DETERMINATION OF VENTILATION EFFICIENCY IN ROAD TUNNELS BY USING TRACER METHODS

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ABSTRACT
This paper reports recent findings from applying tracer methods for the determination of ventilation efficiency and reference velocities in different Swiss tunnels. Fast tracer concentration measurement devices and a mass flow controller were applied together successfully. This has led to the successful validation of the pulsed emission tracer method with the constant emission tracer method in three Swiss tunnels. This new method was further enhanced with a complete evaluation procedure to express measurement uncertainty.

The pulsed emission tracer method was validated with the constant emission tracer method in three Swiss tunnels and further enhanced with a complete budget to express measurement uncertainty.

The constant emission tracer method was and will be applied again in 2012 as reference in a long time measurement campaign that validates velocity measurement devices in two Swiss tunnels (Bözberg AG and Flüelen UR). Future work will include testing the feasibility of using an alternative tracer gas such as C$_2$H$_4$F$_2$ instead of SF$_6$.

Keywords: ventilation efficiency, tracer methods, volume flow of air, velocity measurements

1. INTRODUCTION
Since 2002 the constant emission tracer method has been used by scientists and engineers of the Centre for Integrated Building Technology at the Lucerne University of Applied Sciences and Arts (LUASA) to determine volume flow and leakage in exhaust ducts of twenty-two road tunnels in Switzerland and Europe. Economic considerations initiated the authors of this paper to investigate an alternative tracer method which needs less tracer gas with equal or more precise results as the constant emission method. This new method was tested embedded in a project of the Swiss Federal Roads Office (FEDRO) (see Buchmann, 2010, [1]). These investigations have led to a new method called pulsed emission tracer gas method.

2. CONSTANT AND PULSED EMISSION TRACER GAS METHOD
Both methods are described in detail in Frei & Kägi, 2010, [2] and are illustrated in Figure 1. The present paper gives only a briefly overview. For the development and application of the pulsed emission method a new generation of fast measurement devices and mass flow controllers was essential. Non Dispersive Infrared Spectroscopy (NDIR) and Fourier Transformation Infrared Spectroscopy (FTIR) together with thermal mass flow controllers are
now used in field applications. But even highly sophisticated thermal mass flow controllers had to be improved to really measure “mass flow” and nothing else. The mentioned equipment is able to measure concentrations and control flows of tracer gases like sulphur hexafluoride (SF$_6$), nitrous oxide (N$_2$O), and 1.1-difluorethane (C$_2$H$_4$F$_2$).

![Diagram](image1)

**Figure 1:** Experimental set-up of the constant and pulsed emission tracer method in exhaust ducts

### 3. VALIDATION OF THE PULSED EMISSION TRACER GAS METHOD

First experiments with the pulsed emission method were gathered in road tunnels Kirchenwald (2008), Aescher (2009), and Islisberg (2009) (see **Figure 2**). Single- and multipoint-sampling strategies showed good agreement and therefore excellent mixing even shortly after dosing can be concluded.

![Graphs](image2)

**Figure 2:** Tracer gas pulses downstream in exhaust ducts of road tunnels. From left to right: Kirchenwald, Aescher, Islisberg (according to Frei & Kägi, 2010, [2]).

Further on important pulse-design and pulse-integration-tools were developed with LabView® in a LUASA R & D project in 2010.

As mentioned in Frei & Kägi, 2010, [2] a comparison and validation of experimental results obtained by constant and pulse tracer method had to be realised.
Table 1: Experimental results obtained by constant and pulsed emission method in exhaust ducts of three Swiss tunnels.

<table>
<thead>
<tr>
<th></th>
<th>Kirchenwald tunnel</th>
<th>Aescher tunnel</th>
<th>Islisberg tunnel</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>pulsed emission (pe) singlepoint</strong></td>
<td>concentration integral = 64.4s</td>
<td>concentration integral = 66.6s</td>
<td>concentration integral = 71.3s</td>
</tr>
<tr>
<td></td>
<td>mass flow of air =196.8 kg/s</td>
<td>mass flow of air =198.8 kg/s</td>
<td>mass flow of air =117.5 kg/s</td>
</tr>
<tr>
<td><strong>pulsed emission (pe) multipoint</strong></td>
<td>concentration integral = 64.6s</td>
<td>concentration integral = 69.0s</td>
<td>concentration integral = 72.0s</td>
</tr>
<tr>
<td></td>
<td>mass flow of air =195.9 kg/s</td>
<td>mass flow of air =229.4 kg/s</td>
<td>mass flow of air =113.5 kg/s</td>
</tr>
<tr>
<td><strong>constant emission (ce)</strong></td>
<td>mass flow of air =211.6 kg/s</td>
<td>mass flow of air =217.0 kg/s</td>
<td>mass flow of air =117.1 kg/s</td>
</tr>
<tr>
<td><strong>deviation pe / ce</strong></td>
<td>7.2 %</td>
<td>1.3 %</td>
<td>1.4 %</td>
</tr>
<tr>
<td><strong>deviation singlepoint to multipoint</strong></td>
<td>0.5 %</td>
<td>13.3 %</td>
<td>3.5 %</td>
</tr>
</tbody>
</table>

- Deviation between the pulsed and constant emission method is comparably small with the exception of Kirchenwald tunnel. In this tunnel pulsed emission tracer method was applied the first time by LUASA. Uncertainties caused by dosing a tracer gas in a new way led to this deviation.

- Deviation between singlepoint- and multipoint-sampling is remarkable in Aescher tunnel caused by a short mixing length (196 m).

Furthermore the measurement uncertainty of the pulsed emission tracer method according to ISO-standards had to be defined. For this reason a complete uncertainty budget according to the guide to expression of measurement uncertainty (see GUM, 1995, [3]) was developed. Figure 3 shows the uncertainty budget for the pulsed emission method measurement in Islisberg tunnel (singlepoint). Mass flow of the carrier fluid in this case was (117.5 ± 4.9) kg/s or 117.5 kg/s ± 4.2% (95% confidence interval).

Figure 3: Budget for measurement uncertainty according to the GUM, 1995, [3].
4. RECENT APPLICATIONS OF TRACER METHODS IN SWISS TUNNELS

4.1. Determination of ventilation efficiency in tunnel Mappo-Morettina TI

The Swiss tunnel Mappo-Morettina near Locarno TI has a total length of 5530 m with two sections Mappo and Morettina. This tunnel has separate exhaust and supply air ducts. LUASA determined leakages and the ventilation efficiency in spring 2011 during two night-closures in both sections. The results will cause an intensive duct tightening campaign to lower leakages and enhance ventilation efficiency.

Figure 4: Multipoint-sampling in exhaust duct (left) and measurement devices in supply duct at measurement site MS2 (right).

LUASA applied the constant and pulsed emission tracer method downstream in the exhaust-duct at two measurement sites (MS1 and MS2). Distances from the dosing station was less than 100 m for MS1 and approximately 2300 m for MS2. The measurements have proved that the pulse emission tracer method has the ability for a fast approximation on leakages, mean velocities (derived from distance and delay time), and short circuits. Lessons learnt from tunnel Mappo-Morettina are the following: A rectangular pulse generation for short mixing lengths less than 100 m has to be avoided, otherwise deviation between constant and pulsed emission can exceed 10%. A rectangular pulse generation does not influence deviation at measurement site 2 (under 5%). Further considerations to enhance the pulsed emission method to operate with an alternative tracer gas like 1.1-Difluorethane (C₂H₄F₂) are underway.

Figure 5: Series of pulses downstream at measurement sites 1 and 2 in Morettina section.
4.2. Determination of reference velocities in tunnel Flüelen UR and Bözberg AG

A long-time measurement campaign concerning the measurement of air velocities in road tunnels was initiated in autumn 2011 by FEDRO (contractor Lombardi). Manufacturers of air velocity measurement equipment installed their devices for long-time measurements and data processing in two Swiss road tunnels Flüelen UR and Bözberg AG. Data is collected and stored in time steps of 10 seconds. Every day a backup of 24-hours measurements is sent by GSM router to Lombardi for data processing and interpretation. Possible long-time shifts and a dependence on the installation point of the devices are observed by engineers of Lombardi.

LUASA were asked to provide verification data using the constant emission tracer method. Mean air velocities can be derived from volume air flow and cross-section area. In the current FEDRO project reference mean velocities derived from measured volume air flows by using the constant emission tracer method were to be determined. Measurements under different traffic conditions have been conducted successfully in January 2012. A second series of reference measurements is planned for autumn 2012. Experience from dosing and sampling under traffic conditions will boost the ability to apply the pulsed emission method not only in exhaust ducts, but also in tunnel tubes.

![Figure 6: Dosing of tracer gas SF₆ with small ventilators near the north portal in tunnel Flüelen UR.](image)

![Figure 7: Part of multipoint-sampling in tunnel Flüelen UR (left) and measurement devices in a cross-passage (right).](image)
Figure 8: Dosing and multipoint-sampling of tracer gas SF6 in tunnel Flüelen UR.

Figure 9: Dosing and multipoint-sampling of tracer gas SF6 in tunnel Bözberg AG.

Figure 10: First results from measured local und derived reference mean velocities.
5. CONCLUSION AND OUTLOOK

Comparison measurements of the constant und pulsed emission tracer methods showed good agreement for each single measurement site in exhaust ducts of three Swiss tunnels.

In the exhaust ducts of the Mappo-Morettina tunnel the pulsed emission tracer method delivered results comparable to the constant emission tracer method for all measurement sites. Both methods are equally adapted for ventilation efficiency validation in ducts.

The constant emission tracer method has shown its ability to serve as reference method for velocity measurements in tunnel tubes under traffic conditions.

The enhancement of the constant and pulsed emission tracer method by using an alternative tracer gas like 1.1-difluorethane (C$_2$H$_4$F$_2$) is planned for coming measurement campaigns.

The application of the pulsed emission tracer method to measure volume air flows in tunnel tubes under traffic conditions is under consideration by the authors of this paper.

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7. REFERENCES

