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EMPIRICAL VALIDATION OF SEASONAL 1D TEMPERATURE PREDICTIONS IN A 9 KM NORDIC TRAIN TUNNEL

[1]Erik Östblom, [2]Per Sahlin
[1]EQUA Solutions AB, Sweden, [2]EQUA Simulation AB, Sweden

ABSTRACT

Reliable long-term predictions of tunnel temperatures are critical in several ways, such as for passenger comfort, buoyancy driven air flows, risk of ice formation, thermal loads on tunnel lining etc. In this work, IDA Tunnel temperature predictions are compared with long term measurements in a 9 km twin-bore train tunnel in Sweden. Comparisons were made with measured as well as computed tunnel air velocities. Predictions were in both cases in good agreement with measured data. Barometric pressure differences between the portals were shown to have a significant impact on results, as did the background deep ground temperature level.

Keywords: tunnel simulation, tunnel environment, long term-prediction

1. INTRODUCTION

1.1. Background

In this paper, measured temperatures in the Hallandsås tunnel in Sweden are compared with results from an IDA Tunnel simulation model. The Swedish Transport Administration (STA) decided to perform such measurements in the Hallandsås tunnel and to use the measurement data to validate a simulation model of the tunnel. The tunnel consists of two 8.7 km long tunnel tubes with single-track, one-way traffic.

Air velocities are continuously measured in the tunnel by STA. Measurements of air and wall temperatures in the tunnel have been carried out by the Swedish Road and Transport Research Institute. The measurement data have been compared with results from a simulation model created in IDA Tunnel version 1.2.1. IDA Tunnel is used to analyse climate and 1D airflow in railway and road tunnels. The simulations consider, among other things, actual weather conditions at the site during the measurement period, heat storage in tunnel walls and ground, moisture conditions and the impact of train traffic.

In a separate work, cold and ice in tunnels of a proposed high-speed railway through Sweden have been studied using IDA Tunnel [1]. Two small validation studies using measurements in the Glödberg and Åsa tunnels are presented in the same report.

1.2. Methods for seasonal temperature predictions in underground tunnels

In the 1970's, the 1D Subway Environment Simulation (SES) program was developed by US public authorities. SES allows for dynamic simulation of train piston action and outputs airflows, temperatures, and humidity. SES focuses on the simulation of a single metro rush hour under constant operating conditions but also has a simplified method for predicting annual and diurnal temperatures based on assumed sinusoidal temperature variations. The basic structure of SES, with constant tunnel operating conditions, does not permit the study of tunnel ventilation system control. The last major release of SES, version 4.1, was in 2001.

More recently, the Subway Thermal Environment Simulation Software (STESS) has been developed by researchers at Tsinghua University [2] with the explicit purpose of studying control strategies for metro systems. It is based on an incompressible aerodynamic model that is similar to SES (and thereby to IDA Tunnel). Also similar to IDA Tunnel, it has a finite-difference ground model and can thereby, in principle, compute arbitrary time variations in tunnel operation including the effect of buoyancy driven flows.

STESS relies on a cartesian 2D model of the ground around a tunnel segment, and, thereby, permits the definition of inhomogeneous ground properties. The software applies a combination of monthly and hourly timesteps to capture long-term as well as short-term ground heat-up. The details of this process is not clearly described in [2].

The IDA Tunnel ground model is based on superposition of multiple 1D temperature fields, to capture the true 2D field of (at most) two identical tunnel bores, including the influence from the ground surface. Multiple tunnel wall material layers can be described, but contrary to STESS the surrounding ground is assumed to have constant thermal properties.

Another method for seasonal temperature predictions in train tunnels is using the simulation tools Thermo and ThermoTun coupled, as reported by HBI in [3]. Thermo is developed by HBI and is used for simulation of thermal conditions in train tunnels. ThermoTun is developed by Dundee Tunnel Research and is used for simulation of aerodynamic and thermodynamic phenomena in rail and metro tunnels.

2. MEASUREMENT CAMPAIGN

Measurements of air temperature, relative humidity, wall surface temperature and wall inside temperature were carried out during a 27-month period starting in February 2019 [4]. The tunnel has been equipped with sensors that samples values once an hour.

The positions of the measuring stations are shown in Figure 1.

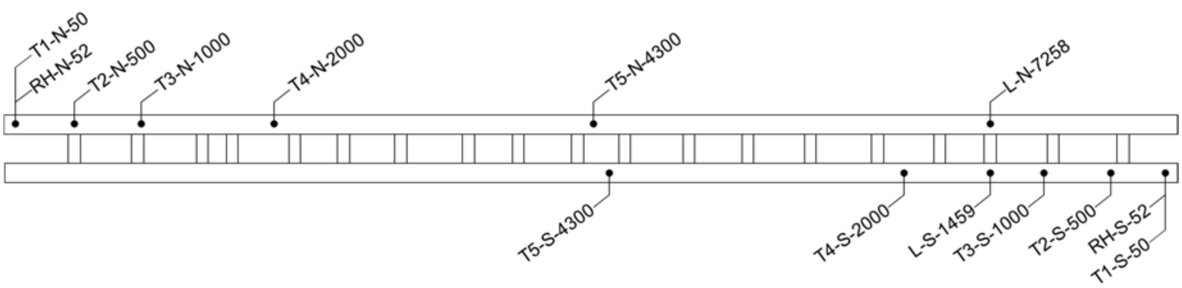

Figure 1: Position of measuring stations. T1-T5=Temperature measuring stations, RH=Relative humidity measuring stations, L=Air velocity measuring stations, N=Measuring station is located in the tunnel with northbound traffic, S=Measuring station is located in the tunnel with southbound traffic. The numbers at the end indicate the distance from the entrance in metres.

Air temperature and surface temperature are measured at measuring stations 50, 500, 1000, 2000 and 4300 m from the entrance to each tunnel tube. Air temperature is measured 1.5 m above the walkway. Surface temperature at measuring stations 50 m from the entrances is measured 0.3 and 3 m above the walkway. Surface temperature at other measuring stations is measured 0.3 and 2 m above the walkway. Wall inside temperature is measured 5 cm into the wall, 50 m from the entrance and 1.3 m above the walkway. Relative humidity is measured 52 m from the entrance and 1.5 m above the walkway.

Air velocities are collected from one anemometer in each tunnel tube from January 20, 2020, and onwards with a sampling period of 10 s. Both anemometers are located 1460 m from the northern portal and around 4.2-4.5 m above top of rail level. The measurements are sensitive to turbulence caused by train passages.

Due to various problems with the data collection, the period between March 2, 2020 and May 31, 2021 was selected for the comparison.

3. SIMULATION MODEL INPUT DATA

3.1. Model variants

Two different variants of simulation models with respect to air velocities have been used in the comparison:

- Simulated with measured air velocity: In this variant, measured air velocity is used as a boundary condition. Simulated air velocity is then equal to measured air velocity.

- Simulated with computed air velocity. In this variant, the air velocity is a simulation result that varies with the influence of buoyancy, portal barometric pressure variations and aerodynamic impact from train passages.

The tunnel became operational by the end of 2015 and the comparison period starts almost five years later. To estimate the initial temperature state of the ground around the tunnel at the beginning of the comparison period, the time until the beginning of the comparison period is simulated separately. Due to the lack of air velocity measurement data during this period it was simulated with computed air velocity only. The resulting ground temperature at the end of the simulation period is used in describing the initial state for both model variants used in the comparison.

3.2. Geometry and height profile

Figure 2 shows the tunnel height profile, cross section area and which part that has concrete lining. The southern portal is located 13 m above the north portal. There is a high point 6440 m from the northern portal. The gradient is 3 ‰ between the high point and the portals.

Around 84 % of the lined tunnel length consists of precast concrete segmental linings and the rest of cast in-situ concrete lining. About 30% of the rock tunnel sections are covered by insulated drains. All changes to the cross-sectional area consist of smooth geometric transitions that are assumed to result in negligible pressure losses.

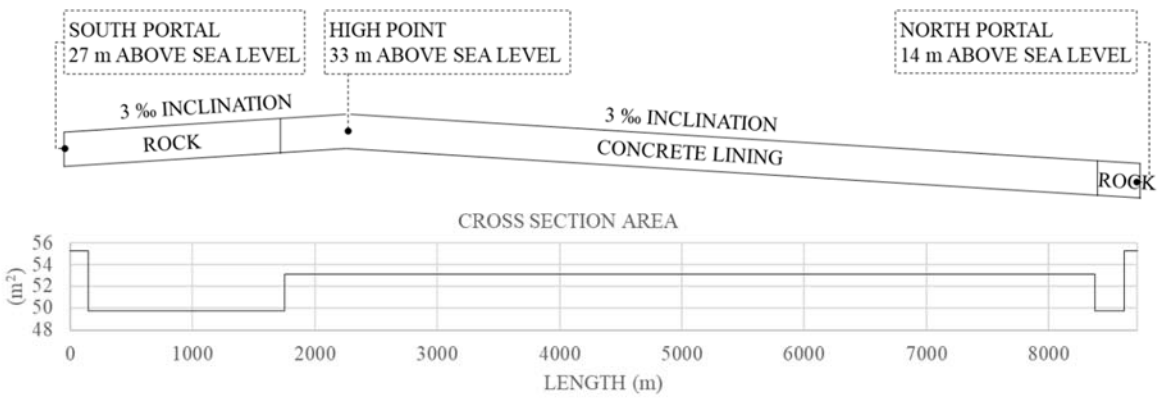

Figure 2: Tunnel height profile, cross section area and parts with concrete lining vs bare rock.

A Darcy-Weisbach friction factor of 0.02 is assumed as an average value for the whole tunnel.

There are 19 cross passages for emergency evacuation between the tubes. The cross passages have fire doors in each end which are closed during normal operation. Air leakage through the fire doors is considered to be insignificant and the cross passages have therefore not been modelled.

3.3. Ground

Table 1 shows values for thermal parameters of the ground around the tunnel and tunnel construction materials used. All values in the table are assumed. Polyethylene mat and air gap are used in insulated drains. The thickness of all construction material layers varies and is not reported here.

Table 1: Thermal parameters of ground and tunnel construction material. λ is thermal conductivity W/mK; ρ is density, kg/m^3 ; c_p is specific heat capacity, kJ/kgK;.

Material	λ	ρ	c_p
Ground (rock)	3.5	2 700	880
Concrete	1.7	2 300	880
Shotcrete	1.7	2 300	880
Polyethylene mat	0.04	20	940
Air gap	0.5	1.2	1 006

The deep, undisturbed ground temperature is an important boundary condition and initial value. An accurate measurement of this key input is difficult to achieve, especially in an urban environment. Normally, the historic average air temperature is applied with some compensation for the heat island effect. Here, the value of this input parameter has been adjusted through a parametric study to increase agreement between measured and simulated wall surface temperature during the comparison period. This has resulted in the value +9.6°C being used for the deep, undisturbed ground temperature. Incidentally, this corresponds to the average air temperature that was measured by a nearby weather station during the period from when the tunnel became operational until the start of the comparison period.

Heat flux through the ground and wall between the parallel tunnel tubes are simplified by superposition of temperature fields where one tunnel tube is considered to have an exact copy 20 m next to it, i.e. the temperature of the actual adjacent tunnel tube (which has the opposite direction of traffic) is not considered. This simplification is considered to have limited impact on the results.

Groundwater seepage into the tunnels varies during the comparison period varies between 2.0 and 4.5 l/s in the north and 5.3 and 5.6 l/s in the south, respectively [5]. The advected heat will influence the temperature profile into the tunnel wall. It is assumed that no groundwater is exposed to tunnel air.

3.4. Ambient

Recorded ambient air temperature, relative humidity and pressure is used as boundary conditions at the portals.

For air temperature and relative humidity, the monitoring station closest to the north portal is located about 4.5 km northeast of the northern portal [6] and the monitoring station closest to the south portal is located about 9.25 km northwest of the southern portal [6]. The monitoring stations sample data with half hour intervals.

For barometric pressure, the monitoring stations closest to the tunnel are located about 60 km north-northeast of the north portal [7] and 8 km south-southeast of the south portal [8]. Due to the large distance between the monitoring stations, a barometric gradient has been calculated between them which has been used to estimate the barometric pressure at the portals. The monitoring stations sample data with hourly intervals.

Impact from wind pressure is assumed to have a negligible influence on results and is not considered.

3.5. Trains

Table 2 shows train types and a number of relevant parameters used to model them.

Table 2: Train types used in the simulation and some of the parameters describing them.

Parameter	Unit	X31	X55	X61	Freight train
Train length	m	79	107	74	466
Front area	m^2	9.3	11.5	11.4	13.2
Perimeter of front area	m	11.4	12.6	12.6	12.8
Nose drag coefficient	-	0.50	0.45	0.45	0.62
Skin friction coefficient	-	0.012	0.014	0.012	0.031
Total weight incl. pass./cargo	ton	180	310	179	1125
Tractive power	kW	2 300	3 180	2 000	3 600
On-board services heat	kW	40	85	40	0
Average number of passengers	-	115	123	117	-
Davis formula coefficient A	m/s^2	0.0103	0.0071	0.0092	0.013
Davis formula coefficient B	1/s	0.0003	0.00019	0.0004	0.00027
Speed	km/h	180	200	160	86

The number of train passages per day and tunnel tube is shown in Table 3.

Table 3: Number of train passages per day in each tunnel tube.

	X31	X55	X61	Freight trains
Weekdays	19	2	7	0.8 – 8.8
Saturdays	16	5	0	0.8 – 8.8
Sundays	16	5	0	0.8 – 8.8

3.6. Heat loads

The only heat loads in the model are the ones generated by the trains.

4. RESULTS

To improve readability, the graphs show measurement data and simulation results as daily averages. However, no averaging has been applied to any of the input data.

Since several measuring stations in the tube with southbound traffic were not able to record data during long periods of time, results are shown only for the tube with northbound traffic. The level of agreement between measured values and simulation results in the tube with southbound traffic, during periods when recording of measured values worked, is similar to that observed for the tube with northbound traffic.

Figure 3, 4 and 5 shows air and wall temperatures 50, 1000 and 4300 m, respectively, into the tube with northbound traffic (from the entrance). Figure 6 shows air speed and wall inside temperature at 7258 and 50 m, respectively, into the tube with northbound traffic (from the entrance.

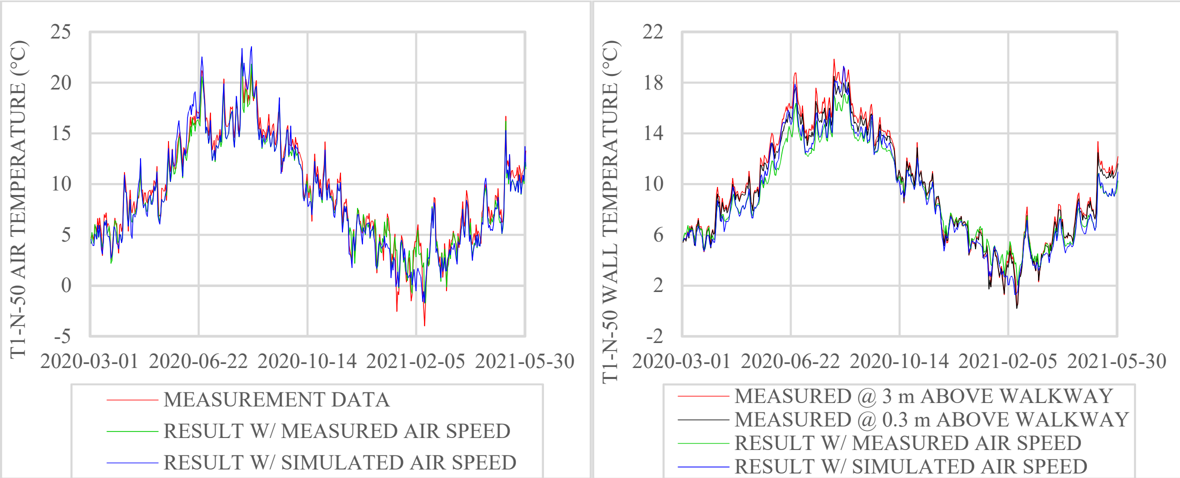

Figure 3: Daily average air and wall surface temperature 50 m into to the tube with northbound traffic (from the entrance).

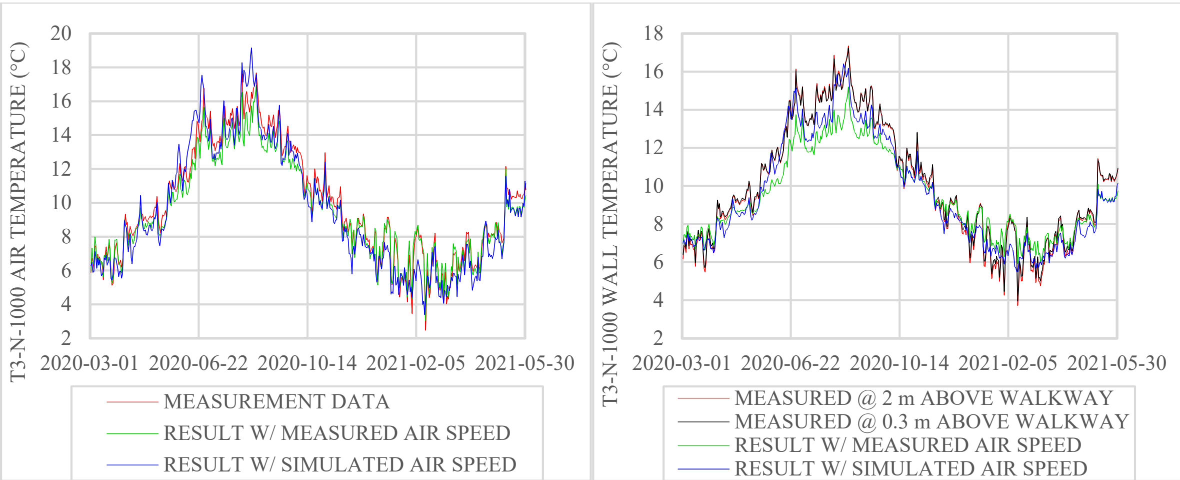

Figure 4: Daily average air and wall surface temperature 1000 m into the tube with northbound traffic (from the entrance).

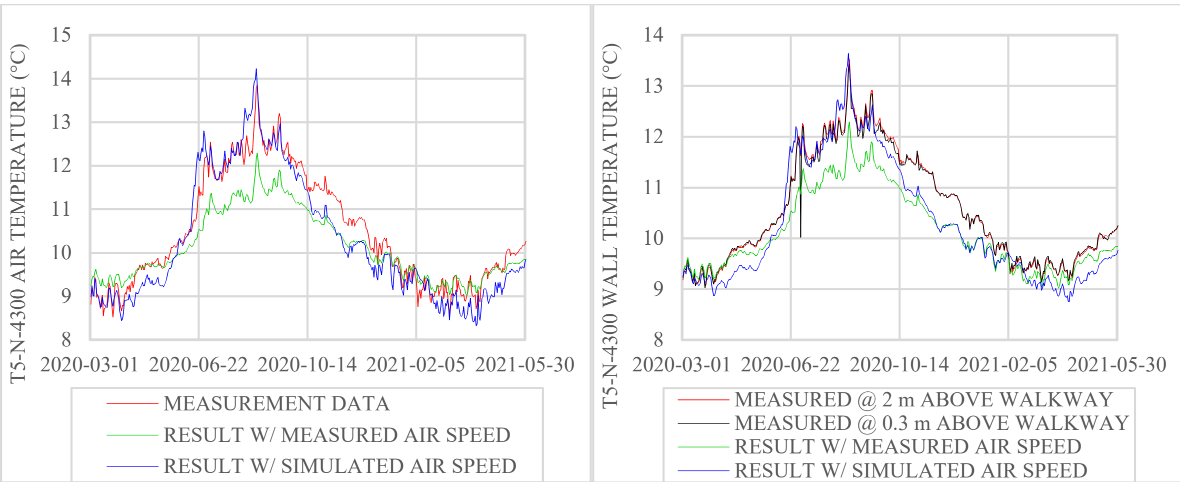

Figure 5: Daily average air and wall surface temperature 4300 m into the tube with northbound traffic (from the entrance).

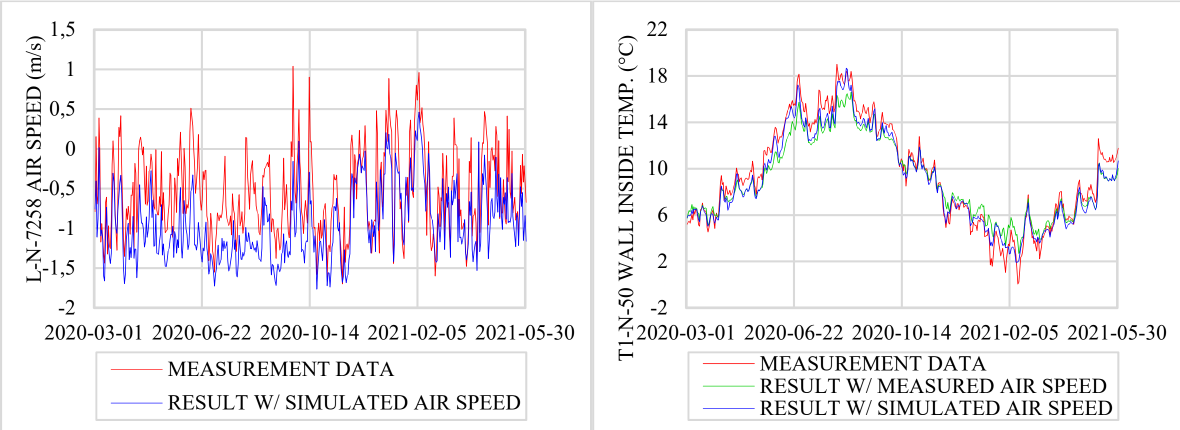

Figure 6: Left: Daily average air velocity (negative value means in the direction of traffic) 7258 into the tube with northbound traffic (from the entrance). Right: Temperature 5 cm into the wall, 50 m into the tube with northbound traffic (from the entrance).

5. DISCUSSION

The comparisons show that the simulation results are generally in good agreement with the measured values. The simulation models deal with a large set of parameters that are important in temperature studies of tunnels, such as thermal properties of tunnel construction materials and surrounding ground, geometry, elevation profile, actual weather conditions and train traffic.

Two important sources of error are uncertainties in the input data indicating the barometric pressure at the tunnel portals and the deep, undisturbed ground temperature. These parameters have a significant impact on results and are typically difficult to find input data for. The weather stations from which air pressure measurements were taken are located at great distances from the portals. This introduces uncertainty in the barometric gradient calculated from the weather station data that is used to estimate the barometric pressure difference between the portals.

The value used for the deep, undisturbed ground temperature was +9.6°C, as this value provided the best agreement between simulation results and measurement data. This value was found to correspond to the mean temperature of the weather station nearest to the southern portal for the four previous full years before the start of the comparison period. The corresponding mean temperature for the weather station closest to the northern portal was +8.6°C. In sparsely populated areas the deep, the undisturbed ground temperature usually corresponds to the annual mean temperature for the site, so a better agreement would have been expected if the deep, undisturbed ground temperature had been set equal to the mean of the temperatures of both the northern and southern portals for a large number of years before the comparison period. Here, effects from groundwater flow may be part of the explanation.

Another obvious source of error is the estimate of traffic in the tunnel. Although good records of timetables and types of trains were found, the mixture of passenger and freight trains is not ideal for this type of study. No tuning of the traffic parameters was done and as Figure 6 (left) indicates, the computed air velocities were slightly higher than those measured. It may be somewhat counterintuitive that the simulations with computed air velocities sometimes show better agreement between simulated and measurement temperatures, than simulations based on measured air velocities.

Air velocities are measured with only one anemometer in each tunnel and the measurements are sensitive to turbulence caused by train passages. As air velocity affects the temperature in the tunnel, this is a source of error in the simulation where measured air velocities are used as a boundary condition. In addition, it makes it difficult to assess how well simulated air velocities correspond to the actual ones.

6. CONCLUSION

The present study gives an indication of the type of accuracy that can be achieved with a reasonable amount of data collection and effort in using IDA Tunnel. As for any field study, the agreement is not perfect, but trying to achieve improved accuracy by a more elaborated physical model, e.g., in 2D or 3D, is difficult to motivate. The accuracy of the predicted results is well in line with inherent inaccuracies in measurements and obtainable input parameters.

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