DETERMINATION OF AERODYNAMIC BURDEN IN RAIL TUNNELS USING MEASUREMENTS AND SIMULATION

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ABSTRACT

When a train passes through a tunnel, pressure waves at nearly the speed of sound are propagated in the tunnel. If the train is not absolutely pressure-tight, these pressure changes are partly transmitted inside the train and may be uncomfortable for the passengers. The difference between the pressure outside and the pressure inside the vehicle puts an alternating load onto the train body. Likewise, the tunnel installations are also exposed to these pressure variations. Mainly high train speed combined with small tunnel cross sections results in pressure variations with high amplitudes and simultaneous heavy air flows. The usual operative situation is the passage of a single train through the tunnel even if the tunnel is designed for double-track use. In this case, the loads resulting from the pressure variations in general represent the construction reference for the endurance limit of the trains and of the built-in components of rail tunnels.

The authorisation of new rolling stock on the "Westbahn" section (e.g. Stadler KISS WEST-bahn) or the increase of the sectional speed limit up to 230 km/h (e.g. railjet) in the unrestricted mixed rail-traffic requires analyses and measurements regarding possible pressure loads. In this process, the relevant aerodynamic properties of the rolling stock are determined based on 1:1-tests and compared with the directives of the TSI or the parameters of other, aerodynamically high-quality passenger trains (e.g. ICE 2). They serve as basis for the approval and authorisation of trains and tunnels.

Keywords: TSI, aerodynamic burdens, rail tunnel, pressure wave, measurements

1. INTRODUCTION

When a train passes through a tunnel, pressure waves at nearly the speed of sound are propagated in the tunnel. The compression wave (frontal wave) generated at the moment the train enters the tunnel is reflected at the opposite portal as an expansion wave. When the train tail enters the tunnel, an expansion wave (rear wave) is generated and reflected at the portal as compression wave. Due to the superposition of waves, the pressure amplitude increases, leading to high loads on the tunnel installations in some places. Besides this, the size and the direction of the impact forces change very quickly.

With pressure-tight rolling stock, there are less pressure loads inside the vehicle than with non-pressure-tight rolling stock. Higher pressure loads on pressure-tight trains are registered via the vehicle walls at windows, the doors, the air-conditioning openings etc.

Furthermore, pressure variations are occasionally felt by passengers as being uncomfortable; in extreme cases, they can even cause permanent health damages.

The authorisation of new rolling stock on Austrian railway sections requires e.g. the confirmation of the vehicle aerodynamics evidence pursuant to the directives of the TSI guidelines (cf. [6], [7]) and of the ÖBB Infrastruktur AG (cf. [5]).

With regard to aerodynamics, the vehicles must be constructed in such a way that the required characteristic pressure variations are fulfilled for a given combination (reference case) of train speed and tunnel cross-section. The assumption is that a single train passes through a standard, straight tubular tunnel (without shafts etc.). Since 1:1-measuring of every combination is not possible; calculation results with validated calculation models will be also accepted. The
model building / validation will be based on measured pressure curves. The procedure is presented in details below.

2. GUIDELINES

2.1. Requirements of vehicle aerodynamics for the authorisation in the ÖBB railway network

The requirements of vehicle aerodynamics are listed in the catalogue of requirements for trains applying for authorisation in the ÖBB railway network (cf. [5]). Accordingly, the aerodynamic effects, in particular the pressure waves in the tunnel, must not lead to any negative impact on the oncoming or overtaking train. Corresponding evidence must be provided for the speed level $v_{tr} > 160$ km/h. Alternatively, an expertise based on a comparison with a train already authorised in the ÖBB railway network will be accepted.

2.2. Technical specifications for the interoperability (TSI)

In a series of legal acts, the European Commission has passed technical specifications for the interoperability (TSI) in the trans-European high-speed railway system and in the conventional trans-European railway system and has published them in the respective gazettes of the European communities.

The directive TSI 96/48/EG about the sub-system “Vehicles” applies to class 1 vehicles ($v_{tr} \geq 250$ km/h) or class 2 vehicles ($190$ km/h > $v_{tr} > 250$ km/h) and defines the requirements the vehicles used in railway network of the trans-European high-speed train system must fulfil. The use of the concerned vehicles by a train company on a specific railway section is also subject to compliance with the guidelines 2004/49/EG and 2001/14/EG, modified by the guideline 2004/50/EG.

3. AERODYNAMIC CRITERION / PRESSURE SIGNATURE

The aerodynamic properties of a train in a tunnel can be determined with the pressure curve. Fig. 1 schematically shows the pressure variations generated when a train enters a tunnel or passes another train in a tunnel. This so-called pressure signature includes:

- $\Delta p_N$: Pressure rise generated by the frontal wave of the train nose entering the tunnel
- $\Delta p_{fr}$: Pressure rise generated during the tunnel passage due to the friction
- $\Delta p_T$: Pressure drop due to rear wave generated by train tail entering the tunnel
- $\Delta p_{Hp}$: Pressure drop during the passage of the train nose

Fig. 1: Train / tunnel pressure curve at a fixed place in the tunnel [8]
The applicable characteristic limits for $\Delta p_N$, $\Delta p_{Fr}$ and $\Delta p_T$ are compiled in table 1.

**Table 1: Requirements for an interoperable train passing through a tunnel tube at a speed of $v_{tr} < 250$ km/h [7]**

<table>
<thead>
<tr>
<th>Train type</th>
<th>Reference case $v_{tr}$ [km/h]</th>
<th>$A_u$ [m$^2$]</th>
<th>$\Delta p_N$ [Pa]</th>
<th>$\Delta p_{N+Fr}$ [Pa]</th>
<th>$\Delta p_{N+Fr+T}$ [Pa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_{tr,\text{max}} &lt; 250$ km/h</td>
<td>200</td>
<td>53.6</td>
<td>$\leq 1750$</td>
<td>$\leq 3000$</td>
<td>$\leq 3700$</td>
</tr>
</tbody>
</table>

Evidence must be provided based on 1:1 tests carried out with the reference speed or a higher speed in a tunnel with a cross-section as close as possible to the reference case. Next, the transfer to the reference requirement must be done with verified simulation software.

4. **TEST RUNS**

Extended measurements have been carried out in summer 2011 at different places of the "Westbahn" section regarding the authorisation of new rolling stock on this section (Stadler KISS WESTbahn) or regarding the increase of the sectional limit speed to 230 km/h for the railjet of the ÖBB in the unrestricted mixed traffic. Beside measurements on the free section or on a train station platform, aerodynamic measurements were also carried out in a tunnel. The measurement setup and the measurement technique are described below. Next, the measurement results and the subsequent calculations will be presented.

5. **MEASUREMENTS**

5.1. **Measurement Setup**

The measurements were carried out on three days at the end of August 2011 in the Melk tunnel. Beside the railjet and the KISS WESTbahn train, regular traffic trains were also analysed. The Melk tunnel on the "Westbahn" section has a length of 1845 m. It is a double-tracked tunnel with concrete pavement and has a cross-section of 78 m$^2$ (fig. 2).

![Fig. 2: East portal of Melk tunnel and the measurement setup at km 84.4](image)

For the measurement of the train / tunnel pressure curves, ideally a fixed place is selected in the tunnel. Measurements directly on the passing train are also possible; but the values of the pressure signature must then be approximated by the measured values. The test tunnel must have a constant cross-section and no further pressure waves must be generated inside. Ideally, there must be no ground flow in the tunnel.
Under EN 14067-5: 2006 – “Requirements and test procedures for aerodynamics in tunnels” [8], the equation of the distance \( x_p \) between the entrance portal and the measurement position is:

\[
x_p = \frac{c \cdot L_{tr} + \Delta x_1}{c - v_{tr}} + \Delta + \Delta_1 \quad \text{formula 1}
\]

The extra length \( \Delta x_1 \) (approx. 100 m) ensures a clear time-related separation of the pressure variations over time. The installation of the measurement devices near to the portal is meant to avoid a deadening of the pressure wave. Based on the formula 1, a minimal distance of about 460 m away from the portal is necessary with a train length of 300 m and a maximum speed of \( v_{tr} = 200 \text{ km/h} \). Finally the measurement position was 550 m from the entrance portal in direction of the traffic. The pressure sensor was placed on the tunnel wall, the speed sensor on the sidewalk at a distance of 2.5 m of the middle of the track (measurement height 1.2 m over the rail top edge).

5.2. Measurement Devices

Strict requirements apply to the measurement technique with regard to the measurement frequency and accuracy (cf. [8]). The minimal scan frequency is determined based on the length of the train nose and the train speed.

Piezoresistive miniature differential pressure gauges were used for the pressure measurement in the tunnel. Table 2 shows the characteristic parameters of the pressure gauges.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured area</td>
<td>-6895 to +6895 Pa</td>
</tr>
<tr>
<td>Maximal error</td>
<td>0.33% regarding the maximal deflection</td>
</tr>
<tr>
<td>Resonance frequency</td>
<td>70 kHz</td>
</tr>
</tbody>
</table>

The pressure gauge is integrated in a plate (150 mm x 150 mm) to protect it against mechanical burdens. The pressure signal reaches the sensor via a perforation (1 mm diameter) and a coupling volume. The transfer properties of this system (amplitude and phase response up to 10 kHz) were taken into account in the installation of the measurement equipment.

The flow speed in the tunnel tube was measured with a 2D supersonic anemometer. The advantages of the supersonic anemometer are the higher accuracy, the absence of inertia in the system and the additional recording of the wind components in x and y directions. The supersonic device has 4 supersonic converters with respectively 2 of them placed at a distance of 135 mm opposite the other. The two measuring paths are vertically opposite each other. The converters function simultaneously as sound sender and sound receiver. Since the sound speed is considerably dependent on the air temperature, the velocity of sound is measured on each of both measuring paths in both directions. Thus, an influence of the temperature-related sound speed on the measurement result can be excluded. The measurement rate depends on the sound speed on the measuring length and amounts to <10 Hz.

In accordance with [8], the measurement of the train speed must have accuracy better than 1%. Supersonic sensors were placed at 2 measurement points with a defined distance from each other and the speed was calculated based on the time difference between both signals resulting from the passing train. An additional speed measurement device was place on the train itself for a GPS determination of the speed. The measurement device is suitable for accu-
rate measurement (measurement error ±0.1 km/h) and detailed data recording of speed, position, longitudinal and cross acceleration.

The data recording was performed with a portable Dewetron data logger. The logger has 8 analogue channels and multiple digital inputs and captures measurement signals at scan rates up to 100 kSamples/s for each canal. The filtering and the averaging are done automatically inside the logger. The logger is configured and operated with specially designed software. The pressure signal and the flow speed were captured at a scan rate of 300 Hz and their analogue low-pass filtering done with a Butterworth low-pass filter.

In order to reduce the data quantity, the captured data were not stored in full demand time for the whole test period. The supersonic sensors were additional used as triggers activating a quick measurement whenever a train passed by. At this moment a measurement run were stored with scan rate of 300 Hz (15 seconds before and 300 seconds after the triggering). Thus the storage covers the whole passage of the train trough the tunnel incl. a lag of several minutes.

5.3. Measurement Results

Fig. 3 shows the pressure signals recorded in the tunnel for the KISS WESTbahn train. The train speed was within the range of 198.9 to 201.6 km/h. Therefore, all curves are similar. Two curves (measurement 4 and measurement 6) are particularly remarkable. At the time of both measurements, there was already a flow speed of about 4 m/s in the tunnel before the train passes. The direction of the flow was in opposite to the driving direction of the train in the tunnel. This resulted in higher pressures. All the remaining measurements were done with speeds of flow lower than 1.2 m/s, which results in a very good matching of the pressure curves.

![Fig. 3: TSI pressure signal measured for the KISS WESTbahn in the Melk tunnel](image-url)

6. SIMULATION

6.1. Simulation Program

The measurement results of the Melk tunnel measurement were recalculated with verified software. Some parameters of the analysed train were varied as often as necessary until a
good matching with the measurement was reached. Subsequently, the pressure signatures could be calculated with the programme for the in TSI specified tunnel cross-section ($A_{\text{Tunnel}} = 53.6 \text{ m}^2$).

The software ThermoTun was used for the numerical simulation. ThermoTun is a computer programme accepted worldwide for the simulation of trains in tunnels and of tunnel systems. The correctness is confirmed by extended measurement campaigns (cf. [9], [10]). With the programme, e.g. the following, aerodynamically relevant, unsteady values can be determined:

- Pressure variations of trains passing tunnels and on rolling stocks,
- Traction power requirements for trains in railway tunnels,
- Averaged air speed in the railway tunnel tube,
- Distribution and concentration of pollutants and smoke in railway tunnels.

6.2. Calculation Results

The measurement run no. 2 (fig. 3) has been chosen for the analysis and for the comparison with the ThermoTun software with respect to the lowest air speed before the train entrance in the tunnel (0.3 m/s). Fig. 4 shows the pressure curve of the measurement (red line) and the corresponding ThermoTun computations. The computed values match well with the measurement. Difference can be seen in the development after the passing of the tail wave at approx. 8 seconds. ThermoTun’s ability to reproduce the relatively slow pressure drop is limited. However, the pressure drop due to the tunnel entrance of the train tail is correctly displayed. The pressure drop observable at approx. 10 seconds due to the impacting pressure waves reflected by the exit portal is also reproduced by ThermoTun in a steeper representation.

![Fig. 4: Comparison of measurement (run 2) with ThermoTun computations](image)

In the following reliable analyses for other tunnel configurations can be done using the input parameters determined by ThermoTun. Fig. 5 shows computations with the input parameters based on the comparison for a tunnel cross-section $A_{\text{Tunnel}} = 53.6 \text{ m}^2$. The train-related pressure variations due to the train nose and tail pressure waves and due to the longitudinal friction on the train wall are indicated.


Fig. 5: ThermoTun computation for a tunnel cross-section of $A_{\text{Tunnel}} = 53.6 \, \text{m}^2$

Table 3: Contribution of various causes on the train-related pressure variations

<table>
<thead>
<tr>
<th>Cause of the pressure variation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frontal pressure generated by the train penetrating the tunnel $\Delta p_N$</td>
<td>1.34 kPa</td>
</tr>
<tr>
<td>Pressure difference due longitudinal friction $\Delta p_F$</td>
<td>1.03 kPa</td>
</tr>
<tr>
<td>Tail pressure wave generated by the train leaving the tunnel $\Delta p_T$</td>
<td>0.76 kPa</td>
</tr>
<tr>
<td>Total $\Delta p_N + \Delta p_F + \Delta p_T$</td>
<td>3.13 kPa</td>
</tr>
</tbody>
</table>

7. CONCLUSION

As a requirement for the authorisation of new rolling stock on railway sections e.g. evidence must be produced about the aerodynamics of the train. A new train must be aerodynamically constructed that no damages occur for the train and for the tunnel installations when the train passes through a tunnel or passes by an oncoming train. Besides this, the comfort of the passengers must also be taken into consideration.

This paper describes the authorisation procedure for new trains. It consists in 1:1 measurements being recalculated with verified software and some parameters being varied for a good accordance with the measurements. The measurements were done in the Melk tunnel on the "Westbahn" section in August 2011 and leads to a data set of several train / tunnel pressure curves for the KISS WESTbahn train ($v_T = 200 \, \text{km/h}$), the railjet train ($v_T = 230 \, \text{km/h}$) and numerous trains of the regular traffic with different speeds. Subsequently, any other situation in different tunnels now can be calculated from the results using the ThermoTun software.

8. ACKNOWLEDGEMENT

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9. REFERENCES


