the group “high” and “very high”.

Figure 3: \(f^*\) and lambda values for all measurements

4th International Conference „Tunnel Safety and Ventilation“ 2008, Graz
Based on the analysis of the measurements, the exponent “n” of [Eq. 2] was worked out. Figure 4 shows the distribution of the calculated values of “n”. It can easily be seen that the exponent is very narrowly distributed about 2. The analysis combined tunnels with very low and high leakages. Hence it can be concluded that the leakage flow is mostly of the turbulent type, independent of the amount of leakage.

![Figure 4: Distribution of the exponent n over all measurements](image)

Figure 5 shows a plot to estimate the expected leakage flow using two dimensionless parameters. The $\Gamma$- value combines the important duct parameters and can be seen as a characteristic duct dimension. The $\Omega$- value represents the ratio of leakage flow in respect of the flow through the open dampers and can be seen as a dimensionless volume flow. The two dimensionless parameters are defined as:

\[
\Gamma = \frac{L^3 \cdot P^3}{8 \cdot A^3} \quad \text{Duct characteristic}
\]

\[
\Omega = \frac{V_{\text{Fan}}}{V_{\text{Damper}}} - 1 \quad \text{Dimensionless volume flow}
\]

Other parameters like air density, lambda value and pressure loss over the open dampers may have an impact on the leakage flow. From experience it can be seen that the variation on these parameters from tunnel to tunnel are in a small range and the impact is rather minor. For the graph in Figure 5 the parameters are defined as follows: air density: 1.15 kg/m³, wall friction factor: 0.020, pressure loss over open dampers: 5 times the dynamic pressure in the exhaust duct regarding the exhaust volume flow.

4th International Conference „Tunnel Safety and Ventilation“ 2008, Graz
Before each measurement the exhaust duct gets inspected visually to find potential leakages. One reason therefore is to find a dependency between the visual inspection and the leakage level. Although just a few tunnels are measured one can conclude that the level “low” or “very low” can only be achieved for sealed ducts when almost no gaps or holes are visible. In contrast the level “high” represents an exhaust duct with lots of visible leakage points and no or poor sealing.

Another reason is to catalogue the types of leakages. So far it can be seen that most of the visible leakages are caused by the same reason which can avoid easily:

- drainage
- cabling between road level and exhaust duct
- doors and manhole in weak construction
- interfaces between damper frame and the concrete block out

The tracer gas method is theoretically a convenient and accurate method for leakage measurement. However in practical use some difficulties must be considered:

- cross sensitivity for vapour, temperature and atmospheric pressure
- leakage into the gas sampling tubes
- measurement of the volume flow is very sensitive to measurement errors
- sensitive measurement equipment in a rough environment
- routing cables and tubes through the intermediate ceiling may cause problems

Accordingly it’s very important to seriously control the plausibility of the measurement results.
5. OUTLOOK

The project is intended to be completed by spring 2009. Before the end the following actions are scheduled:

- 5 more measurements in new and existing tunnels in 2008.
- Definition of $f^*$ values for particular types of tunnels (e.g. new, refurbished)
- Evaluation of different construction and sealing methods.
- Comparison of other approaches used to treat leakages in other countries.
- The whole experience of the project will be written down in a “Best Practice Guide”.

6. CONCLUSION

- Modern tunnel emergency ventilation systems extract the smoke close to the fire. In such systems the underpressure in the exhaust ducts is relatively high.
- Leakages into the exhaust duct can have a significant impact on the air quantities to be extracted and must be considered in the design.
- Nowadays just very few established bases are available to quantify leakages, therefore a research project to extensively investigate leakages in exhaust ducts has been started in 2007.
- A main element of this research covers in-situ leakage measurements. At the time of writing 4 tunnels have already been measured.
- An analysis method using a dimensionless value to cover the leakage was presented. This method enables one to directly combine and extrapolate the data to other tunnels.
- Regarding the $f^*$ and the $\lambda$- values, a strong dependency on the age of the tunnel can be seen.
- The leakage flow can be considered as a turbulent flow, even if the leakages are very low.
- A noticeable amount of leakages is caused by drainage holes, cabling, doors and manholes, which may be reduced in number or avoided.
- The tracer gas method to measure leakages in exhaust ducts is suitable but delicate

7. REFERENCES

