

AERODYNAMICS AND CLIMATE IN THE LOETSCHBERG BASE TUNNEL – PREDICTION AND FINDINGS

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Keywords: Loetschberg base tunnel, aerodynamics, climate

ABSTRACT

The 35 km long Loetschberg Base Tunnel (LBT) is in operation since 2007. It features new aspects concerning tunnel aerodynamics and climate. The demanding aero- and thermodynamic conditions due to high-speed traffic in a twin-tube, single-track system, the high-temperatures due to length, rock-overburden and heat release from intense train operation and, finally, the various train types lead to a unique combination of boundary conditions. Measured data from tests and operation are compared to results from simulations and analysis. The focus of the work is on pressure fluctuations, air velocities and climate. The aim of the paper is to provide an overview and the experience regarding the relevant aero- and thermodynamic aspects for similar future rail tunnels.

INTRODUCTION

Scope of work

The Loetschberg Base Tunnel in the Swiss Alps is the first tunnel in operation featuring typical characteristics for a new generation of very long, mountainous rail tunnels. The combination of these characteristics affects the tunnel aerodynamics, the climate and consequently the design of the tunnel. In this regard, some relevant properties are as follows:

- Demanding aerodynamic conditions due to high-speed traffic in tunnels with relatively small free cross-sectional area due to twin-tube, single-track design (Ravn, 2004)
- High temperature due to length of tunnel, high rock-overburden and significant heat release from intense train operation
- Mixed traffic with passenger trains, shuttle-trains and freight trains, i.e. different velocities, blockage ratios, aerodynamic resistances

Practical experience in the field of aerodynamics gained from LBT shall be provided for other long rail tunnels (e.g. Brenner, Ceneri, Guadarrama, Gibraltar, Gotthard, Koralm, Lyon-Turin, Prague-Beroun, Transandino, etc.) or any other high-speed rail project being under construction or at the planning stage (Busslinger, 2008). The focus is on consequences regarding mutual influences of tunnel design, train operation and tunnel aero-/thermodynamics.

Tunnel system of LBT

The Loetschberg Base Line is a new cross-alpine rail link in Switzerland and an integral part of the European high-speed rail network. The central element of this line is the Loetschberg Base Tunnel (LBT; drill and blast, TBM) with a length of approximately 35 km (Figure 1). The typical free cross-

sectional area of the rail tunnels is about 45 m². For financial reasons, the LBT will be built in 2 stages. The first part is in operation since 2007. During this first phase, the southern part of the LBT is a single-track, double-tube system (14 km) and the northern part is operated using one tube in bi-directional mode (20 km). Near the northern portal, the tunnel is again built as double-tube system (1 km). At the final stage, the tunnel along its whole length will consist of 2 single-track tunnels which are connected by cross-passages at distances of approximately every 330 m. In addition, the base tunnel system will include multi-functional stations (MFS) with crossovers and emergency train stops.

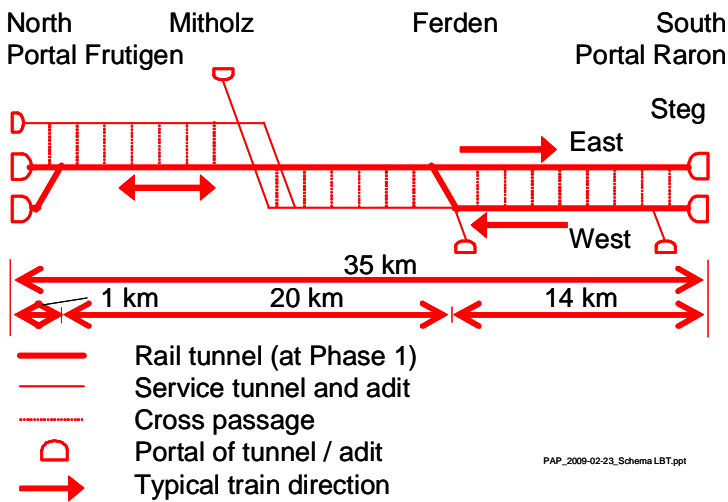


Figure 1 - System overview of the Loetschberg Base Tunnel and test train in tunnel

There are demanding requirements regarding lifetime, reliability, maintainability, availability and safety of long, high-speed rail tunnels, its equipment and rolling stock. Several of these specific requirements originate from the tunnel aerodynamics (Haldimann, 2007).

Aerodynamics and climate of LBT

Tunnel aerodynamics in the sense of this paper deals with the train-induced pressure deviation from normal pressure and its consequences. Compared to other sources of changes of air pressure in a tunnel such as meteorological influences or ventilation, typically, the trains lead to the most extreme and fastest pressure changes. The pressure changes are generated by moving trains at variations of the surrounding free cross-sectional area of the tunnel. Commonly, the most extreme change of the free cross-sectional area occurs during entering or leaving tunnels, i.e. at the portals. Pressure waves propagate through the tunnel with the speed of sound and are (partly) reflected at portals and cross-sectional variations. Additionally, the friction of air along the tunnel wall and along the train surface and the pressure losses at the train nose and tail lead to pressure changes at the train and along the tunnel. The superposition of pressure changes along a moving train with pressure waves travelling through the tunnel lead to complex non-stationary pressure changes in the tunnel and in the train.

The magnitude of the pressure fluctuations in a tunnel is, among other factors, a result of the speed, the cross-section, the length, the shape and the roughness of the train and the length, the free cross-sectional area, the roughness and the civil construction type of the tunnel and the portals. The pressure fluctuations are the cause for several aerodynamic subtopics of engineering interest. Table 1 gives an overview and the relevance regarding these topics for the design of LBT. Additionally, the related location and the relevant mode of tunnel operation are indicated.

Table 1 - General aspects of rail tunnel aerodynamics and relevance for different locations and different operation modes at LBT

Aspect	Major issues	Location of impact				
		Rail tunnel (*)	Other spaces (*)	Station (*)	Outside of portal	Train
Pressure loads	Forces acting on tunnel structures, walls, fixtures, equipment, rolling stock, passengers and staff	N M	M	M	--	N M
Loads due to air flow	Forces acting on signs, signals, train, etc. due to high air velocity	N M	M	M	--	N M
Pressure comfort	Pressure changes within certain time intervals possibly leading to aural discomfort	M	M	M	--	N M
Health limits due to pressure	Harming pressure changes for hearing organs, i.e. eardrum	M	M	M	--	N M
Traction power	Power demand of trains due to aerodynamic resistance	--	--	--	--	N M
Micro-pressure waves	Vibrations or detonation-like, loud bang at opposite portal upon train entry/exit (sonic boom)	--	--	--	N M	--
Comfort and safety due to air flow	Limitation of velocity of air on the platform and along access ways of and station / cross-passage	M E	--	E	--	--
Climate	Air-exchange, release and transport of heat and humidity; resulting temperature, relative humidity and quality of air	N C M E	N C M E	E	--	N C M E
Operation mode: Normal (N), Congested/Disturbed (C), Maintenance (M; normal operation in one tube and maintenance work in parallel tube), Emergency (E); " X " = in focus of this paper; "--" = of no relevance in LBT						
*) "Rail tunnel": Tunnel with train movement incl. cross-passages; "Other spaces": Service tunnels, technical rooms, shafts; "Station": Public spaces of emergency stop away from rail tunnel						

Table 1 represents the view of the tunnel designer, i.e. less the view of the train designer. It indicates that a set of aerodynamic aspects has to be considered at the design stage. Most of the topics are important for certain locations and operation modes only. In this paper, only a limited number of issues can be addressed in more detail which is highlighted by framed, bold letters in Table 1.

Design objectives

For selected aspects of tunnel aerodynamics and climate, design objectives are listed in Table 2. These design objectives are given for the normal mode of tunnel operation only.

Table 2 - Selected aspects of rail tunnel aerodynamics and design objectives or specifications at LBT

Aspect	Design objective or design specification for tunnel, equipment and rolling stock
Pressure loads in rail tunnel	Maximum pressure deviation from normal pressure in rail tunnel: ± 11 kPa; resulting pressure differences across walls, doors, covers of cross-passages, cabinets, drainage and cable-tray systems, depending on boundary conditions
Loads due to air flow in rail tunnel and at train	Maximum pressure: 7 kPa on plane surfaces being exposed to air flow in longitudinal direction of tunnel and cross-passages; no specification given for trains incl. pantograph of train
Pressure comfort in train	Maximum pressure fluctuations in passenger trains: 1.5 kPa in time period of 4 s; for trains with velocities of more than 160 km/h adequate pressure tightness of trains required (e.g. pressure tightness coefficient $\tau > 10$ s as sealing quality; (Ravn, 2004))
Traction power of train	No specification given for trains, however, expected available traction power of trains to be larger than required for speed
Micro-pressure waves at portal	No non-acceptable micro-pressure waves (e.g. according Japanese experience $\Delta p < 20$ Pa outside 20 m away from portal at 45° - angle)
Climate in rail tunnel	Maximum air temperature: $\leq 35^\circ\text{C}$; Max. relative humidity: $\leq 70\%$; sufficient exchange of air to remove further pollutants and methane in drainage system (Busslinger, 2003)

In most cases, the civil design of the tunnel was not modified in order to ease the aerodynamic conditions but was adapted to cope with the resulting aerodynamic conditions. For example, no civil measures were taken to reduce pressure fluctuations in the tunnel or to reduce the traction power demand of trains. Instead, the tunnel, its equipment and the rolling stock were specified to be more robust or powerful.

Tools for analysis and simulations

During the design and test phase of LBT, investigations about the tunnel aerodynamics and climate were carried out for different tunnel configurations. The simulations were conducted mainly with THERMOTUN, an approved program for numerical, one-dimensional investigation of the aerodynamics in rail tunnel networks. It is based on the method of characteristics (Vardy, 2004; Vardy, 1976). THERMOTUN allows simulating pressure waves and fluctuations, air flows, propagation of other gaseous substances and traction power requirements of trains based on the movement of trains, the performance of tunnel ventilation and other boundary conditions. The programme has been used for several rail tunnel and underground projects.

All simulations related to the *tunnel climate* were carried out with THERMO, a tool for the one-dimensional investigation of parameters such as temperature and relative humidity of air in rail tunnels. THERMO was developed by HBI Haerter Ltd. and it allows precisely predicting the climate based on the thermal behaviour of the surrounding ground of the tunnel, the effect of water ingress, the passage of each single train, the air flows, the outside weather conditions, ventilation, etc. The code has been used for several rail and underground projects, e.g. for 6 alpine base tunnel projects.

Additionally, in-house tools or literature were used for further analysis. For example, the analysis regarding micro-pressure waves was based on literature only.

Devices for measurements

The pressure measurements were performed with micro-pressure transducers, integrated into plates. Pressure signals were transferred by pressure taps to the piezoresistive transducers. Mobile data

acquisition systems were used to record the pressure data. Pressure probes were placed at representative locations in the rail tunnel, in cross-passages, in cabinets of cross-passages as well as at selected places in- and outside of different train types (Figure 2).



Figure 2 - Pressure transducer on window of train; 3-axis anemometer on sidewalk in cross-over; 1-d ultrasonic anemometer in single track tunnel; micro-accelerometers underneath cover plate of cable tray of sidewalk; Prandtl's pitot tube at pantograph of train; temperature and humidity sensor in single track tunnel

Air velocities were recorded using one- and three-dimensional, ultrasonic sensors for air speed. One-dimensional measurements were conducted with sensors which were mounted at opposite tunnel walls recording the average air velocity in the tunnel cross-section, i.e. the tunnel longitudinal air flow (Figure 2). Three-dimensional flow fields were locally monitored by ultrasonic, three-axis anemometers (Figure 2). These were installed, for example, on the sidewalk of the tunnel. Temporarily, some vane anemometers were placed inside the drainage system to record train induced air-exchange here. For recording the air velocity near the pantographs or at other selected locations at a train, newly developed pressure probes based on Prandtl's pitot tube were used (Figure 2). Each probe contained two piezoresistive pressure transducers.

To monitor the possible displacement of equipment in the tunnel due to pressure loads and air-flow, micro-accelerometers were installed, for example, at covers of cable-trays (Figure 2).

Required traction power of trains in tunnels was measured, for example, by coasting tests. The acceleration or deceleration of the trains was monitored using the tachometer of the train and/or micro-accelerometers.

For the measurement of temperature and relative humidity of the air in the rail tunnel, sensing devices were permanently installed along the tunnel, i.e. near cross-passages (Figure 2). At regular distances of about 330 m or 1'000 m probes were placed. The data were continuously transmitted to the tunnel control centre. Major meteorological data was obtained from nearby weather stations.

Repeated and adequate calibration of the measuring chains allowed for a high quality of the measurements. A summary regarding the tools for simulation and measurements of the selected aerodynamic parameters is given in Table 3.

Table 3 - Selected aspects of rail tunnel aerodynamics and tools for analysis, simulations and measurement used at LBT

Aspect	Tool for simulation and analysis	Tool for measurement
Pressure loads in rail tunnel	THERMOTUN	Pressure transducers in tunnel, inside equipment and rolling stock
Loads due to air flow in rail tunnel and at train	THERMOTUN / Recommendation of Deutsche Bahn see (Deutsche Bahn, 2003)	1-/3-dimensional ultrasonic and vane anemometers; Prandtl's pitot tube
Pressure comfort in train	THERMOTUN / in-house tools with MatLab / Excel	Pressure transducers in tunnel, in tunnel equipment and rolling stock
Traction power of train	THERMOTUN / in-house tools with MatLab / Excel	Recording tachometer of train, micro-accelerometers
Climate in rail tunnel	THERMO	Thermocouples, moisture measuring devices

PRESSURE LOADS IN RAIL TUNNEL

Phenomena and design specifications

Train-induced pressure fluctuations lead to mechanical forces acting on tunnel structures, walls, fixtures, equipment, rolling stock, passengers and staff. A maximum pressure deviation from normal pressure in the rail tunnel of ± 11 kPa was used in LBT as design specification (see Table 3 for tool). This maximum pressure load was determined by the assumption that shuttle trains as used in the Channel Tunnel could be operated in LBT at a later stage (e.g. $v_{\text{Train}} = 140$ km/h, $A_{\text{Train}} = 18$ m²).

Comparison of analysis/simulation with measurements

The pressure fluctuations resulting from normal operation of LBT are shown in Figure 3. Figure 3 refers to the middle of the section with bi-directional traffic. The simulations and the measurements consider the typical train types during normal operation, however, in the absence of high-speed trains and shuttle trains as in Channel tunnel. The magnitude of pressure fluctuations is well matched by the simulations. However, number, clearance and mix of train types differ. Therefore, the results from the design phase do not exactly superpose with the measurements.

Maximum pressure deviations from normal pressure were specified to be $\Delta p_{\text{max}} = \pm 11$ kPa. The measured typical pressure fluctuations in the tunnel at the initial stage of operation are significantly smaller. The main reason for this difference is that the load determining train types are not in operation yet.

The simulated and measured pressure changes for a single train run are shown Figure 4. The simulation is based on the data for the test train. The measurements are taken for a time period without substantial meteorological or thermal draft. During the test run, major pressure fluctuations were noted at the crossover caverns with typical changes of the cross-sectional area from approximately 160 m² to 45 m² or vice versa.

The simulated range of pressures and the characteristic changes match the measurements very well.

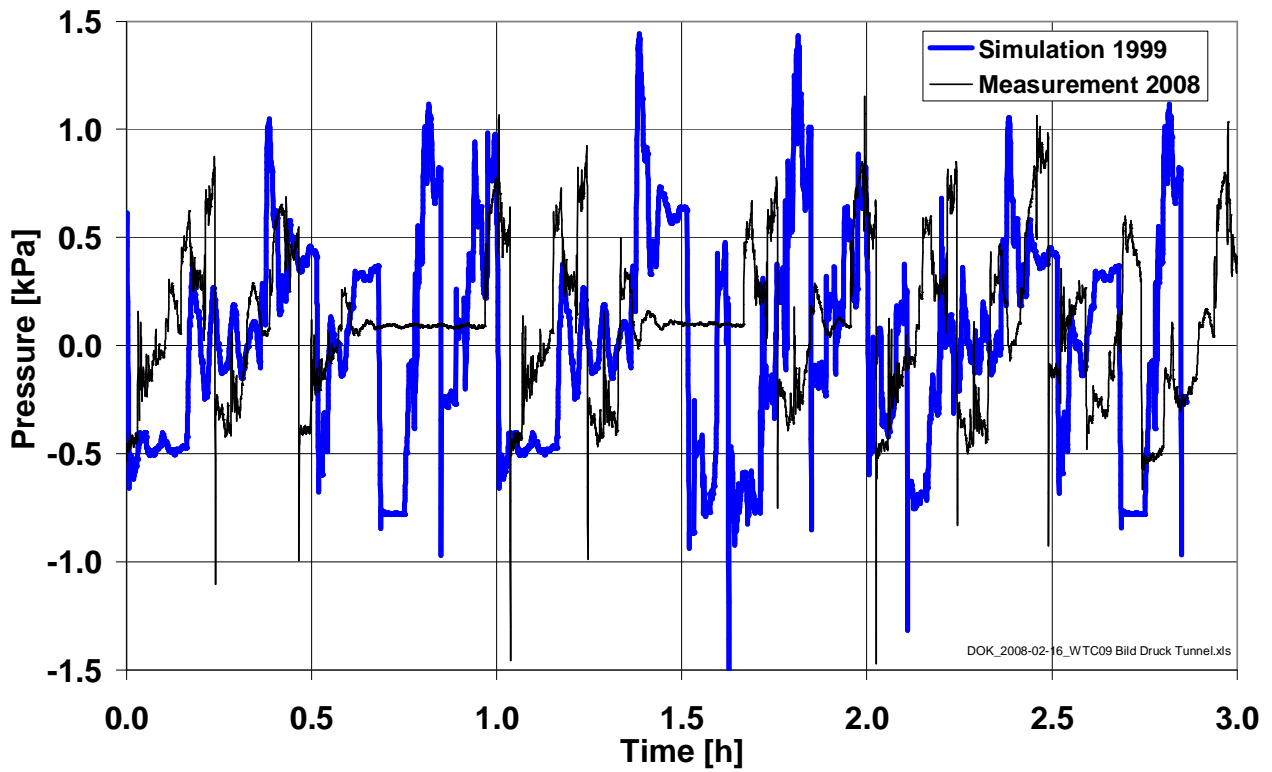


Figure 3 - Simulated fluctuation or pressure deviation from normal pressure at a certain location in LBT and resulting maximum positive and negative pressure deviation from normal pressure along tunnel

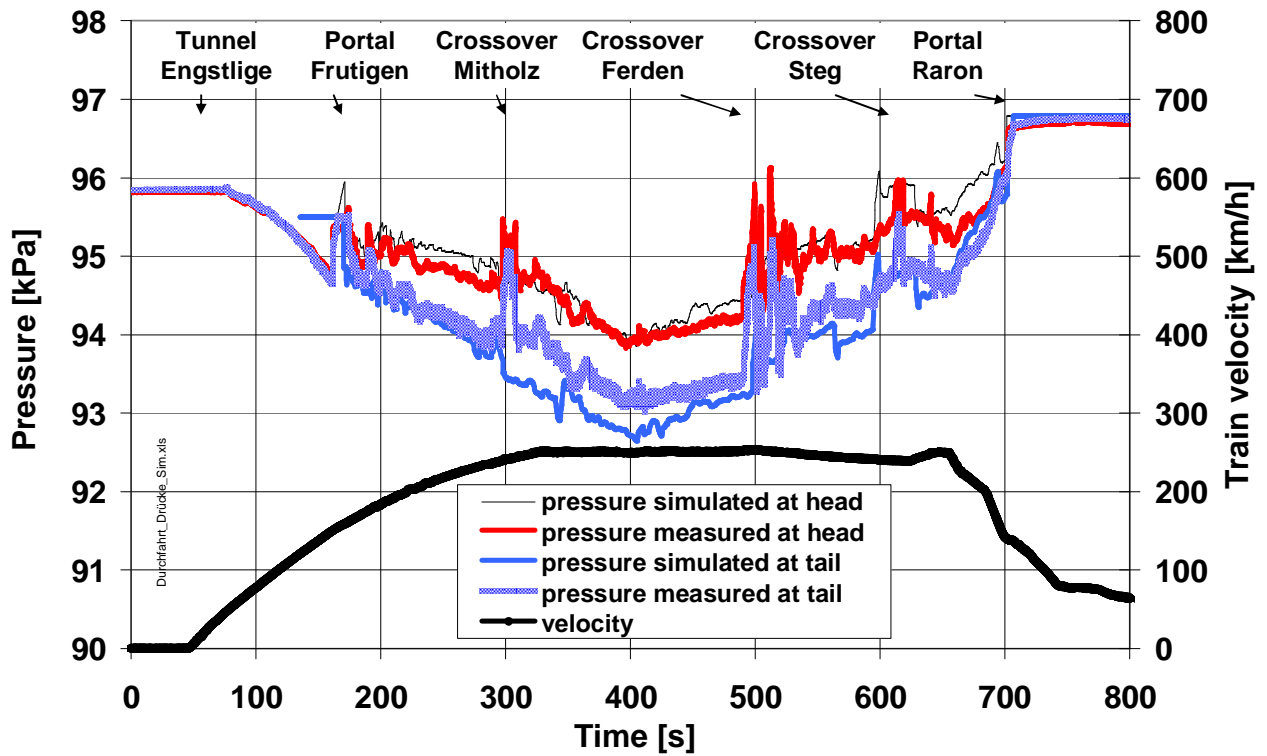


Figure 4 - Measured and simulated pressure at a test train in LBT

LOADS DUE TO AIR FLOW IN RAIL TUNNEL

Phenomena and design specifications

Train-induced pressure fluctuations lead to flow of air in the tunnel. Within the tunnel two situations are to be considered:

1. the immediate passage of the train at a certain location, i.e. near-field effects
2. the distant effects in front and far behind the train, i.e. far-field effects

The first situation is dominated by the "near-field" flow of air along the train. During a train passage, complex, 3-dimensional flow fields with extreme velocities particularly at nose and tail of the train are noticed. The train-induced gusts lead to short-term pressure peaks and are the determining factor for the mechanical forces acting on signs, signals, trains, etc. A maximum pressure of 7 kPa on plane surfaces being exposed to air flow in the longitudinal direction of the tunnel and cross-passages was specified as design criteria (see Table 3 for tool).

The second situation is characterized by more moderate flow velocities in front and far behind the train. These more long-term velocities are most relevant for the air-exchange in the tunnel. Thus, their precise modelling is essential for reasonable predictions of the tunnel climate. Away from the trains, air-velocities in the longitudinal direction of the tunnel of ± 10 m/s were expected (see Table 3 for tool).

Comparison of analysis/simulation with measurements

Upper limits of air velocity in a rail tunnel outside the vehicle gauge were investigated by Deutsche Bahn for different train velocities and free cross-sectional areas of tunnels. The resulting guideline (Deutsche Bahn, 2003) which includes considerable safety margins is shown in Figure 5 (left). While short-term peaks of air velocity may reach the train speed for tunnels with a free cross-sectional area of 40 m², larger cross-sectional areas of tunnels lead to lower upper limits of air velocity, e.g. 50 % of train speed in a tunnel of 80 m².

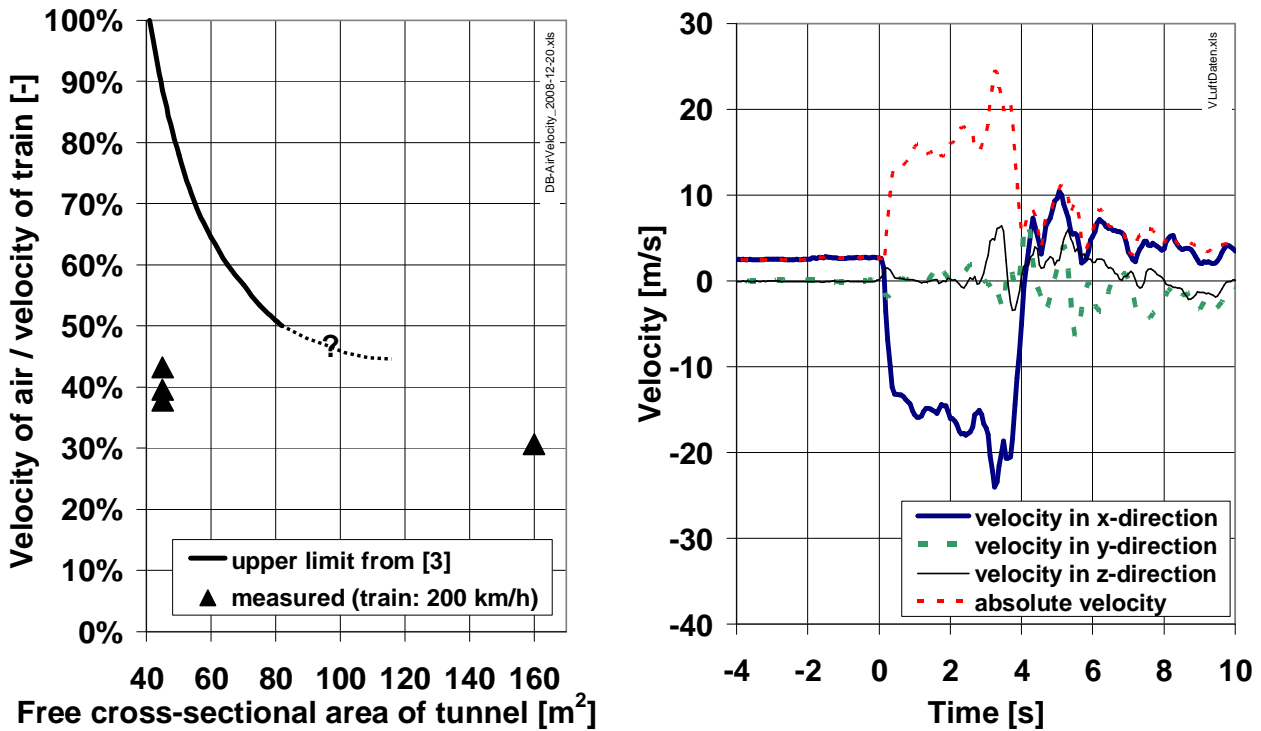


Figure 5 - Left: Upper limit of flow velocity in tunnel outside vehicle gauge according (Deutsche Bahn, 2003); Right: Flow velocity measured during train passage in LBT on sidewalk (1.4 m away from vehicle gauge and 1.9 m above top rail; x-direction = tunnel longitudinal axis from south to north; y-direction = horizontal axis from centre to wall; z-direction = vertical axis from centre to ceiling)

Figure 5 (left) shows as well a comparison of maximum velocities which were recorded on the sidewalk during the immediate passage of trains. Results were obtained for 2 different free cross-sectional areas, i.e. in a regular tunnel and in the cavern of a crossover. The comparison shows that the measured velocities are well below the upper limit as given by (Deutsche Bahn, 2003).

Figure 5 (right) illustrates in more detail components of the 3-dimensional flow field during a single train passage (passenger train at 200 km/h). During train passage the maximum velocity is noted in the longitudinal direction of the tunnel. It reaches about 24 m/s, i.e. 43 % of train velocity. The flow direction reverses during the immediate train passage. The flow components perpendicular to the tunnel axis are substantially lower.

A comparison of one-dimensional simulations and measurements is given in Figure 6. The simulated range of velocities and the average velocity match the measurements very well. The simulation is based on the initial design data from 1999. The measurements are taken for a time period without substantial meteorological or thermal draft leading to velocities of max. ± 9 m/s. The differences between simulation and measurement are due to different train schedules (type, number, headway, velocity, etc.).

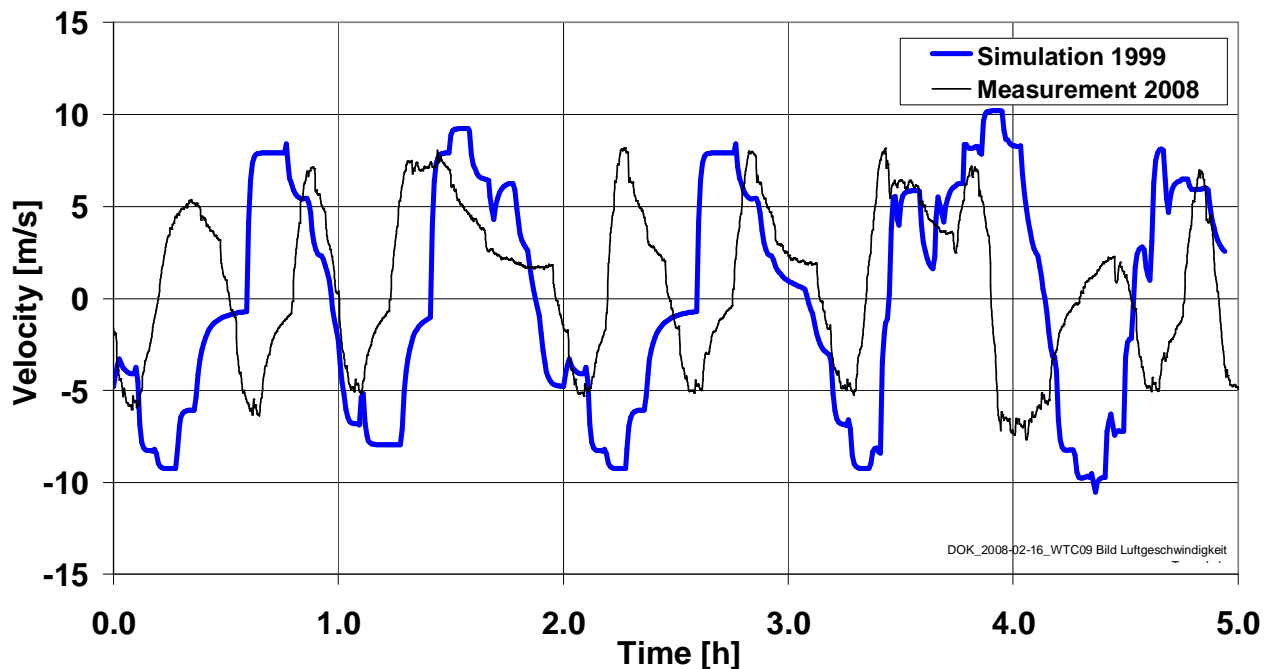


Figure 6 - Simulated and measured velocities of air in longitudinal direction of tunnel for a 5-h-intervall of normal operation

PRESSURE COMFORT IN TRAIN

Phenomena and design specifications

Sudden pressure changes might create discomfort to train passengers and staff. In extreme cases, the pressure changes can even inflict damage to the eardrum. The criteria for the pressure comfort are commonly defined by the maximum pressure change within a given time period. At LBT the pressure comfort in passenger trains was specified to be acceptable at pressure changes below 1.5 kPa within a time period of 4 s.

Comparison of analysis/simulation with measurements

As indicated in Figure 4, the passage of portals and crossovers leads to pressure fluctuations at and in the train. For the same test run the resulting pressure changes in a 4-s-interval are shown in Figure 7. They are compared to the comfort limit, i.e. $\Delta p = 1.5$ kPa in 4 s. As indicated for the test run the comfort limit is exceeded only for non-sealed trains. If sealed trains are used the pressure comfort stays well below the given limits (e.g. with pressure tightness coefficient of $\tau = 8$ or 15 s).

The test run shown in Figure 4 and Figure 7 is an example only. It is characterized by low velocities at portals. The results may not be generalized to normal operation and other tunnels.

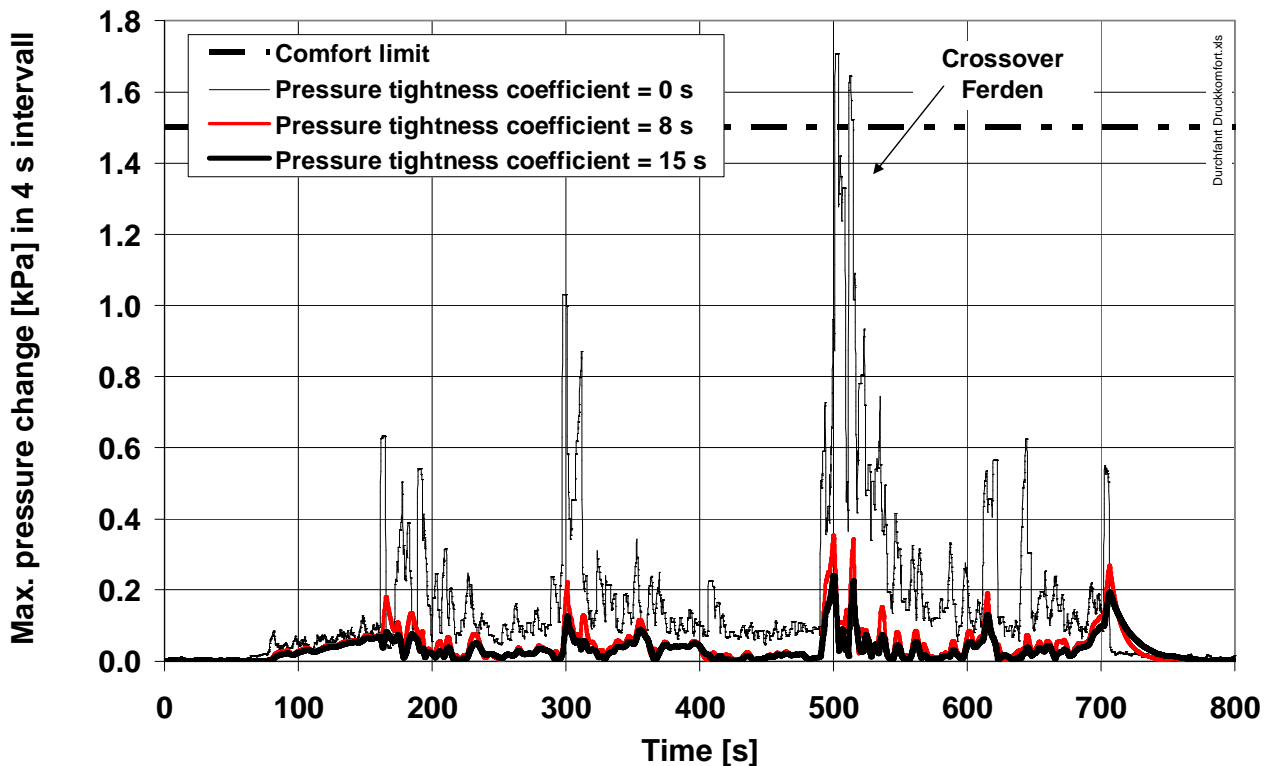


Figure 7 - Measured maximum pressure change at train in time interval of 4 s (Pressure tightness coefficient: $\tau = 0$ s - non-sealed train; $\tau = 15$ s - well-sealed train)

CLIMATE IN RAIL TUNNEL

Phenomena and design specifications

The tunnel aerodynamics influences the climate in a tunnel system. The prediction of the tunnel climate during normal and maintenance operation is a main design criterion of long railway tunnels and affects the choice of the tunnel system, i.e. double tube, portal geometry, etc. Vehicle-induced pressure fluctuations replace air of the tunnel by fresh air from outside through portals and shafts. Heat, humidity and pollutants are removed from the tunnel. In long tunnels, the heat released from trains and technical equipment and the seepage of water accumulate along considerable distances. Additionally, a high overburden of rock leads to ingress of heat. Initial rock temperatures of more than 45°C were noted locally for the LBT. An air temperature below 35°C and a relative humidity in tunnel below 70 % were specified as design criteria. A sufficient exchange of air to remove further pollutants and methane should be achieved as well.

Comparison of analysis/simulation with measurements

The model used to predict the tunnel climate of LBT takes into account the factors that predominantly influence the tunnel climate (Busslinger, 2001):

- meteorological conditions at the portals defining the state of air and trains at portals
- heat transfer through the surrounding rock to/from the tunnel
- heat exchange between tunnel air and rock through the tunnel lining
- seepage / water ingress in the tunnel through the tunnel lining
- water ingress by trains
- heat exchange between tunnel air and trains
- waste heat from the locomotives and dissipation of frictional losses
- technical heat sources like the traction power supply, lighting, signals, etc.
- heat and humidity transfer by air flow

The variety of parameters and their individual range of uncertainty lead to substantial uncertainties in the prediction of tunnel temperature and relative humidity. Many assumptions are lacking verification within similar tunnel systems. Due to the various influencing parameters, it is not possible to document these here in detail.

Two predictions of the tunnel temperature need to be distinguished:

- simulation from 1999 based on the planning parameters as known at that time
- simulation from 2008 taking into account the modified train schedule (types, number, velocities, headways, directions, etc.), higher initial rock temperature as measured during construction, reduced water ingress based on measurements in test section in 2003)

The two simulations are compared with the measurements for a typical summer day (30.06.2008). According to Figure 8, already the simulations from 1999 correctly determined the characteristic temperature distribution in the tunnel. However, the simulation from 1999 predicted the maximum temperature 5 K lower than measured. The optimised simulation from 2008 results in a much closer prediction with a maximum overestimation of the temperature by 2 K. Particularly, the temperatures in the northern part of the tunnel with bi-directional traffic (oscillating air column) are very well calculated.

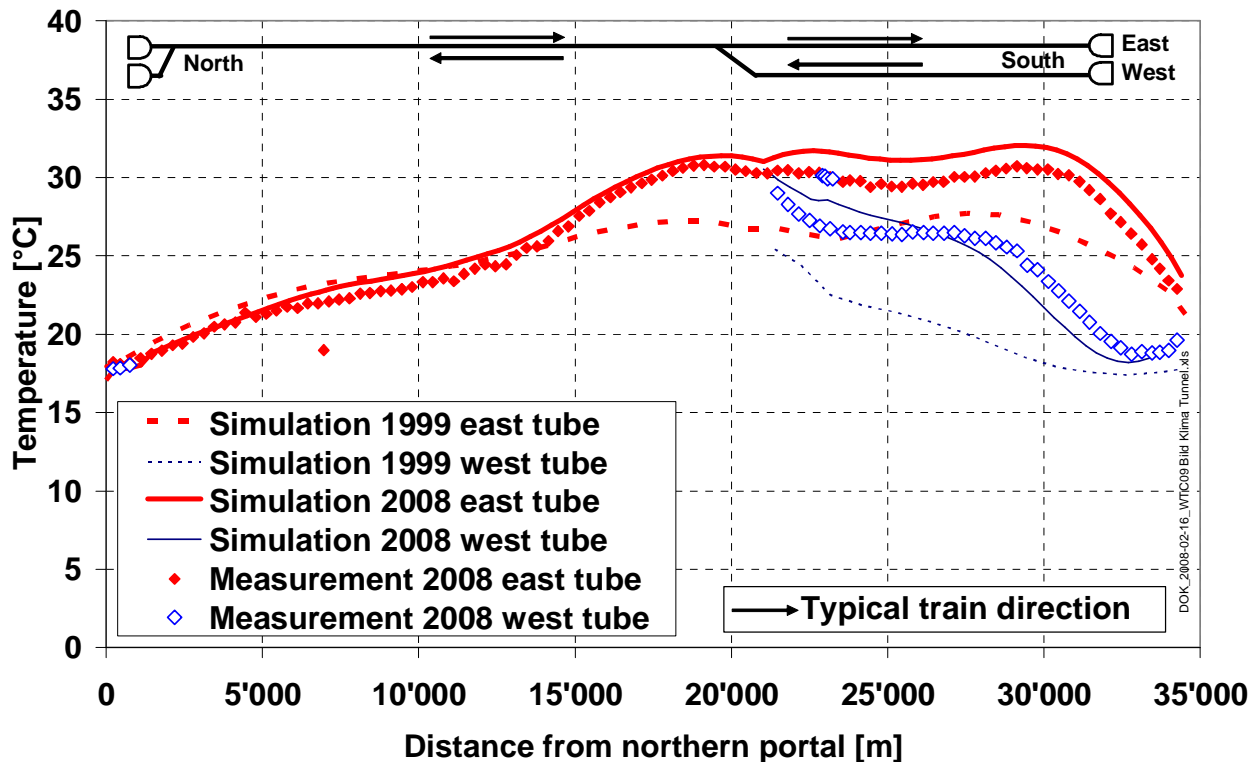


Figure 8 - Simulation from 1999 and 2008 of air temperature in the rail tunnel sections of the Loetschberg base tunnel on summer day (daily average; measurement on 30.06.2008)

In Figure 9 the two simulations are compared with the measurements of the relative humidity for a typical summer day (30.06.2008). In general, a higher relative humidity is predicted than measured. Previous analysis has shown that changes of the maximum water ingress lead to substantial change of the relative humidity but to a limited change of the temperature.

Final conclusions can not be drawn yet. Further iterative simulation will highlight the missing pieces to complete the tunnel climate prediction, not only for LBT but also for other challenging tunnel projects.

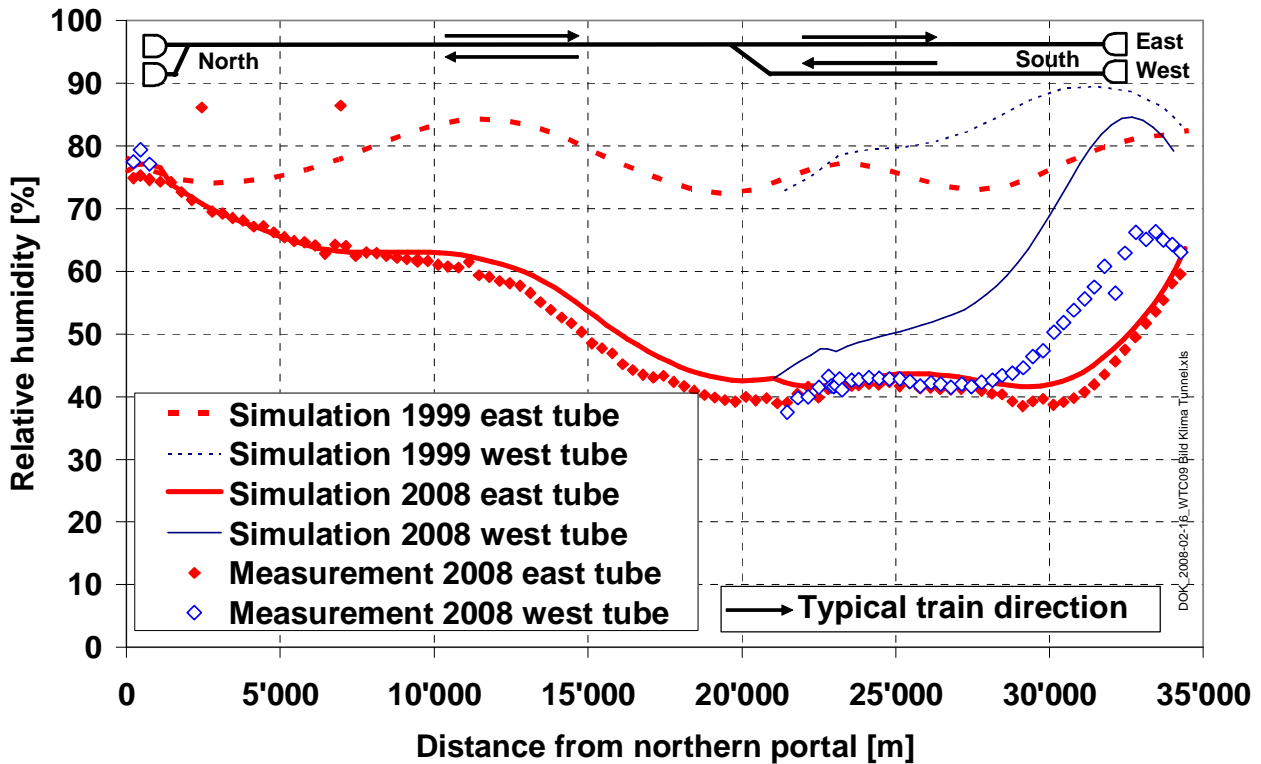


Figure 9 - Simulation from 1999 and 2008 of relative humidity of air in the rail tunnel sections of the Loetschberg base tunnel on summer day (daily average; measurement on 30.06.2008)

CONCLUSION

As most other modern long, high-speed tunnels, the Loetschberg Base Tunnel is designed as twin-tube, single-track system. Such tunnels might cause extreme aerodynamic conditions (pressure deviation from normal pressure, pressure differences, pressure fluctuations in time, micro-pressure waves) and might lead to increased traction power demands. Unidirectional traffic in twin-tube tunnels improves, however, the air-exchange and quality of the tunnel climate, which is essential for very long tunnels (cf. Table 4).

In general, the comparison between analytical work and measurements shows:

- Numerical simulations for well defined boundary conditions allowed a precise prediction of the aerodynamic and resulting climate conditions for engineering purposes.
- Design specifications for LBT were always on the safe side, i.e. the real conditions were often much less extreme as specified. This was done to cope with uncertainties regarding future train operation, train types, ground conditions, etc.
- Major uncertainties are often not of technical nature but related to open issues regarding the future operation of the tunnels.

Table 4 - Selected findings for analysis, simulations and measurement used at LBT

Aspect	Selected findings for train-induced aerodynamics
Pressure loads in rail tunnel	During normal operation in rail tunnel ± 2 kPa deviation from normal pressure; significantly below pressure fluctuations as specified in design phase due to lower velocity at portals and no operation of such shuttle trains which served as design case
Loads due to air flow at rail tunnel	Flow velocities in tunnel away from trains in the range of ± 9 m/s; during passage of trains outside vehicle gauge velocities well below upper limit of (Deutsche Bahn, 2003)

Aspect	Selected findings for train-induced aerodynamics
Pressure comfort in train	Pressure fluctuations below comfort limits during normal operation mainly because of moderate velocities at portals
Climate in rail tunnel	Good prediction of characteristic distribution of temperature and humidity; major uncertainties remain regarding water ingress and train-bound transport of water in tunnel (condensation)

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