CURRENT STATE OF CLIMATE PREDICTION FOR THE GOTTHARD BASE TUNNEL AND FURTHER STEPS

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ABSTRACT

In the Gotthard Base Tunnel (opening expected in 2012/13) uncommon climate conditions are expected due to its exceptional length (57 km) and its significant rock overburden (max. 2500 m). Furthermore, the scheduled heavy traffic for passenger and freight trains as well as many other parameters will lead to a climate in the tunnel deviating considerably from existing tunnels. The precise prediction of the distribution of temperature and humidity along the base tunnel is important for the project. Climatic requirements for normal operation and for maintenance work have to be fulfilled. Additionally, in the locations for electronic equipment, certain limits for temperature and humidity must not be exceeded.
Within the Aerodynamics and Climate Working Group of AlpTransit Gotthard AG, HBI Haerter Ltd. predicts the climate in the tunnel system. Based on the parameters considered to be reasonable the tunnel climate remains within the acceptable limits for temperature and humidity. Further preliminary studies have been carried out to identify the most significant parameters like the humidity ingress from the tunnel lining or the rock temperature. These studies showed that under worst case condition temperatures of more than 40°C and relative humidities of up to 100 % may occur in major parts of the tunnel.
In this paper the current state of the climate prediction for the Gotthard Base Tunnel is presented. The temperature and humidity distribution along the two single-track rail tunnels is shown. The authors introduce the main physics of heat exchange between air, tunnel lining and trains, which are implemented in THERMO, a simulation tool for tunnel climate developed by HBI Haerter Ltd.. In addition, an overview of the most important parameters and their influence on the tunnel climate is given.
Since many of those parameters are uncertain over a considerable range, further steps to improve the climate predictions have led to a measurement campaign during the construction of the tunnel system. The parameters to be measured and the measurement techniques are briefly introduced.
At last, the optional measures are introduced that will be employed in case that temperature and humidity exceed acceptable limits.

1 INTRODUCTION

In long tunnels deep below ground high temperatures and air humidities may occur. The Gotthard Base Tunnel comprises two single-track tubes with a length of about 57 km each (cf. Figure 1) and a maximum rock overburden of nearly 2500 m. Due to these circumstances, increased climatic values must be expected.
There are requirements for the climate concerning normal operation and maintenance work in the tunnel. For example, during a shift of 7 h of normal maintenance work the limit of 35°C temperature and 70 % relative humidity must not be exceeded. Furthermore, in the vicinity of electronic equipment

certain climatic conditions should be maintained (e.g. +10° to +35°C and 35 % to 80 % humidity for special equipment). Therefore, an adequate prediction of the tunnel climate is important with regard to the tunnel design. Particularly, the prediction influences the choice of temporary ventilation or air conditioning systems for maintenance work as well as for permanent ventilation or climate systems in special locations of electronic equipment. In addition, the climate prediction is the basis for measures in case of intolerable temperature and/or humidity conditions during normal operation in the main tunnels.
Papers for the Gotthard and the Loetschberg base tunnel (34 km) dealing with predictions of the tunnel climate in earlier stages of the project (cf. [1], [2], [3]) have been published. Since their publication, some new knowledge could be gained. Therefore, the following article will concentrate on the current state of the climate prediction for the Gotthard Base Tunnel.

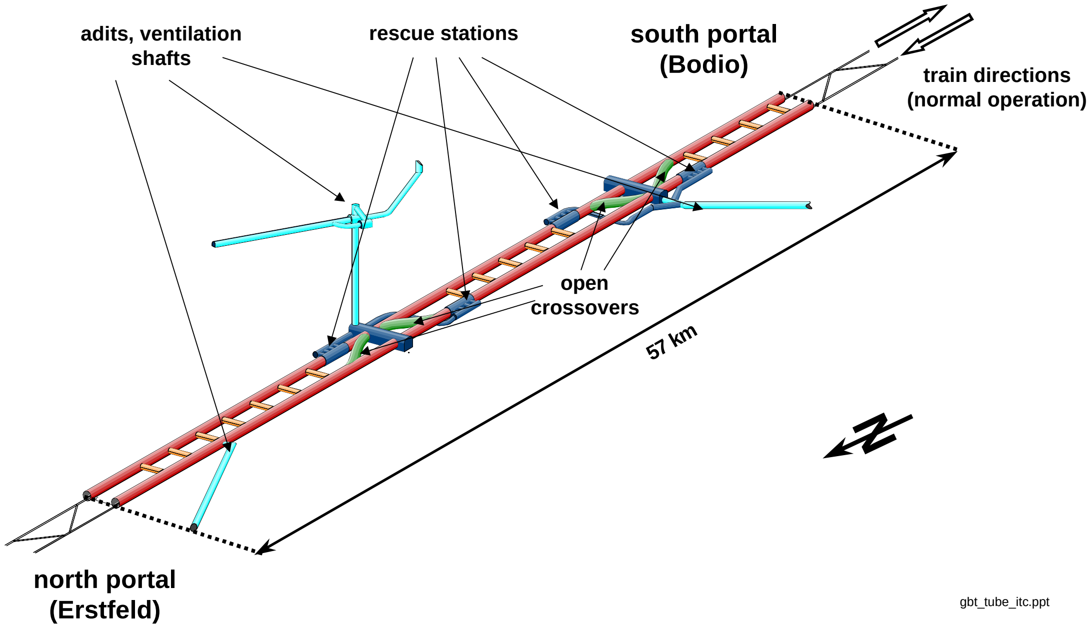

Figure 1 Overview of the tunnels of the Gotthard Base Tunnel

2 MODEL ASSUMPTIONS

The climate in a tunnel is characterised by different and partly coupled aerodynamic and thermodynamic effects. The aerodynamics of a tunnel system such as the Gotthard Base Tunnel is mainly governed by the scheduled train traffic. The space- and time-dependent distribution of air velocities and pressure is neatly connected to the rolling stock used, scheduled speeds etc.. However, this paper will concentrate on thermodynamics. Detailed information on the aerodynamics in tunnels may be given in [4] and [5].
The model developed to predict the tunnel climate for the Gotthard Base Tunnel takes into account the factors that predominantly influence the tunnel climate. In addition, these factors are often interconnected in a complex way (cf. Figure 2):

- meteorological conditions at the portals defining temperature and humidity of the air and the trains that enter the tunnel system
- 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), leading to evaporation at the tunnel surface and to an increase of humidity
- water ingress by trains
- heat exchange between tunnel air and trains, which defines the amount of heat transferred into/out of the tunnel

- waste heat from the locomotives dependent on the tractive requirements (in account of aerodynamic drag, rolling resistance, change of altitude, efficiency ratio of the locomotive)
- technical heat sources like the catenary system, lighting, signals, electronic equipment etc.
- heat transfer by air flow
- humidity transfer by air flow

These heat sources, mechanisms of heat transfer and humidity effects all contribute to the heat content and temperature in a tunnel section. The according relations are schematically shown in Figure 3. The related performance equation is given with equation (1). The humidity content in a tunnel section mainly depend on the humidity transfer by the air flow and on the evaporation of water on the tunnel surface. This water originates from seepage through the tunnel lining. The mass balance scheme and related equation are shown in Figure 3 and equation (2).

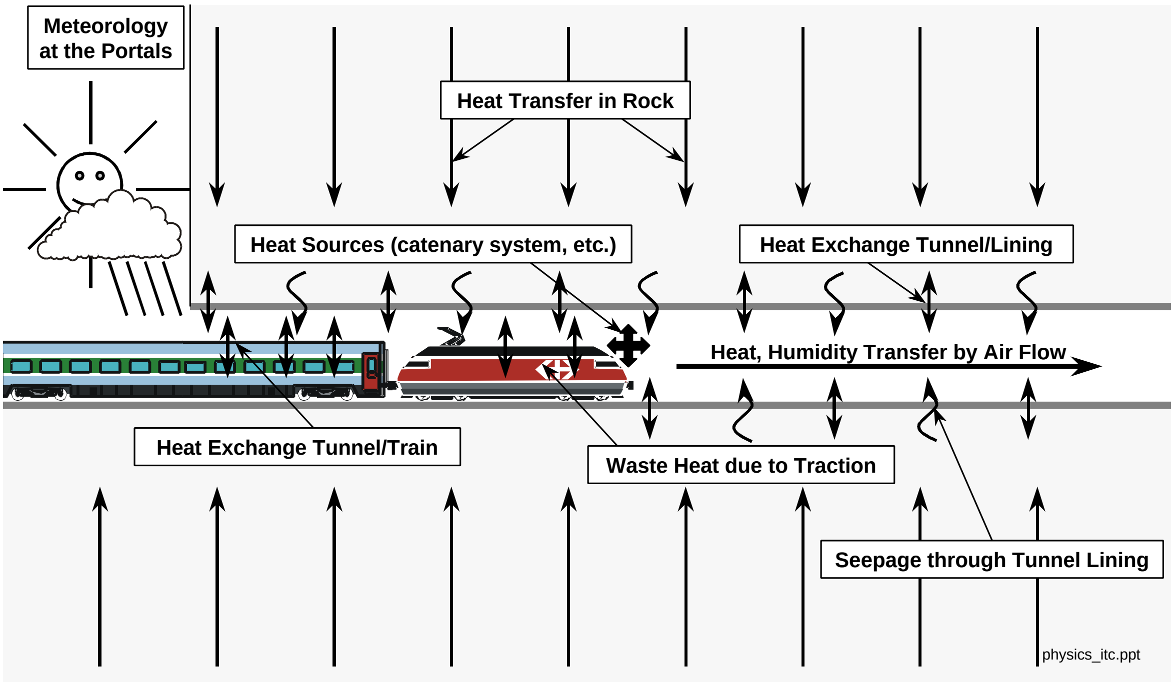

Figure 2 Schematic overview of the factors influencing the tunnel climate

$$\dot{Q}_{Tunnel} = \dot{Q}_{Flow} + \dot{Q}_{Train} + \dot{Q}_{Source} + \dot{Q}_{Evaporation} + \dot{Q}_{Lining} \ \text{: heat transfer in tunnel air [W]} \qquad (1)$$

with:

$\dot{Q}_{Flow}$: heat transfer by air flow [W]

$\dot{Q}_{Train}$: heat transfer by trains [W]

$\dot{Q}_{Source}$: heat sources in the tunnel (e.g. catenary system) [W]

$\dot{Q}_{Evaporation}$: heat generation due to evaporation [W]

$\dot{Q}_{Lining}$: heat exchange between tunnel air and lining [W]

$$\dot{M}_{Tunnel} = \dot{M}_{Flow} + \dot{M}_{Evaporation} \ \text{: mass transfer of water in tunnel air [kgs}^{-1}\text{]} \qquad (2)$$

with:

$\dot{M}_{Flow}$: humidity transfer by air flow [kgs^{-1}]

$\dot{M}_{Evaporation}$: humidity input due to evaporation [kgs^{-1}]

All these effects are taken into account by THERMO, a complex simulation tool for tunnel climate developed by HBI Haerter Ltd.. This code allows to model the development of tunnel climate in complex geometries considering for example the passage of each single train through the system, the thermal behaviour of the rock, the effect of water ingress etc..

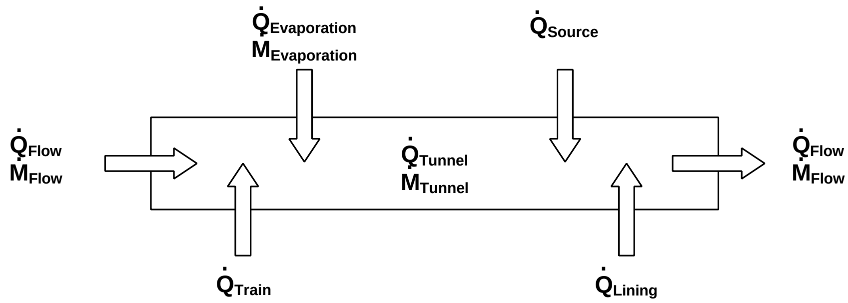

Figure 3 Heat and mass balance for a tunnel section

3 CURRENT STATE OF PREDICTION

In the following text a presentation of the current predictions of the climate for the Gotthard Base Tunnel is given. Air velocities, temperatures and humidities along the main tubes of the base tunnel (cf. Figure 1) will be shown. The long term climate is of principal interest (corresponding to the "climatic equilibrium"). Therefore, no short term phenomena like pressure, temperature or humidity fluctuation due to single train passages, maintenance work or daily changes of meteorology will be discussed. The basis of the climate prediction presented is a set of (input) parameters (e.g. rock temperature, speed of the trains, meteorological conditions at the portals). The values of these parameters are considered to be reasonable. However, one must take into account that there are considerable uncertainties in the determination of some of these parameters.

A major parameter for the tunnel climate is the air velocity induced by the scheduled trains. For the long-term evolution of the tunnel climate the average value of air velocity is the determining parameter. In Figure 4 the average air velocities along the eastern and western tube of the base tunnel are illustrated. The direction of the air flow (eastern tube: N to S, western tube: S to N) is directly related to the direction of the train traffic (cf. Figure 1). The overall average (average over 2 h period of train schedule) in both tubes is about 6 ms^{-1}. The minor fluctuations of the air velocity along the tubes are mainly caused by changes in the tunnel cross section. The minima may be found in the area of the open crossovers at 21 km and 40 km (cf. Figure 1)

The corresponding air temperatures along the eastern and western tunnel tube of the base tunnel are illustrated in Figure 5. The daily temperatures are averaged for typical summer and winter days. In general, the temperature increases in direction of the train traffic for both tubes in summer and winter. Maximum values may be found in the area of the exit portals. Each curve includes two temperature steps along the tubes at about 21 km and 40 km. These steps are caused by the mixing of tunnel air between the tubes via the open crossovers. A strong seasonal fluctuation of temperature in the tunnel is caused by changing climatic conditions at the portals. Maximum temperatures reach about 35°C.

The humidity distribution along the tunnels is included in Figure 6. Again daily averages for a typical summer and winter day are presented. In contrast to the shown temperatures the relative humidity decreases in direction of the train traffic along the tubes in both seasons. This is related to the strong increase of temperature. The heated tunnel air is able to store much more water that is supplied by the seepage through the tunnel lining. As a result the relative humidity decreases. Maximum values lie in the vicinity of the portals at the entrance of the tunnel. The mixing of air via the open crossovers again leads to steps along the humidity curves at about 21 km and 40 km. Due to higher humidity at the portals the humidity all along the tubes is remarkably higher in summer time. The highest average values are about 75 %.

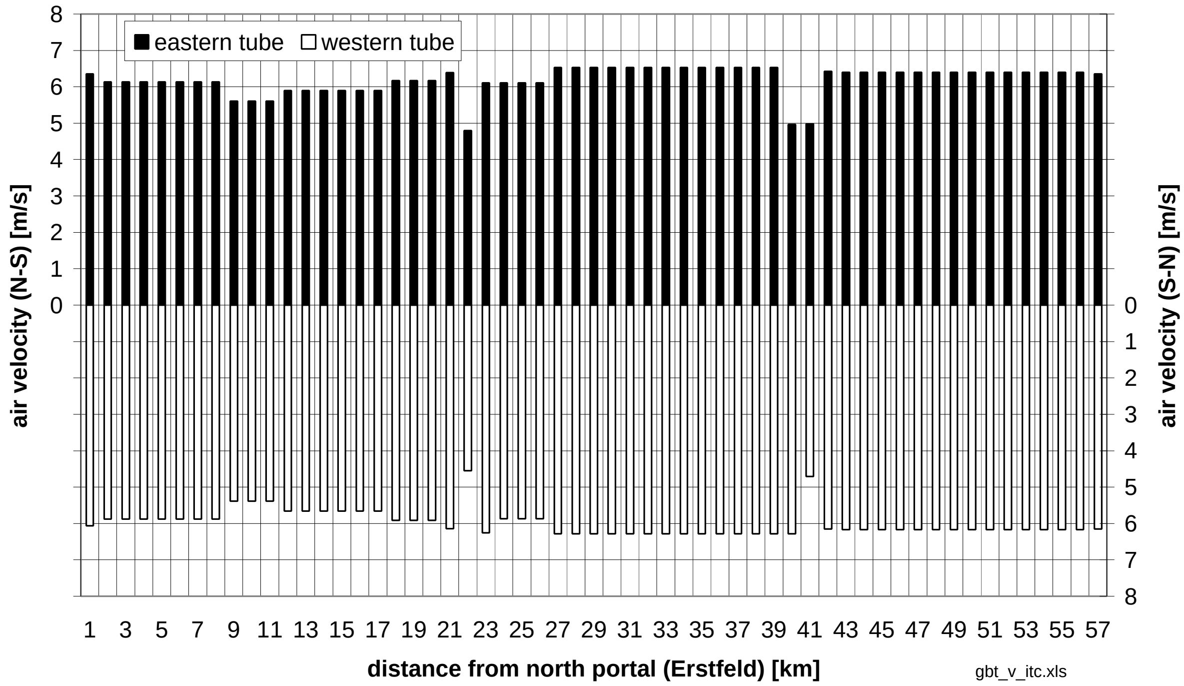

Figure 4 Air velocities along the main tubes of the Gotthard Base Tunnel (normal operation: eastern tube with traffic from north to south, western tube with traffic from south to north; cf. Figure 1), average of 2 h (period of the train schedule).

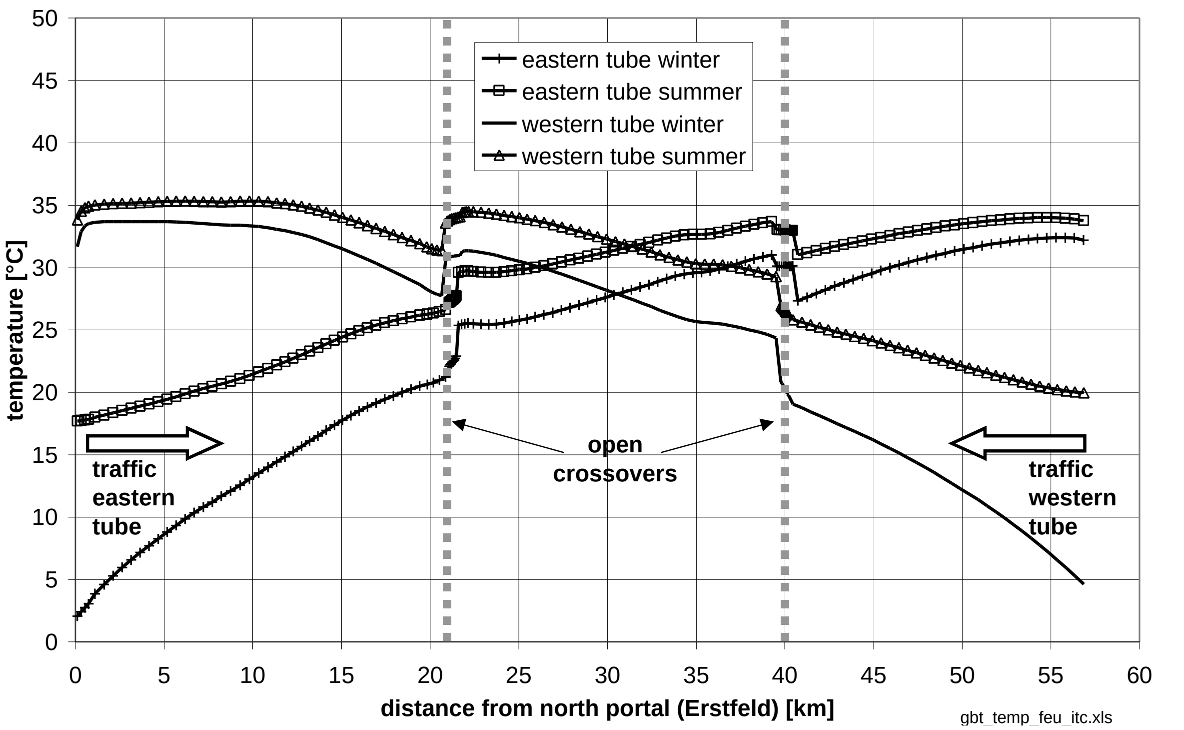

Figure 5 Temperatures along the main tubes of the Gotthard Base Tunnel (normal operation: eastern tube with traffic from north to south, western tube with traffic from south to north; cf. Figure 1), daily average in summer and winter

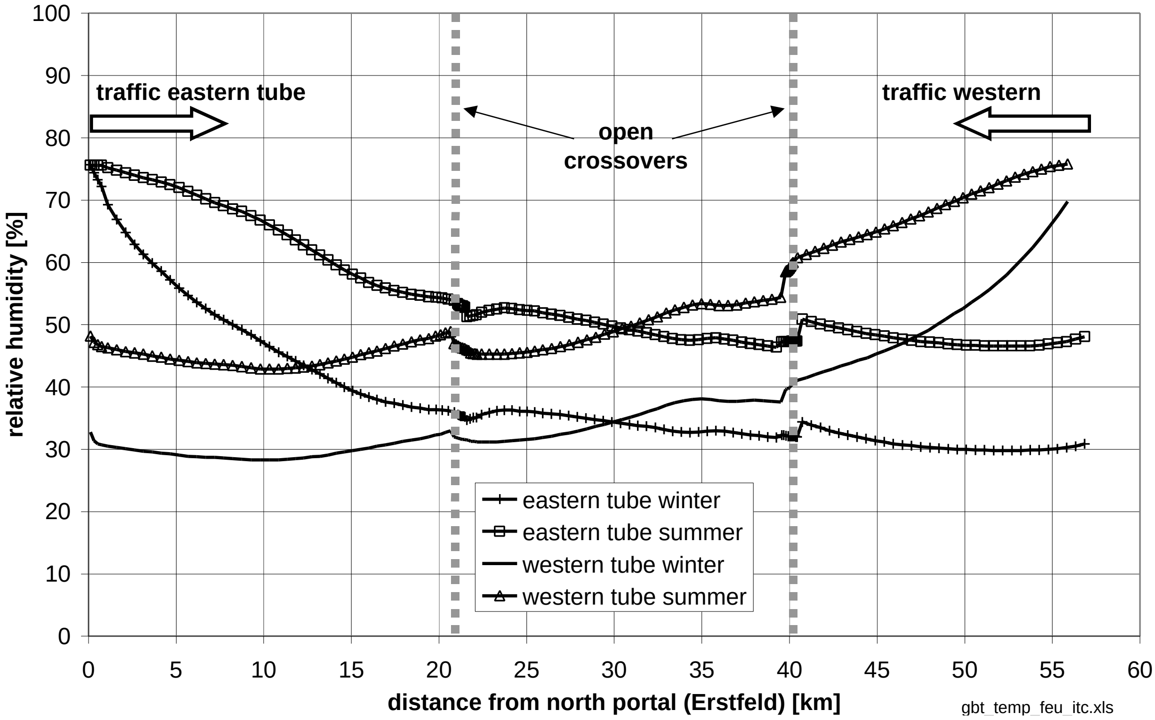

Figure 6 Relative humidity of air along the main tubes of the Gotthard Base Tunnel (normal operation: eastern tube with traffic from north to south, western tube with traffic from south to north; cf. Figure 1), daily average in summer and winter

As mentioned before, the climate prediction shown is based on assumptions concerning the various parameters that influence the climate. Consequently, a "reasonable worst case" was defined where some of these parameters were assumed to deviate to unfavourable values within a range of tolerance. Former studies showed (cf. [1], [3]) that the rock temperature, the amount of water ingress through the tunnel lining, the thermally active mass of the train (defined as the mass of the train that participates in heat exchange), technical heat sources (e.g. the catenary system), the temperature of entering trains and friction coefficient of trains in the tunnel are some of the most influencing parameters. By changing these parameters, a "reasonable worst case of temperature" and a "reasonable worst case of humidity" could be defined. The resulting climate predictions for the Gotthard Base Tunnel are shown in Figure 7 and Figure 8. Only summer conditions are illustrated, since these lead to higher temperature and relative humidity.

The assumptions of the reasonable worst case of temperature lead to very high temperatures along the tubes of the Gotthard Base Tunnel (cf. Figure 7). The maximum values reach about 50°C. This equals an increase in temperature of about 15°C compared to the reference case. In contrast, the relative humidity is reduced to minimum values of about 15 %. The reason for this behaviour lies within the strong reduction of water ingress in the tunnel which results in a smaller evaporation rate on the tunnel lining.

Looking at the reasonable worst case of humidity (cf. Figure 8) the relative humidity is strongly raised in both tunnel tubes compared to the probable case (cf. Figure 5 and Figure 6). Most values rise higher than 90 %. On the other hand the temperatures have significantly decreased (up to 8°C) compared to the probable case. The reduction of temperature is predominantly caused by the enhanced evaporation of seepage through the tunnel lining.

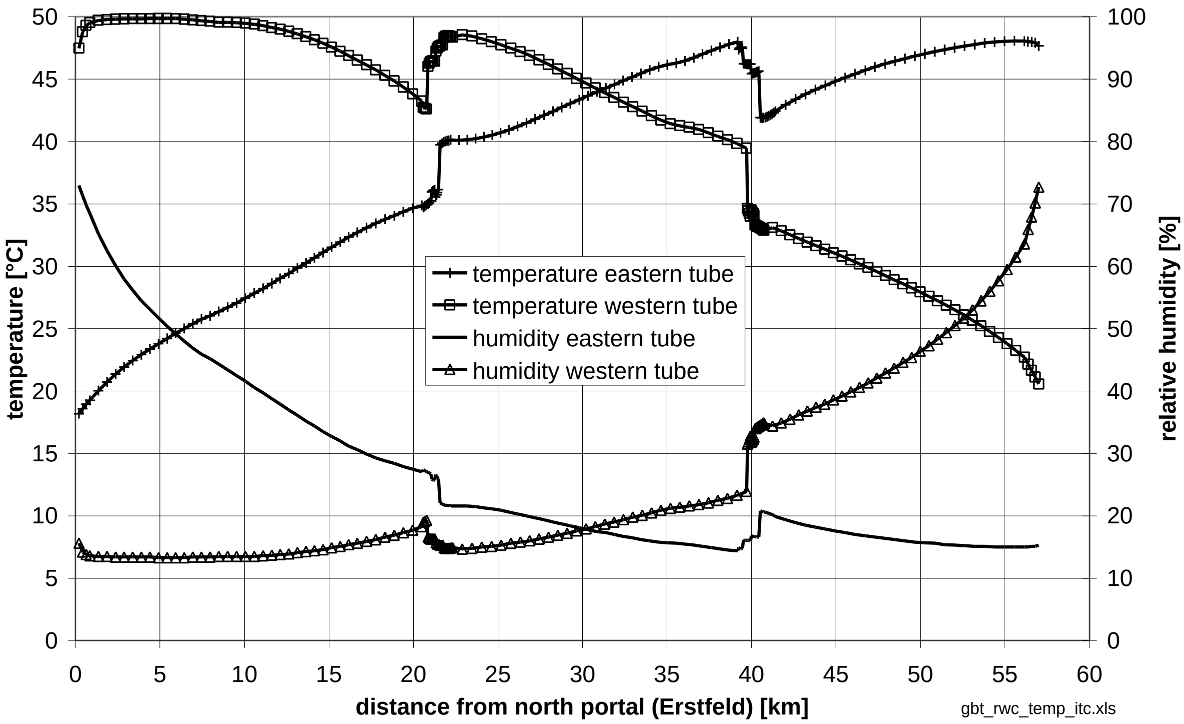

Figure 7 Temperature and relative humidity along the main tubes of the Gotthard Base Tunnel, daily average in summer for the reasonable worst case of *temperature*

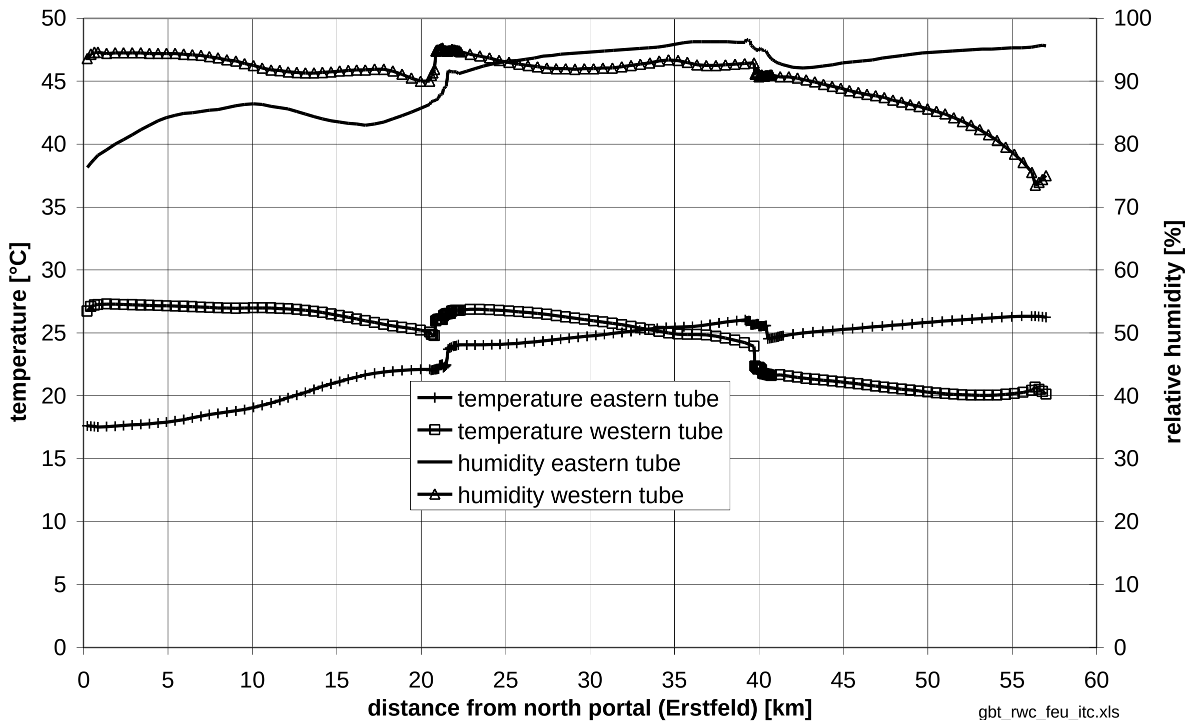

Figure 8 Temperature and relative humidity along the main tubes of the Gotthard Base Tunnel, daily average in summer for the reasonable worst case of *humidity*

The probability that all parameters of such worst cases may occur at the same time is very small. But nevertheless, since this case can not be excluded, further steps had to be thought of to improve the reliability of predicting the tunnel climate.

As a consequence of these results a special investigation has been carried out to systematically

- define all parameters influencing the climate in the Gotthard Base Tunnel
- find the most important parameters amongst them
- determine their accuracy
- evaluate the possibility to increase the accuracy
- estimate the impact of improving the precision on the prediction of the tunnel climate

As a result, the most important parameters to predict the tunnel climate could be found. Two groups of parameters are relevant:

- parameters related to the surrounding rock:
  - thermal conductivity of the rock
  - undisturbed or initial rock temperature
  - water flow in the rock
  - seepage through the tunnel lining
- parameters related to the rolling stock:
  - train schedule
  - friction coefficient of the trains
  - heat transfer coefficient train/tunnel air
  - thermally active mass of the trains
  - thermally active surface of the trains
  - temperature of entering trains
  - humidity of entering trains

Most of the uncertainties of the parameters related to the rolling stock exist for freight trains. This is caused by the variety of different freight and train compositions leading to significant aerodynamic and thermodynamic influence.

The possible improvement of the accuracy of each parameter has been quantified. By increasing the precision of the parameters related to the surrounding rock, the range of uncertainties in the climate prediction should be reduced by about 40 %. A further reduction of about 20 % could be reached by optimising the precision of the parameters related to the rolling stock.

In the following chapter the methods that have been chosen to improve the accuracy of these parameters are described.

4 FURTHER STEPS

The importance of a precise prediction of the tunnel climate and the related necessity of accurate basic parameters has been recognised. A monitoring concept has been developed to collect data during tunnel construction. The current monitoring includes the following measurements:

- undisturbed rock temperature at least every 2 km, measured in boreholes perpendicular to the tunnel line
- discrete water ingress through springs/fractures
- total amount of rock water for different geological units, measured in the drainage system
- thermal conductivity of rock samples at least every 2 km, measured in special laboratories
- heat capacity of rock samples at least every 2 km, measured in special laboratories
- density of rock samples at least every 2 km, measured in special laboratories
- seepage through the tunnel lining for different geological units, measured by the change of humidity along the tunnel

These measurements evidently improve the accuracy of the parameters mentioned above. The monitoring will start with the beginning of the construction of the main tubes of the Gotthard Base Tunnel in 2001.

To optimise the precision of the parameters related to the rolling stock two different methods have been discussed:

- laboratory measurements in climate chambers
- measurements in existing tunnels

Based on the experience of former studies climate chamber measurements do not seem to provide the desired data. It would be necessary to collect data from complete and different train compositions (especially freight trains).
Measurements of climatically relevant parameters like the friction coefficient of trains have been carried out in the past (cf. [6]). Different proposals have been made to collect data to increase the accuracy of the friction coefficient, the thermally active mass and surface of trains for the Gotthard Base Tunnel project in existing tunnels like the Simplon railway tunnel.
In addition the simulation model will be refined (e.g. to consider the influence of possible cavities between the tunnel lining and the surrounding rock).

5 OPTIONS FOR THE TUNNEL CLIMATE SYSTEM

In case of a predicted climate that exceeds the chosen limits for temperature and/or humidity, different measures are planned or proposed. To date air exchangers are the preferred measure. The precautions to realise the air exchangers are implemented in the design. Preparations for the installation of these exchangers are underway. There are three possible locations namely at the adits of Amsteg, Sedrun and Faido (cf. "adits" in Figure 1) where fresh and cold air from the outside could replace warm or humid air from the tunnel. A possible configuration of such an air exchanger system in the Gotthard Base Tunnel is schematically shown in Figure 9. The amount of air that will be exchanged at each of these location is 200 m^3s^{-1}. Even though the efficiency of this measure decreases with distance from the air exchanger, they could improve the climatic situation within a range of circumstances.

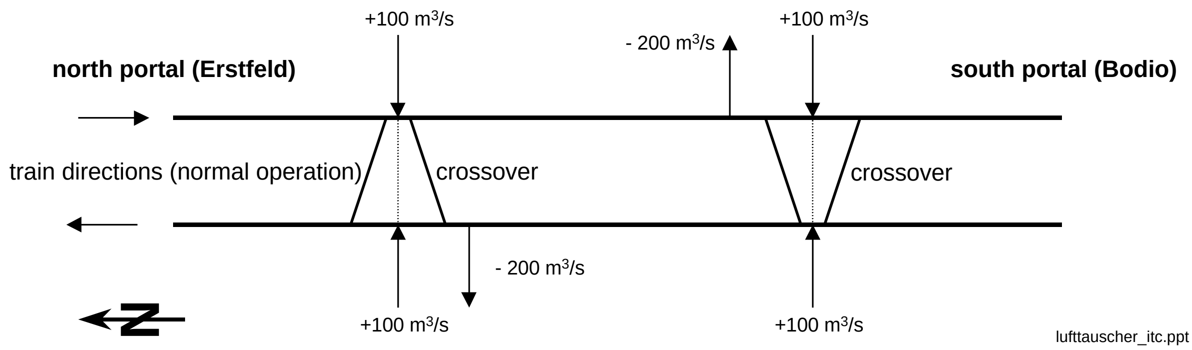

Figure 9 Possible configuration of an air exchanger system in the Gotthard Base Tunnel with the flow rates of supplied and removed air

A further possibility to improve the climate are cooling pipes along tunnel areas where the given climatic limits are exceeded (as in the channel tunnel).
The impact of such optional climate systems on the tunnel climate has been investigated. This will enable the project management to check their current decisions and if necessary to evaluate other measures at early stages in the project.

6 CONCLUSIONS

The following results could be gained by the current prediction of the tunnel climate:

- Based on the parameters considered to be reasonable the tunnel climate remains within the acceptable limits for temperature and humidity.
- Uncertainties remain in the determination of the key parameters.
- A "worst case" of the tunnel climate which would cause significant expenses for air conditioning systems (air exchangers) can not be excluded.
- Only a complex code like THERMO will be capable to predict the climate of extended tunnel systems with acceptable precision.
- Measures to improve the accuracy of the climatically relevant parameters, like the monitoring during tunnel construction, must be found and realised.

7 ACKNOWLEDGEMENT

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8 LITERATURE

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