Effectiveness of pressure relief shafts – full scale assessment

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Abstract

The use of pressure relief shafts has often been proposed as a means of reducing pressure fluctuations and of improving passenger comfort on board high-speed trains in tunnels. The recently opened rail-link between Mattstetten-Rothrist in Switzerland is one of the first rail projects where such shafts became an integral part of the project right from the design stage.

The effectiveness of pressure relief shafts has been proven during the commissioning phase of this 45 km long new rail-link. Several aerodynamic measurements were conducted in different tunnels with and without pressure relief shafts and with different train types. One example is the double-track Emmequerung tunnel with a free cross-sectional area of A_{tunnel} = 76 m^2 with two pressure relief shafts (A_{shaft} = 12.25 m^2). The same tunnel without any pressure relief shafts would have required a larger free cross-sectional area of A_{tunnel} = 105 m^2 in order to satisfy the project specific comfort criteria for various train types (Δp_{train} < 1.5 kPa within 4 s).

In general, smaller tunnel cross-sections lead to reduced construction costs. Furthermore pressure relief shafts can be combined with additional functions (egress path, smoke extraction, climate improvement, etc.). These advantages must be balanced with possible disadvantages (noise emissions, increased local air flows in the tunnel, etc.) and the limitations (ground overburden). The experience gained from the new Swiss rail-link shows that under certain conditions pressure relief shafts are effective and reasonable.

1. Introduction

The extension of the European high-speed railway network leads to various challenges to provide an adequate level of comfort for passengers. Among these demands and in the case of tunnel passages, the pressure comfort is an important aspect. Pressure variations are perceived individually in a different manner. As a result, definitions and national guidelines may differ from one another.

The required type and complexity of measures to improve pressure comfort for passengers are determined by:

- the definition of the pressure comfort criteria (for example small or large pressure variations in different time intervals)

- the measures at the rolling stock (e.g. sealing of vehicles, quality of the maintenance and overhaul work)
- the operational measures (e.g. train velocity, schedule)
- the specific civil measures (for example cross-sections, openings, portal design, shafts, etc.)

2. Pressure variations and pressure comfort criteria

Sources of pressure variation

Pressure waves in rail tunnels are generated by moving trains and changes in the surrounding free cross-sectional area of the train in the tunnel. Commonly, the most extreme change of the free cross-section occurs during entering or leaving tunnels (see [4], [9]). Pressure waves propagate in the tunnel with the speed of sound and are (partly) reflected at portals and cross-sectional variations. Additionally, the friction of air on the tunnel wall and the train surface lead to a pressure decrease along the train and the tunnel. This decrease of static pressure interferes with train induced pressure waves in the tunnel.

Limits for pressure variations in trains – pressure comfort criteria

Frequent and strong pressure variations in trains lead to discomfort and may be harmful to health in extreme cases. The so-called pressure comfort criteria were developed in order to protect passengers and staff from excessive pressure variations. Commonly, the guidelines and recommendations for the pressure comfort specify the amplitudes of pressure variations in certain time intervals.

Pressure comfort criteria for Rail 2000-Projects in Switzerland

The new rail-link between Mattstetten and Rothrist has been realized as part of the traffic concept Rail 2000 of the Swiss Federal Railway (SBB). The rail-link was put in operation in 2004. The project specific pressure comfort criterion shown in Table 1 was defined in 1991. This criterion has been defined for unsealed trains. Simultaneous train passages in the tunnel are not considered.

Table 1: Pressure comfort criteria of UIC and for the Swiss Rail 2000 project

Time interval [s]	UIC-criteria – max. pressure variation [kPa] in time interval (2002)	Rail-2000-criterion – max. pressure variation [kPa] in time interval (1991)
1	≤ 0.5	-
3	≤ 0.8	-
4	-	≤ 1.5
10	≤ 1.0	-
60	≤ 2.0	-

Pressure comfort criteria of the International Union of Railways

The International Union of Railways (UIC) published a guideline for sealed trains (see [1]) in order to harmonize the different international recommendations. The recommendations representing current standards are shown in Table 1.

Medical limit for pressure variations

The medical limit for pressure variations is defined within the "Technical Specifications for interoperability" (TSIs) by the European Committee for Standardization (see [2]). Therein the maximum pressure variation during an entire train passage through a tunnel is restricted to 10 kPa.

3. General measures to ensure pressure comfort criteria

Choice of the pressure comfort criteria

The acceptance of pressure comfort depends on different factors, for example:

- the number of the tunnels along a journey
- the length of the tunnels
- the further disturbing factors (noise, train air-conditioning, climate, vibrations, health condition of the passengers, degree of distraction of the travellers)

It should be noted that some passengers will already feel mild discomfort within defined limits, as some people are more sensitive than others. To which extent the UIC pressure comfort criteria need to be maintained and/or whether measures to comply with the criteria are to be taken or not, must be considered together with the various boundary conditions and functions of the tunnel system.

Sealing of rolling stock

Pressure variations are transferred by openings into the interior of the coach. Large openings, e.g. between single coaches or bad sealing, cause an almost undamped pressure equalisation. The pressure tightness coefficient τ is used to specify the sealing quality of a single, static vehicle. It describes the time in which a difference between the internal and the external pressure has decreased from 100 % to approx. 37 % of the initial pressure difference according Figure 1.

It should be noted that specifying the sealing quality of a vehicle by a single time constant such as τ is a significant simplification. τ-values of the coaches might vary significantly depending on the location, the pressure gradient, the time and the condition of the coach. The impact of different pressure tightness coefficients on the decreasing pressure difference between the exterior and the interior of the train is shown in Figure 1. Typical pressure tightness coefficients are listed in Table 2.

Table 2: Comparison of typical pressure tightness coefficients for different train types

Train type	**Pressure tightness coefficient τ**
unsealed train (e.g. regional transport)	$\tau < 0.5$ s
poorly sealed train (e.g. Eurocity)	0.5 s $< \tau <$ 6 s
well sealed train (e.g. ICE1, TGV)	6 s $< \tau <$ 15 s
excellently sealed train (e.g. ICE3)	$\tau >$ 15 s

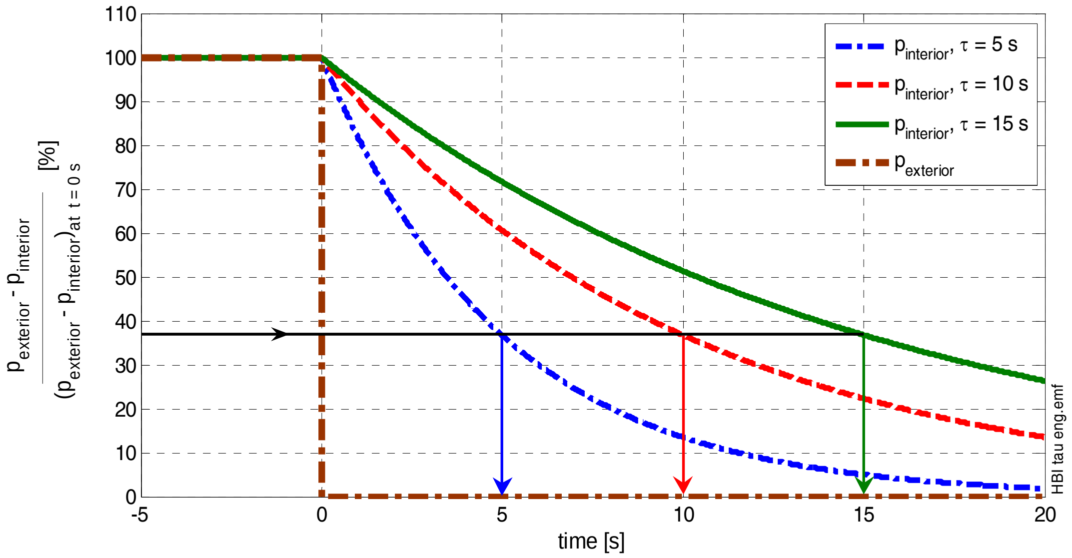

Figure 1: Pressure development in train for a sudden pressure difference to the exterior at t = 0 s (τ = 5, 10 and 15 s)

Operational measures

Pressure comfort criteria can be satisfied by applying operational measures like:

- reducing the train velocity during the entry or exit of the tunnel
- reducing the number of trains passing in the tunnel (double-track)
- increasing the time gap between succeeding trains (adapting the train schedule in very long tunnels)

In principle, these measures are applicable in order to enhance the pressure comfort for passengers and tunnel staff. However, those measures are commonly impractical for modern high-speed rail lines.

Civil measures

Several civil measures allow reducing pressure variations in tunnels, such as:

- increased cross-sectional area of the tunnel
- pressure relief shafts
- portal design
- open cross-passages or pressure relief ducts

The following chapter details some of the possible civil measures.

4. Increasing the pressure comfort by civil measures

Table 3 lists different civil measures which allow decreasing the pressure variations in rail tunnels. To which extend the use of the measures is reasonable depends on several aspects, e.g.

- the degree of sealing of the rolling stock
- the choice of the comfort criteria (e.g. duration of time intervals, if pressure gradients are taken into account)
- frequency of passing trains
- a multitude of civil boundary conditions

Table 3: Comparison of civil measures reducing pressure variations in tunnels

Measure / impact	Possible advantages	Possible drawbacks
Pressure relief shaft / Pressure waves are partly reflected at shafts. Hence, the amplitude of pressure waves decreases.	– cost-saving compared to other measures, for example increase of cross-sectional area of tunnel – if possible use for smoke extraction, emergency exit, for climate improvement (additional measures might be required)	– measure applicable only under certain circumstances (e.g. low overburden of ground) – noise emission – ambient factors affecting the tunnel (e.g. snow, ice, dirt, leaves, rain, etc.)
Increased tunnel cross-section / Increased tunnel cross-sections lead to reduced blockage ratios. Hence, the pressure wave generated upon train entry is reduced.	– reduced pressure fluctuation in the tunnel for any train type, schedule, etc. – less extreme aerodynamic conditions (less aerodynamic loads on equipment and trains, less traction power required)	– major increase of construction costs – higher flow rates required for ventilation and smoke extraction purposes
Portal widening / The amplitude and steepness of the initial pressure wave are reduced.	– in several circumstances economic solution – possible measure to reduce the risk of sonic boom	– increased space requirements in the portal region – portal modifications have to be applied along a few hundred meters
Pressure relief ducts between 2 single bore tunnels / Pressure waves are partly reflected at openings. Hence, the amplitude of pressure waves decreases.	– economic solution – in tunnels with high rock overburden or under-water tunnels the major alternative	– requirement for further measures because of aerodynamic coupling between two or more tubes (dampers, doors, etc.) – more extreme pressure fluctuations because of superposition of pressure variations from different tubes – side wind on trains

Potential civil measures are sketched in Figure 2. A single optimum civil solution to reduce the pressure fluctuations can not be given. In fact, different aspects have to be considered, e.g.:

- free cross-sectional area and length of a tunnel
- aerodynamic coupling between different tunnels
- sensible areas above the tunnel (e.g. residential areas, parks, etc.)
- safety concepts (e.g. smoke extraction)
- train schedules (e.g. train speed, distance between succeeding trains, frequency of passing trains, etc.)
- proposed shafts for additional tasks (e.g. sonic-boom reduction, draught relief, etc.)

- costs for investment and operation

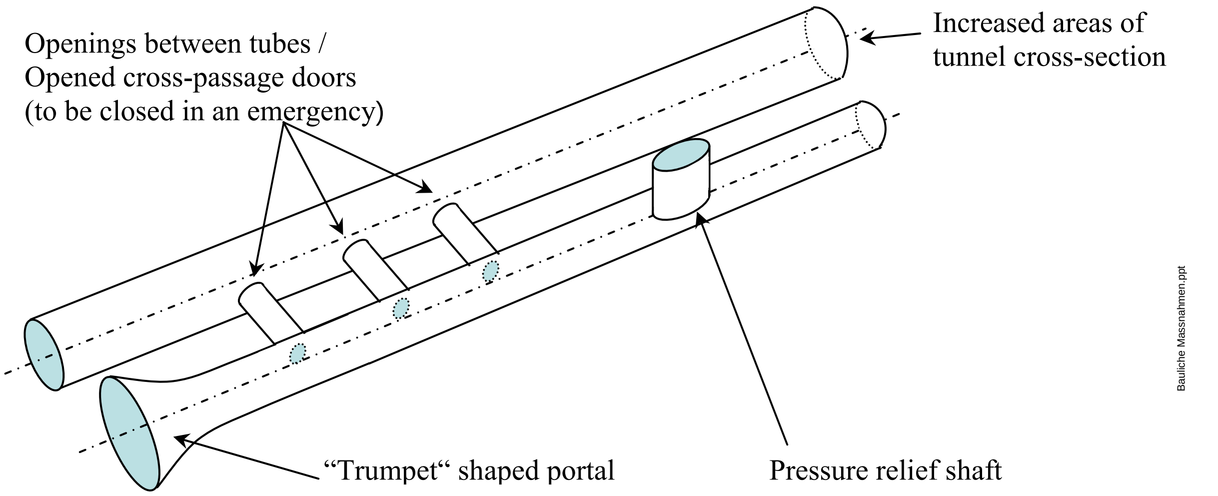

Figure 2: Measures in tunnels in order to decrease the pressure fluctuations

5. Principal functions of shafts in rail tunnels

The primary purpose of pressure relief shafts is reducing the amplitudes of train induced pressure waves. However, it can also be coupled with further functions like tunnel ventilation or fire safety. Major shaft types, their functions, their locations and their sizes (cross-sectional area are summarized in Table 4.

Table 4: Comparison of different shaft functions in tunnels with respect to aerodynamic, climate and ventilation topics.

Shaft type	**Function**	**Typical locations in tunnel**	**Typical cross-section**
Pressure relief shaft	– to ameliorate pressure comfort by reducing pressure variations	– distance of 500 m or more from the portals, also along the tunnel, the best position and the cross-section depend primarily on the tunnel geometries, the rolling stock and train schedules	5 – 15 m^2
Draught relief shaft	– to reduce air velocity mainly on underground platforms / stairwells – to reduce the required traction power due to reduced air transport in front and behind the train	– immediate vicinity of stations	25 – 80 m^2

Shaft type	**Function**	**Typical locations in tunnel**	**Typical cross-section**
Smoke extraction and/or ventilation shaft	– to exchange fresh- and tunnel air between the tunnel and the environment	– close to ventilation station or as passive air intake / smoke exhaust	5 – 20 m^2
Shaft for reducing micro-pressure waves	– to eliminate unacceptable micro-pressure waves (sonic boom) at exit portal by decreasing the steepness and the amplitude of pressure waves in the tunnel	– close to the portals	10 m^2
Shaft for climate improvement	– to improve the tunnel climate by increased air exchange between the tunnel and the environment	– close to the portals (e.g. anti re-circulation shaft). – along the tunnel in order to improve the air exchange and to reduce the required traction power	30 m^2
Shaft for emergency exit	– to shorten escape distance by additional emergency exits (possibly ventilated)	– along the tunnel – close to stations	10 m^2

The use/impact of pressure relief shafts was documented by Figura-Hardy ([5]). General investigations about openings in tunnels were conducted by Bellenoue and Auvity ([6]).

6. Pressure relief shafts of the tunnel Emmequerung

The tunnel Emmequerung is part of the rail-link between Mattstetten and Rothrist in Switzerland. The basic data of the Emmequerung tunnel are listed in Table 5. It is one of few new rail lines in Europe that has systematically been equipped with pressure relief shafts in tunnels in order to improve the pressure comfort.

During the design phase, investigations about the pressure comfort were carried out (see [3]). Aerodynamic studies were conducted for different configurations. The simulations were carried out with THERMOTUN ([7], [8]), an approved one-dimensional program for tunnel aerodynamics and ventilation, based on the method of characteristics.

The simulations were carried out considering different train types, train velocities and shaft positions, shaft cross-sections as well as varying numbers of shafts. The finally chosen pressure relief shafts are identical in size and are shown in Figure 3.

Table 5: Characteristics of the Emmequerung tunnel, built for the project Rail 2000 between Mattstetten and Rothrist in Switzerland

Parameter of Emmequerung tunnel	Value
type / construction	single-bore / double-track
free cross-sectional area [m^2]	76
length [m]	1633
elevation between tunnel portals [m]	8
number of pressure relief shafts	2
distance between pressure relief shafts and the portals [m]	approx. 500
free cross-sectional area of each pressure relief shaft [m^2]	12.25
track type	approx. 50 m ballast track at each portal region; else slab track

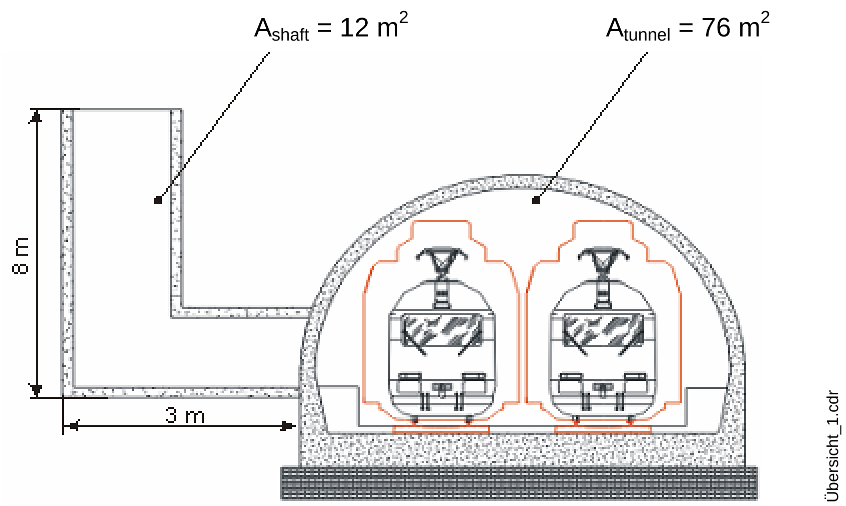

Figure 3: Schematic view of the cross-section of the Emmequerung tunnel with a pressure relief shaft

7. Confirmation of the simulations by measurements

Measuring devices

The pressure measurements were performed with Kulite micro-pressure transducers, integrated into plates. Pressure signals were transferred by pressure taps to the transducers. Two Gould-Nicolet data acquisition systems were used to record the pressure data. The calibration of the measuring chain allowed for a high quality of the measurements.

The devices developed can be quickly installed on the train and would even allow measuring during regular train operation. In total, less than 20 min are needed to install the plates and to test the data acquisition system.

Trains

For the commissioning phase of the new rail-link, aerodynamic measurements were conducted in order to prove the efficiency of pressure relief shafts. Two different train types – Cisalpino ETR 470 train and the SBB Re 460 / EW IV train (see Figure 4) – were prepared for two extended measurements in August and September 2004. Train details are listed in Table 6. The train speed during both measurements varied between v_{train} = 160 km/h and v_{train} = 220 km/h.

Figure 4: Trains for the measurements (left hand: SBB test train at east portal of the Murgenthal tunnel, white arrows indicate the pressure measuring positions, right hand: Cisalpino test train)

Table 6: Specific train data of the two train types for the aerodynamic measurements

Train parameter	Type / value 1st measurement	Type / value 2nd measurement
locomotives / number	SBB Re 460 / 2	Cisalpino ETR 470 / 7
coaches / number	SBB EW IV / 6	
train length [m]	196	236
train speed [km/h]	160 - 220	160 - 210
cross-sectional area [m^2]	11.0	10.0
perimeter [m]	11.4	11.3

Methodology

During the test runs, pressure measurements were conducted in one tunnel. First a tunnel with no shafts or other openings has been chosen (Murgenthal tunnel). The pressure data from this tunnel were used to identify the aerodynamic characteristics (e.g. friction c_F) of the train (SBB Re 460 and EW IV coaches) and finally to improve the simulation quality. Afterwards for the second train (Cisalpino ETR 470) the pressure measurements were conducted in the Emmequerung tunnel close to the west portal and next to the pressure relief shaft. The pressure signals (Figure 5) show a strong impact of the shaft.

Simulations were performed with the aerodynamic characteristics of the trains. Figure 5 contains the comparison between the measured data and the results of the simulation. For both tunnels the results fit sufficiently. Additionally, for the Emmequerung tunnel a simulation result is shown for the case of a tunnel without pressure relief shafts. The pressure rises from approx. max. 0.8 kPa to max. 1.3 kPa. The strong impact of the pressure relief shafts is evident.

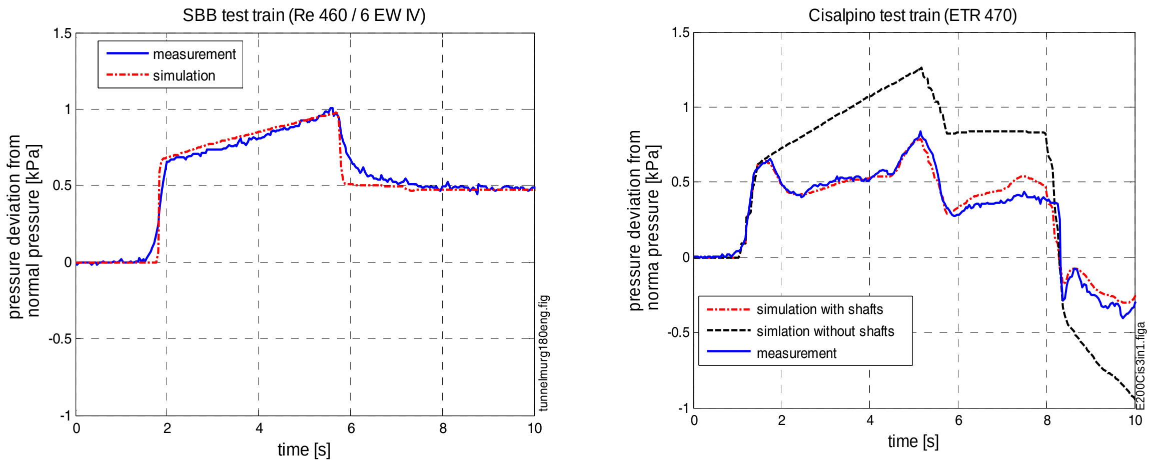

Figure 5: Pressure signals from Murgenthal tunnel (left hand, no pressure relief shafts) and from Emmequerung tunnel (right hand, two pressure relief shafts)

Findings

The effectiveness of the pressure relief shafts will be demonstrated by the result of one test drive with the SBB Re 460 train at a velocity of 220 km/h. The measured exterior pressure close to the train nose and tail are shown in

Figure 6 for the passage through the Emmequerung tunnel.

Additionally, Figure 6 contains the results of the simulations for:

- the measurements with 2 pressure relief shafts and a free cross-sectional area of $A_{tunnel} = 76\ m^2$
- the situation without pressure relief shafts and $A_{tunnel} = 76\ m^2$
- the situation without pressure relief shafts and $A_{tunnel} = 105\ m^2$

THERMOTUN simulations and the measurements lead to similar results. It can be seen, that a train passage through the same tunnel without pressure relief shafts would cause greater pressure variations and, hence, lead to higher pressure variations in the train. For example, the pressure deviation from normal pressure at the train tail would rise to 2 kPa for the case without shafts instead of 1 kPa for the situation with shafts. Similar pressure levels arise at the train nose, too.

For any given time interval of 4 s the maximum pressure difference was determined in order to check the compliance with the project specific pressure comfort criterion. The result of the analysis is shown in Figure 7 for the measurement and the different THERMOTUN calculations.

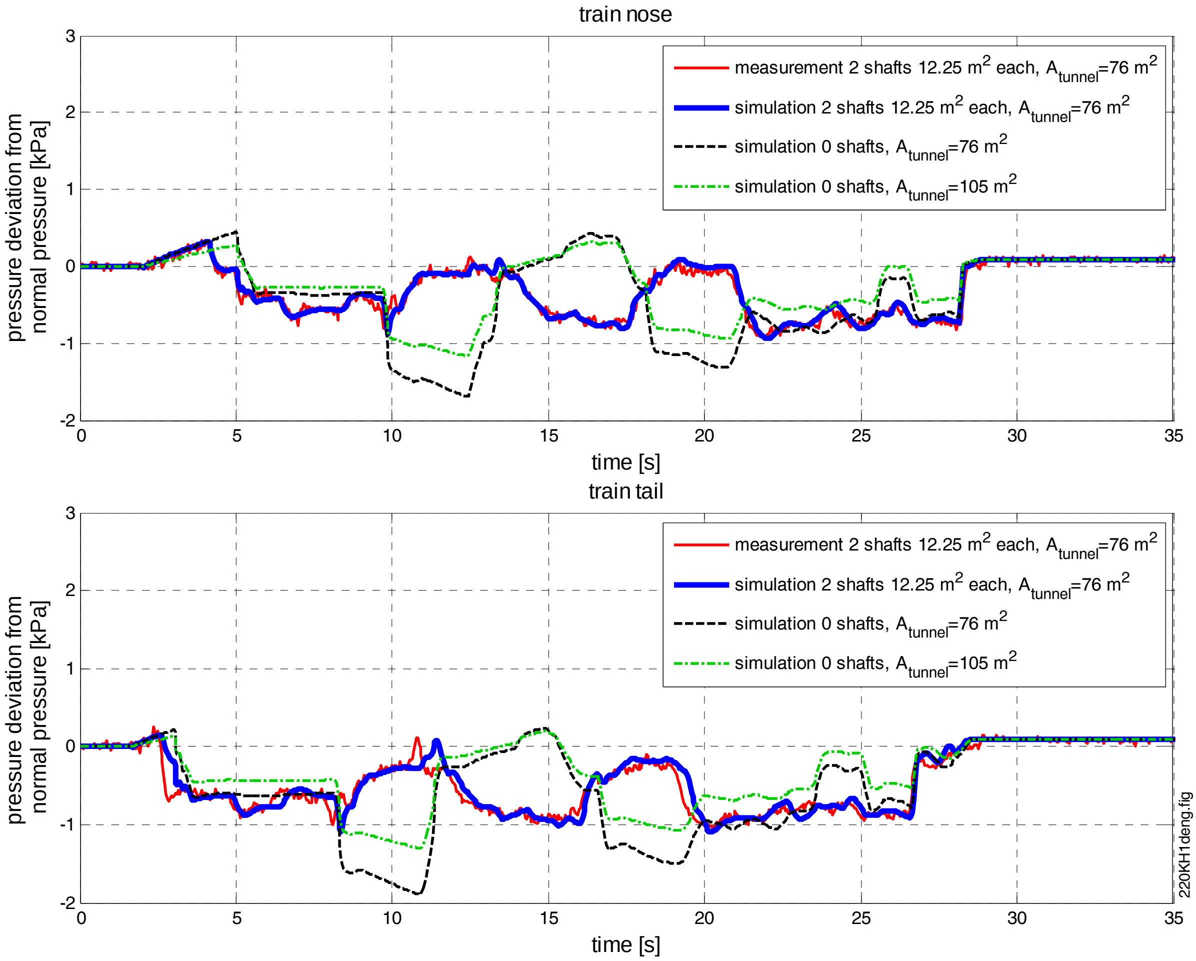

Figure 6: Simulated and measured pressure deviation from normal pressure close to the train nose and tail (v_{train} = 220 km/h)

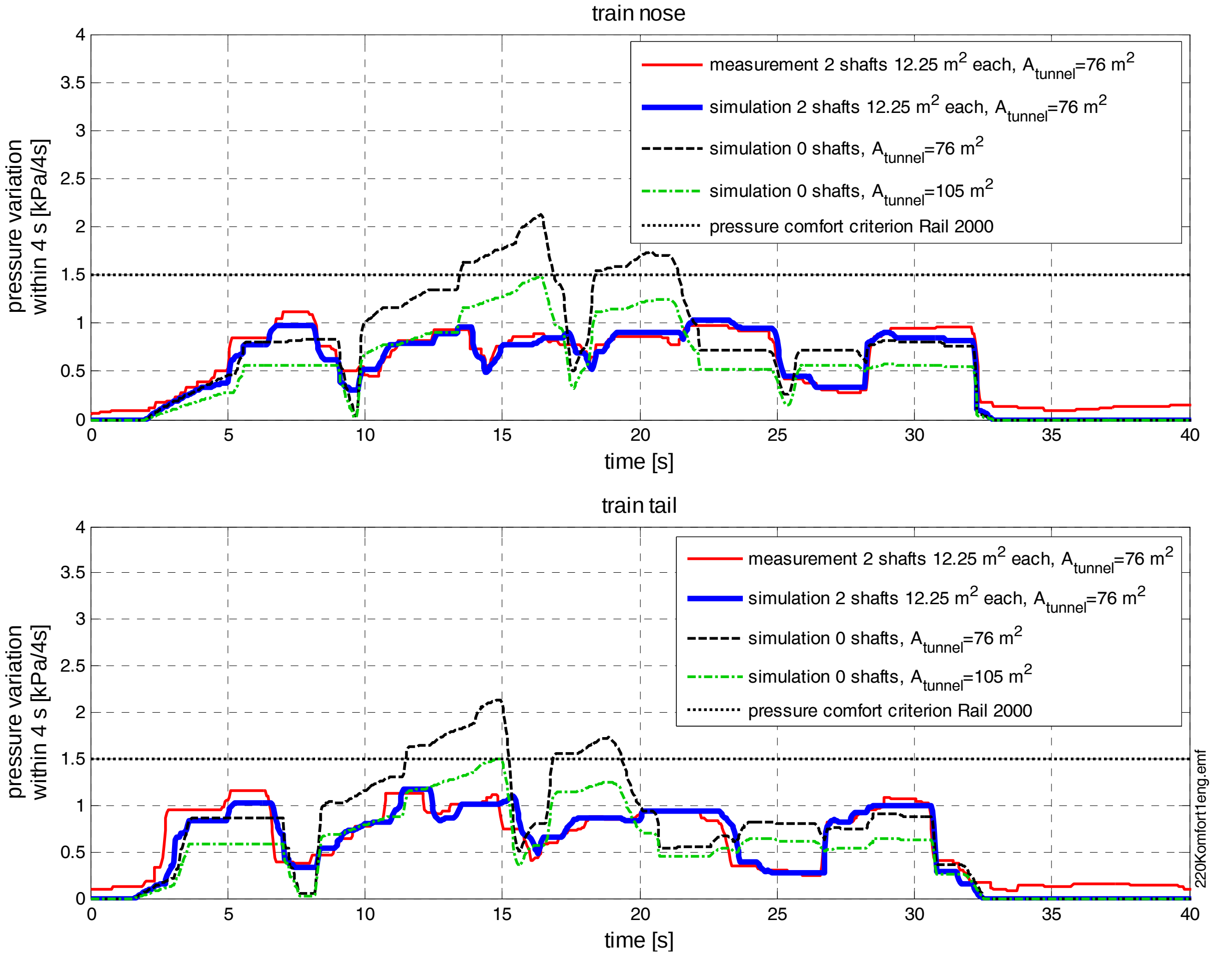

Figure 7: Measurement and simulation for Emmequerung tunnel (2 shafts and without shafts) of pressure variation in 4 s compared to pressure comfort criterion

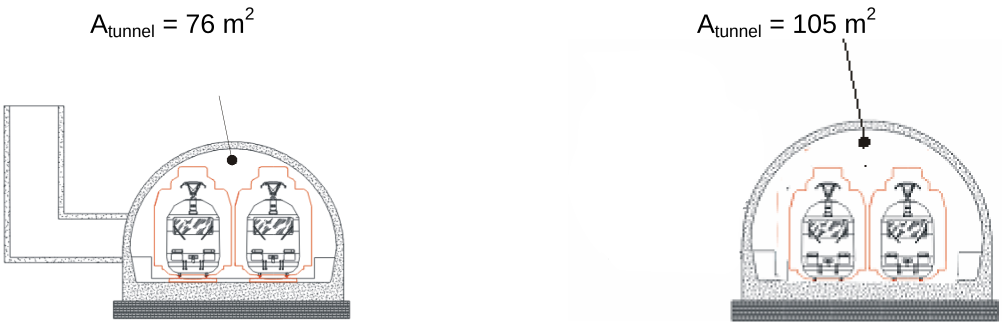

Figure 8: Measures to reduce pressure fluctuation in the Emmequerung tunnel in order to comply with the pressure comfort criterion (left: 2 pressure relief shafts each 12.25 m^2, tunnel cross-section A_{tunnel} = 76 m^2, right: increased tunnel cross-section A_{tunnel} = 105 m^2, no pressure relief shaft).

As shown, the measurements and the simulation results fulfil the pressure comfort criterion during the entire train passage (Δp_{max} < 1.2 kPa within 4 s < Δp_{max}, criterion). A maximum pressure variation of Δp_{max} > 2 kPa within 4 s appears for the same tunnel without pressure relief shafts. For the specific test case, the free cross-sectional area of the tunnel without shafts would need to be increased to $A_{tunnel} = 105\ m^2$ (see Figure 8) in order satisfy the SBB Rail-2000 pressure comfort criterion. Additionally, the pressure relief shafts give a higher degree of pressure comfort for the passengers compared to the increase of the cross-sectional area for the Emmequerung tunnel (see Figure 7).

8. Further optimization

The design of the pressure relief shafts for the new rail-link in Switzerland focused exclusively on the improvement of the pressure comfort. For future projects the following aspects could also be considered:

- the additional use of the pressure relief shafts as escape routes (only in combination with further safety increasing measures such as remote controlled doors)
- the use of pressure relief shafts for ventilation and smoke extraction purposes
- the effect of the shafts to decrease the energy consumption (required traction power) of the trains and/or the climate improvement of the tunnel

9. Summary

Pressure relief shafts allow reducing the magnitude of pressure fluctuations, generated by high-speed trains during the passages of tunnels, hence improving the pressure comfort of the passengers and staff. The efficiency of pressure relief shafts has been confirmed by measurements during the acceptance tests. Additionally the high precision of the simulation tool THERMOTUN has been demonstrated.

The use of 2 pressure relief shafts ($A_{shaft} = 12.25\ m^2$) allowed the reduction of the free cross-sectional area of the tunnel from $A_{tunnel} = 105\ m^2$ to $76\ m^2$ while improving the pressure comfort for the passengers and staff.

As a consequence, smaller cross-sections of several tunnels of the new rail line between Mattstetten and Rothrist minimised the construction costs.

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