MEASURING LEAKAGES IN ROAD TUNNELS

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ABSTRACT

Leakages in exhaust ducts can reduce the effective smoke-extraction rate to values below the ones required for effective smoke management and prescribed in guidelines. This aspect can have dramatic consequences from the point of view of tunnel safety but also in terms of engineer’s liability. Leakages have been long accounted for in a very approximate manner. Due to the lack of reliable data in new and older structures, ventilation design is frequently based on questionable assumptions. The present paper deals with experimental techniques used for measuring leakages in exhaust ducts. Several techniques were applied in the Gotthard road tunnel. The results allowed for a comparison of different measuring techniques, from the point of view of accuracy, practical applicability and cost.

Keywords: tunnel ventilation, smoke extraction, leakages, experimental techniques

1. INTRODUCTION

One fundamental safety element in long road tunnels is concentrated smoke extraction from the immediate vicinity of the fire source. This capability is typically required for tunnels longer than 0.5-1.5 km in case of bidirectional traffic or frequent traffic congestion and 3-5 km in case of unidirectional traffic with low congestion frequency. The combination of two distinct elements is necessary for ensuring a proper smoke management: sufficient smoke-extraction rate and adequate control of longitudinal air velocity. The present paper deals with the experimental determination of smoke extraction rates and the evaluation of leakages.

In normal operating conditions, leakages of ventilation ducts can lead to non-ideal distributions of fresh air and exhaust. More serious consequences are unlikely. Conversely, in case of fire with concentrated smoke extraction, leakages from exhaust ducts can lead to substantial differences between the total exhaust flow rate provided by the fans and the net exhaust flow rate extracted at the fire location. This problem is widespread in older tunnels and becomes very serious while upgrading existing ventilation systems, particularly where substantial increases of smoke-extraction rates are required. In the latter case extensive investigations are frequently needed. The primary objective of such measurements is proving that the design goals are achieved. This requires the measurement at the flow rate in the exhaust duct, just downstream of the extraction location. A secondary objective, particularly important in the case of retrofits, is the measurement of leakages for assessing the duct quality. This allows for a correct specification of smoke extraction fans characteristics and, if required, for the planning and execution of periodic renovations of the infrastructure.

Measurement techniques for the leakages of exhaust ducts are therefore of utmost importance, particularly in the retrofitting process of older tunnels. Accessibility to existing tunnels is usually very limited and simple experimental techniques are called for. The following chapters deal with the experiences gathered with such measurements. On this basis recommendations are formulated concerning advantages and limitations of the different techniques. The content of this paper is mostly based on an extensive campaign carried out in 2002 in the Gotthard road tunnel. Additional information was provided by a number of measurement campaigns, including the Mont Blanc (2001-2002) and Branisko tunnels (2006).
2. DESIGN GUIDELINES AND THE NEED FOR VERIFICATION

Detailed prescriptions for evaluating leakages are given in the Swiss FEDRO (2006) directive in the Austrian RVS (2001). The leakages can be evaluated separately for the tunnel structure and for the dampers:

\[
q_{\text{Tunnel}} \left[ \frac{m^3}{s} \right] = \begin{cases} 
0.3 \cdot \sqrt{\Delta p} & \text{Switzerland} \\
5 & \text{Austria}
\end{cases}
\]

\[
q_{\text{Dampers}} \left[ \frac{m^3}{s} \right] = \begin{cases} 
0.003 \cdot \sqrt{\Delta p} & \text{Switzerland} \\
0.07 & 1'000 Pa \\
0.10 & 2'500 Pa \\
0.13 & 4'000 Pa & \text{Austria}
\end{cases}
\]

It should be noted that the Austrian values are prescribed as maximum allowable limits, while in Switzerland no limit is specified and the values mentioned are indications for design. The Austrian values are much lower in the typical operating range, 1’000-2’000 Pa. The German RABT (2006) and the French Circulaire (2006) clearly state the necessity for accounting for leakages in ventilation design, without specifying maximum values or detailed design criteria.

Figure 1: Flow rate and pressure distribution in case of fire for different leakage rates (Gotthard road tunnel, southernmost ventilation section, Airolo-Motto di Dentro). The curves indicate the results obtained imposing a constant extraction rate of 200 m³/s through 3 open dampers with high (thickest lines), average and vanishing leakage rates (thinnest lines). The leakage rates correspond to the prescriptions of the Swiss directive as well as half resp. twice this value.

3. MEASURING LEAKAGES IN THE GOTTHARD ROAD TUNNEL

The 16.9 km long Gotthard road tunnel is in operation since 1980. In spite of continuous maintenance the tunnel structure and equipments are showing their age. The tunnel was originally equipped with fixed openings for smoke extraction, which allowed only for a uniformly distributed smoke extraction. Under such conditions leakages were not a serious concern. After upgrading the original tunnel ventilation system, by means of smoke exhaust dampers (Bettelini et al., 2003), it was decided to carry out a thorough investigation of the system’s performance and effectiveness, including leakages. The main goals were the determination of the smoke-extraction capability of the tunnel in case of fire, the verification of the system’s performance in normal operating conditions and the verification of the aerodynamic stability limits of the exhaust fans after this major ventilation upgrade.
The initial and most thorough part of the effort was carried out during 2002 and was mainly devoted to the southern ventilation sector. With a length of 2.3 km and smoke extraction concentrated on one side, in the ventilation station Airolo, this sector represented one of the weakest links of this powerful ventilation system. Moreover the tragic fire of 24 October 2001, which took place about 1 km from the southern entrance, contributed to an additional weakening of the structure. Owing to the thorough test of the different equipments it was then possible to simplify significantly the investigation of the remaining four ventilation sectors of the tunnel. It should be noted that the measurement campaign constituted also one essential basis for the subsequent upgrade of the ventilation station Airolo, completed in 2007 (Chinotti and Bettelini, 2006).

4. MEASUREMENT PRINCIPLES AND TECHNIQUES

The determination of the leakage rate requires an accurate measurement of the flow rate at the smoke-extraction location and at the end of the duct. The second measurement is mostly provided with sufficient accuracy by the fixed measurement devices installed on the fans.

The basic techniques available for measuring flow rate and leakages are:

- Direct flow rate measurement through a number of velocity measurements.
- Indirect measurement of flow rate through measurement of tracer gas concentration.
- Indirect measurement of leakages through measurement of the pressure distribution along the exhaust duct.

These techniques are discussed in the following chapters, based mainly on the experiences from the extensive measurement campaign carried out in 2002 in the Gotthard road tunnel. The main findings, conclusions and recommendations are summarized in chapter 11.

5. FLOW RATE MEASUREMENT

Direct measurement of the flow rate thorough the dampers is usually not possible with any reasonable accuracy, because of the complex flow filed. An exception is e.g. the Mont Blanc tunnel (e.g. Bettelini et al., 2001), where the exhaust duct is located under the road and the secondary extraction ducts are well accessible.

Net measurement techniques are long established. The measuring principle is simple: the average velocity can be computed with high accuracy as the arithmetic average of the velocity values measured at a number of suitably selected locations in the section considered. The techniques adopted vary in detail, depending on assumptions on the velocity profiles, but the results are quite consistent. For our validation it was decided to adopt the Log-Tschebyschew rule using a network encompassing 6 x 6 measurement points, Figure 2. As showed by Richter (1972), the flow rate measurement error can be expected to be in the range of 1% for regular profiles and increase to 4% for highly irregular profiles.

Two measuring stations, one just upstream of the exhaust fan of the station Airolo, the second just downstream of the smoke extraction section and close to the duct far end, were installed. The home-made Pitot tubes (diameter 2/1.5 mm) were tested in the ETH wind channel and proved to be pitch-insensitive in a range of ±10°. The pressure signals were conveyed by plastic hoses to a Scanivalve connected to pressure transducers. Signals were displayed on an oscilloscope. Reference pressure for calibration was provided by means of Betz water manometers. Data acquisition was conceived and carried out by personnel of the Institute of Fluid Dynamics of ETH Zurich.

Representative velocity profiles are presented in Figure 3. The results were entirely consistent and permitted to compute the flow rates. The results are discussed in chapter 9.
Figure 2: The array of 6 x 6 Pitot tubes used for measuring the flow rate in the exhaust duct of the Gotthard road tunnel. A point ultrasonic anemometer is visible on the left hand side of the picture. The ventilation station Airolo is visible in the background.

Figure 3: Velocity profiles in the tunnel (left) and close to the ventilation station Airolo (right). The peculiar shape of the second profile is related to the tunnel’s curvature in the portal area (radius 760 m).

6. FLOWRATE FROM VELOCITY MEASUREMENTS

Much simpler methods for evaluating flow rate are direct velocity measurements. During the measurement campaign in the Gotthard road tunnel, where tunnel availability was critical and measuring time short, it was decided to validate reduced measurement techniques in the first tunnel section, in order to apply only them in the remaining ventilation sections of the tunnel. It was decided to use rugged ultrasonic point and line anemometers: 6 point measurement devices type TunnelCraft Flow 550 (range ±40 m/s, accuracy ±0.4 m/s, installation on the vertical wall, height 1.8 m, wall distance 35 cm), 2 line measurement devices type Flowsic 200 (range ±40 m/s, accuracy ±0.4 m/s, installation through the expected velocity peak) and data logger type EasyLog 4304 JUMO. All devices and the data acquisition system were delivered and operated by ACP (Bienne). Further verification measurements were carried out by means of conventional propeller anemometers.

The typical error to be expected from point and line measurements can be estimated based on a conventional 1/n power law for the velocity distribution in a circular pipe, with n ≈ 7-10 for Re ≈ 10⁵-10⁶. The error for point measurements will be in the range of the ratio of the
maximum to the average velocity, i.e. about 16-23% for the present application. Smaller errors, about 10-15%, can be expected while using average values over the diagonal. CFD results for the fully developed flow in this particular exhaust duct, conducted for an average velocity of 20 m/s and vanishing curvature, show that the maximum velocity is 17% higher than the average. Line averages, assuming horizontal measurements, show errors in the range of 5 to 7.5% for measurements heights between 1 and 2 m from the duct bottom. Line-averaged values are typically too high, because they do not account properly for the proportionally larger surface of the boundary layer region.

The accuracy level mentioned for point velocity measurements cannot be expected to be sufficient for leakages measurements. However, the cross-section of exhaust ducts is mostly constant. In such cases it is sufficient to place the point measurements of all measuring stations at exactly the same geometrical location within every profile. If the velocity profile is fully developed, the measured velocity is related to the average velocity by a constant proportionality factor, which can be determined by means of only one accurate flow rate measurement. This can be achieved by means of one Log-Tschebyschew or tracer measurement at one station or directly using the readings from the anemometers installed on the fans. After careful calibration in the southern most ventilation sector, this technique was used in all remaining ventilation sectors. The same approach was used in the Branisko tunnel, chapter 10.

7. TRACER MEASUREMENT

The tracer measurement technique was originally developed for the measurements in the Gotthard road tunnel described here and was later used routinely in several tunnels. This investigation was carried out by HTA’s (Fachhochschule Zentralschweiz, Lucerne-Horw) Prüfstelle HLK. The measuring principle is based on the injection of a known flow rate of an inert tracer gas, in this case SF6, into the exhaust duct, downstream of the last open damper, and measuring its concentration at two downstream locations. The flow rate it the exhaust duct at both locations can be computed using the known tracer flow rate and the measured tracer concentration. The downstream reduction of the tracer’s concentration is a direct measure for the leakage rate. In this case the relevant parameters were: injection of 2-5 g/s SF6, first measuring station 190 m downstream, second station 1’750 m further downstream. The SF6 concentration, in the range of 2 to 10 ppm, was measured by standard Bruel & Kjaer IR-PAS analyzers (measuring range 0.005-5’000 ppm) with an uncertainty estimated at 6.7%. The estimated resulting uncertainty was of the order of 7% for the flow rate and 4% for the leakage rate. Gas sampling at different locations within the measuring section confirmed that the gas concentration was sufficiently uniform at both locations.

8. MEASUREMENT OF PRESSURE DISTRIBUTION

The axial pressure gradient for fully developed flows in straight ducts with constants cross section is proportional to the longitudinal velocity squared. This inexpensive measurement proved to deliver a very useful verification of the results gathered by means of other techniques. In the Gotthard tunnel campaign the pressure difference between exhaust and main tunnel was measured at 6 locations by means of standard pressure transducers (Jumo 4304, 0-10 kPa) and self-constructed water manometers. Both measurements showed entirely consistent results.
9. ANALYSIS OF RESULTS

The decision of applying different measurement techniques in the Gotthard road tunnel was motivated by the urgency of the investigation, necessary for planning upgrades of the ventilation system, and by the reduced time slots which could be allotted for the measurements (the tunnel needs to be closed before accessing the exhaust duct and this is only possible for 20-25 nights yearly). The possibility of comparing several experimental techniques was a very useful side effect.

The results are presented in Figure 4. Depending on the data available, the reference flow rate is either the Log-Tschebyschew or the tracer value. If both values were available, their average was used. For velocity measurements the diagrams show the product of the velocity with the duct cross-section, without correction.

![Figure 4](image)

**Figure 4:** Comparison of the different measuring techniques tested in the Gotthard road tunnel, measuring station in the tunnel (left) and close to the ventilation station Airolo (right).

The main findings can be summarized as follows:

- The Log-Tschebyschew and tracer measurements are entirely consistent and the difference is, with the exception of one point with a difference of 6%, typically well below 3%.

- The values based on diagonal velocity measurements are, as expected, consistently too high. The correction if of the order of 10-15% but can vary depending on the installation location. Once this correction is applied, an uncertainty of about ±5% can be expected.

- The point velocity measurements obviously need calibration and the correction factor depends on the location of the measuring point. Once this correction is applied, the resulting values have an uncertainty of about ±5%.

Based on these results it was decided to reduce the subsequent measurements campaigns in the Gotthard road tunnel, for the remaining ventilation sectors as well as for all measurements carried out after extensive sealing efforts in the exhaust duct, to rely mainly on direct velocity measurements (point and diagonal) and pressure. Significant economic savings and time reductions, important considering the tight tunnel closure schedule, could be achieved.

The initially measured leakages in the southern ventilation sector of the Gotthard road tunnel proved to be very high, up to 30-40%. Much lower leakages were observed in the other ventilation sections, not or only marginally affected by the 2001 fire. An extensive intervention for reducing leakages was subsequently carried out. A second series of measurements showed that this intervention was successful.
10. MEASURING LEAKAGES IN THE BRANISKO TUNNEL

The Branisko Tunnel in Slovak Republic is in operation since 2003. The tunnel system consists of a single tunnel of nearly 5 km length with bidirectional traffic and parallel emergency escape gallery, transversally connected to the main tube by 13 cross connection galleries. The semi-transverse ventilation system allows, in case of fire, for a conventional smoke extraction through dampers, exhaust duct, vertical shaft and ventilation station in the central part of the tunnel. A safety analysis was carried out, according to the EU/EC 2004/54/EC (Bakos et al., 2007). It quickly was clear that the performance of the fire ventilation system played a central role in this tunnel and it was decided to investigate its performance in great detail, by means of 1D and 3D simulation techniques as well as an experimental investigation of the key performance parameter, the effective smoke-extraction rate (Bettelini et al., 2007). Since the tunnel is in operation, all investigations had to be conducted on a tight schedule during nighttime closures. Based on the experiences reported in the previous chapters, it was decided to combine several experimental techniques. The measurements were carried out based on SF6 injection and concentration measurements, precision anemometers, pressure gauges and the built-in fan flow rate measuring devices.

![Figure 5: Measuring techniques in the Branisko tunnel. Left: SF6 injection; right: SF6 suction and velocity measurement. The damper shown in the right picture was sealed by a steel plate.](image)

![Figure 6: Leakages measured in the Branisko Tunnel.](image)

The results presented in Figure 6 allowed for an accurate determination of the effectively available smoke-extraction rate. They also allowed confirming the presence of very substantial leakages, of the order of 25% for fire locations in the vicinity of the portals. This comparatively simple and inexpensive campaign provided therefore results, which are considered fundamental for the tunnel’s safety.
11. CONCLUSIONS AND RECOMMENDATIONS

Several experimental techniques have been validated under real life conditions in the Gotthard road tunnel and applied to other tunnels. The main findings and recommendations regarding the applicability of different techniques for measuring leakages in tunnels, in terms of accuracy, flexibility, time requirements and cost are:

- The Log-Tschebyschew and tracer techniques are very accurate (better than 3-5%) and (particularly for the tracer technique) insensitive towards “irregular” velocity profiles, related to tunnel curvature, variable cross-section, obstacles etc. Both techniques are comparatively time consuming (this holds particularly for the Log-Tschebyschew technique). They both require specialized equipment and personnel. Specialists can carry out tracer measurements without the need for much “customization” while the Log-Tschebyschew technique requires substantial adaptation to different tunnels but has the advantage of delivering an accurate velocity profile.

- Techniques based on one or a few point velocity measurements are quick and very inexpensive but usually require calibration at least at one station. The problem is easily solved if the accuracy of the fixed fan flow rate measurement is adequate. If some basic requirements are satisfied (well established velocity profiles, weak tunnel curvature, aerodynamically correct positioning etc.) a suitable calibration allows for accuracy of the order of ±5%. This technique is particularly interesting where several measuring locations are required, e.g. while looking for concentrated leakages, and in order to realize quick approximate evaluations.

- Techniques based on diagonally averaged velocity measurements represent an intermediate level between the simplest point measurements and the more complex Log-Tschebyschew and tracer techniques, both in terms of accuracy and requirements. The main disadvantage is related to the specialized equipment required and to the needs for a careful installation.

- Pressure measurements are simple and inexpensive. They are recommended as an additional mean for verifying the consistency of the results from other techniques.

While preparing measurements it should be evaluated if a few quick but careful CFD simulations of the exhaust duct can help simplifying a measurement campaign.

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13. REFERENCES


