STATISTICAL DISTRIBUTION OF AIR FLOWS IN RAIL TUNNELS AND RESULTING RISK OF FLOW REVERSAL DURING FIRE INCIDENTS

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ABSTRACT

In tunnels without mechanical ventilation, the movement of air is governed by pressure forces induced by the traffic, the underground aero-thermal conditions and the meteorological conditions outside the tunnel. Together, these forces may lead to different flow directions of air in the tunnel during normal operation. In case of a subsequent "hot incident" in an inclined tunnel, the heat of the fire causes a thermal draught, which superposes with the aforementioned pressure forces of normal operation. Depending on the strength and direction of the different forces, the heat of fire may turn a down-flow to an up-flow of air and smoke.

The flow direction of air and smoke affects the self-rescue, the evacuation and the fire-fighting activities in the tunnel. A change of the flow direction during an incident might become highly critical for the following reasons:

- Previously tenable egress and access paths become unexpectedly filled with smoke.
- Occupants and emergency services are suddenly exposed to non-tenable conditions, become disoriented and cannot identify the proper egress and access direction.
- The change in flow direction is accompanied by high flow velocities which disturb the smoke stratification and, thus, reduce the visibility in the incident tube.

In this paper, the possibility of changing flow directions in the event of a fire in a typical rail tunnel with monotonic inclination and without mechanical ventilation shall be presented. The results are based on one-dimensional simulations of the tunnel environment prior to fire. The daily and annual changes of the aero-thermal conditions of tunnels are considered. Statistical distributions of flow conditions for high-speed rail tunnels in Germany and France are given illustrating the impact of, for example, tunnel slope, ground overburden, weather conditions and train operation. The paper gives a better insight into the flow conditions prior to fire and the resulting possibility of changing flow directions during an incident.

Keywords: tunnel environmental conditions, natural thermal draught, flow reversal upon fire, rail tunnel incidents

1. INTRODUCTION

Most of the existing high-speed rail tunnels in Europe have the following features:

- Single-tube, twin-track layout
- Uniform, monotonic inclination
- Not equipped with mechanical ventilation

In such inclined rail tunnel tubes, the flow direction of air is influenced by the pressure differences induced by moving trains, outside wind acting on the portals, meteorological pressure differences across mountain rims and / or thermal draught due to the different average temperatures inside and outside the tunnel. Together, these pressures may lead to an up- or downflow of air in the tunnel during normal operation.

At the onset of a fire and the accumulation of hot smoke in the tunnel, the average tunnel air temperature increases. In the initial phase of a fire, the smoke propagation follows the prevailing air flow direction. After a while, the upwards directed, fire-induced pressure force might become dominant and the flow direction of the smoke/air may turn. Smoke may rapidly spread to other parts of the tunnel, which were smoke-free before. This change of flow direction occurs only if the flow of air and smoke is initially directed downwards. The change of smoke direction, the high flow velocities and the turbulence lead to the rapid mixing and entire filling of major tunnel sections by smoke. This typically unexpected smoke behaviour poses an additional threat for the egress and rescue activities in the event of an emergency.

In order to better assess this risk, a statistical analysis of the environmental conditions inside of rail tunnels is necessary. Quantifying the possibility of flow reversal requires the modelling of a tunnel's aero-thermal conditions for an entire year taking the train operation and the daily as well as seasonal changes of outside conditions into account.

2. OBJECTIVES

The range of pressure fluctuations and resulting air flows in a high-speed rail tunnel shall be determined. For this purpose, common features of tunnels and their operation conditions shall be identified. The aerodynamic and thermal conditions of these tunnels shall be modelled by varying key influential parameters considering their daily and yearly cycles. The parameters to be changed shall include length, inclination, rock/ground overburden, free cross-sectional area, train headway and train directions.

3. LIMITATIONS

Amongst others, the following aspects are NOT in the focus of this paper:

- Individual tunnels but generic cases only[1]
- All possible conditions and tunnels types but selected conditions and types only
- Pressures and air flows during immediate train passages but conditions shortly after trains have left the tunnel or have stopped
- Analysis of smoke propagation during fire incidents but of flow prior to incident only

4. MODELLING OF TUNNEL ENVIRONMENT

The environmental conditions inside a tunnel, i.e. the tunnel climate, are described, amongst others, by the temperature, the humidity, the pressure variations, the air velocity and the concentrations of dust, pollutants or natural gas. Heat from the ground, the technical installations and trains (traction power waste heat, air conditioning, etc.) influence the aero-thermal conditions. Additionally, the rate of air-exchange with the ambient via portals and shafts as well as the outside weather conditions determine the conditions inside tunnels (see Figure 1). The outside climate and the thermal behaviour of the ground are influenced by several parameters which vary from tunnel to tunnel. On the one hand, all these parameters would need to be evaluated for each individual tunnel. On the other hand, a categorisation of the tunnels allows insight into the dominant physical processes and a simpler extrapolation of results to tunnels which are not investigated in detail. Therefore, a generic analysis shall be undertaken by defining a reference case and variation of selected parameters.

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[1] The work at hand forms part of the Franco-German research project REHSTRAIN (see Chap. 9). Therefore, the study is based on typical parameters of high-speed tunnels of France and Germany; [Krokos, Wehner, 2017a/b]

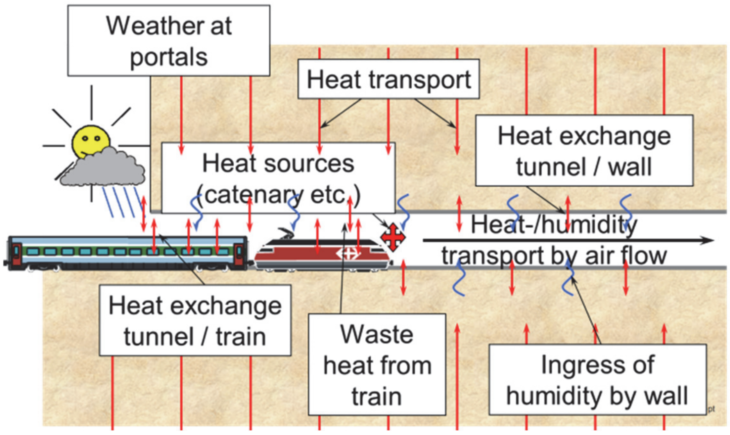


Figure 1: Factors affecting tunnel climate (tunnel environment)

Modelling the tunnel climate requires taking into account the following key phenomena:

- Pressure forces induced by moving trains and resulting motion of air
- Pressure forces induced by temperature/density difference between outside and inside
- Pressure force by meteorology (wind, pressure difference across mountain rims
- Heat and humidity transport by bulk motion of air including exchange of air at portals
- Heat sources in the tunnel (rolling stock, trackside equipment)
- Heat transfer between tunnel air, tunnel walls and surrounding ground/rock
- Heat transfer by condensation and evaporation of water at tunnel and train walls
- Heat transfer from and to trains

For the purpose of this study, the numerical codes THERMOTUN and THERMO are used:

- THERMOTUN (7) is a program for the simulation of aerodynamic and ventilation phenomena in rail and metro tunnels and based on the method of characteristics. Tunnel properties are modelled in a one-dimensional manner. The program allows modelling complex tunnel systems computing air velocities, pressure variations, traction power, temperatures, propagation of smoke and pollution in a tunnel. THERMOTUN is a development of Dundee Tunnel Research (www.thermotun.com).
- THERMO (2.1) is simulates the thermal conditions in rail tunnels. THERMO considers the thermodynamic interaction between trains, the tunnel air as well as the tunnel wall enabling the program to include heat transfer from the ground and the trains. Tunnel properties are modelled in a one-dimensional manner. The heat transfer in the surrounding rock is approached with a cylinder symmetric shell structure. When coupled with THERMOTUN the program includes the air-induced velocities and the heat load from trains (traction power, loss from catenary systems, auxiliary systems etc.). The computation of the humidity of tunnel air considers water ingress from the portals, the trains and the tunnel walls. The amplitudes of the yearly and daily temperature fluctuations at the portals are considered as well in order to provide a long-term analysis of the tunnel climate. THERMO is a development of HBI (www.hbi.eu).

In THERMOTUN and THERMO, the simulation domain is split into discrete elements. In THERMO, the tunnels are divided into segments and tranches, the latter being a subdivision of the former. The surrounding rock is divided into (generally) axisymmetric shells. The length of a shell is identical to the length of the tranche it belongs to.

THERMO is based on a forward Euler discretization using an explicit procedure. While this procedure imposes constraints on the ratio of the time step to the spatial step to ensure convergence, this constraint does not pose any problems for typical tunnel applications.

5. COMBINATION OF THERMOTUN AND THERMO BY MATLAB

In order to simulate the varying aero-thermal conditions in rail tunnels for a complete year, different time scales need to be considered:

- Simulation of the train aerodynamics requires high temporal resolution ("in range of less than seconds") resulting in long computation time.
- Simulation of the tunnel environment requires low temporal resolution ("in range of hours“) resulting in short computation time.
- Simulation of an entire year of tunnel operation for calculation of the distribution of up- and downwards directed thermal draught flows requires low temporal resolution ("in range of hours“), however, resulting in long computation time to cover a whole year incl. several years for prior convergence of the ground temperature distribution

The different simulation tools are integrated by MATLAB to the scheme shown in Figure 2.

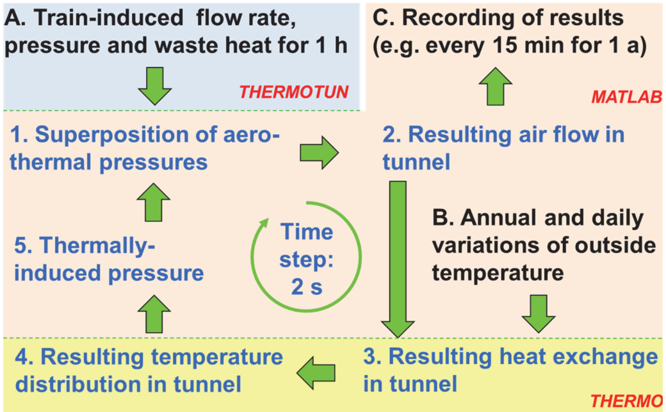


Figure 2: Loop of simulation using THERMOTUN, THERMO and MATLAB

The scheme allows an efficient computation of the tunnel environment considering the different relevant time scales and the purpose of the computations.

6. ASSUMPTIONS AND COMMON DATA

Assumptions and key parameters used for all simulations are given in Table 1 and Table 2.

Table 1: Assumptions for all calculation cases

Parameter	Assumption
Tunnel height profile / vertical alignment	Constant slope
Tunnel rock/ground overburden	Constant and uniform
Rock/ground properties (e.g. heat conductivity)	Constant in radial and longitudinal direction
Wind or barometric pressure difference on portals	None
Rock initial temperature profile	Constant along length
Outside temperature profile	Annual + daily sinusoidal curve
Train operation	Passenger trains with constant headway and velocity

Table 2: Constant parameters for all calculation cases

	Parameter	Data	
Ambient	Normal pressure at sea level	101.3	kPa
	Elevation above sea level	300	M
	Medium yearly outside temperature (Kassel/Lyon climate)	11.25	°C
	Annual amplitude	+/- 8.0	K
	Daily amplitude	+/- 3.5	K

	Parameter	Data	
Tunnel	Wall friction factor (Darcy-Weisbach)	0.021	---
	Wall density (concrete)	2000	kg/m^3
	Wall heat capacity (concrete)	880	J/kg/K
	Wall heat conductivity (concrete)	1.0	W/m/K
	Water seepage	0	g/km/s
	Equipment heat release	70	W/m
	Sum of pressure loss factors for both portals	1.6	---
Ground	Density	2700	kg/m^3
	Heat capacity	800	J/kg/K
	Heat conductivity	3.0	W/m/K
	Water seepage	None	
Train	Reference train type	Hypothetical multi-unit as 2-unit ICE3	
	Overall length	400	M
	Cross-sectional area	11	m^2
	Perimeter	11.5	M
	Surface area	4600	m^2
	Travel speed	250	km/h
	Skin friction factor (Darcy-Weisbach)	0.012	---
	Nose and tail loss coefficients	0.05 / 0.07	---
	Rolling resistance factor	0.00075	---
	Mass	900’000	kg
	Thermally active mass	60	% of mass
	Body heat capacity	450	J/kg/K
	Temperature at entry	Equal to outside temperature	
	Maximum traction power	16	MW
Kassel (D) and Lyon (F) taken as representative locations of the French-German high-speed rail networks.			

The objective of the numerical analysis is to study the sensitivity of the results regarding the main influential factors. A reference tunnel with standard train operation is defined. For the purpose of studying the sensitivity of results, variations from the reference case are introduced (see Table 3). All chosen parameters are based on the analysis of the typical range of tunnel parameters and typical parameters of trains and train operation.

Table 3: Variable parameters of the calculation cases

Parameter	Reference case		Variations
Tunnel length	3.0	km	1.5 km, 5 km, 7 km
Free cross-sectional area	80	m^2	40 m^2, 60 m^2, 100 m^2
Hydraulic diameter (coupled with cross-sectional area)	9.18	m	6.45 m, 7.95 m, 10.26 m
Inclination	1.25	%	0.5 %, 3 %, 4 %
Average uniform height of ground overburden	75	m	25 m, 150 m, 300 m
Initial ground temperature related to overburden height	13.5	°C	12 °C, 15.75 °C, 20.25 °C
Traffic type	Twin-direction		Single-direction
Number of trains	3 per h and direction		2 per h and direction
Traffic headway (coupled to number of trains)	20	min	30 min
Traffic staggering for opposite directions	10	min	15 min
Operating time per day	24	h	20 h

7. RESULTS

7.1. Aero-thermal conditions during a year of operation

Selected results are shown in this section in order to illustrate the steps during the analysis. Figure 3 shows the train induced-pressure fluctuations and resulting longitudinal air flow in the middle of the tunnel for the reference case during 1 h of train operation, i.e. with 6 train crossings with alternating direction. The results do not include any other impact, e.g. no impact of thermal draught, wind at portals, shafts, crossovers, etc. At individual tunnels, these other effects might become influential as well.

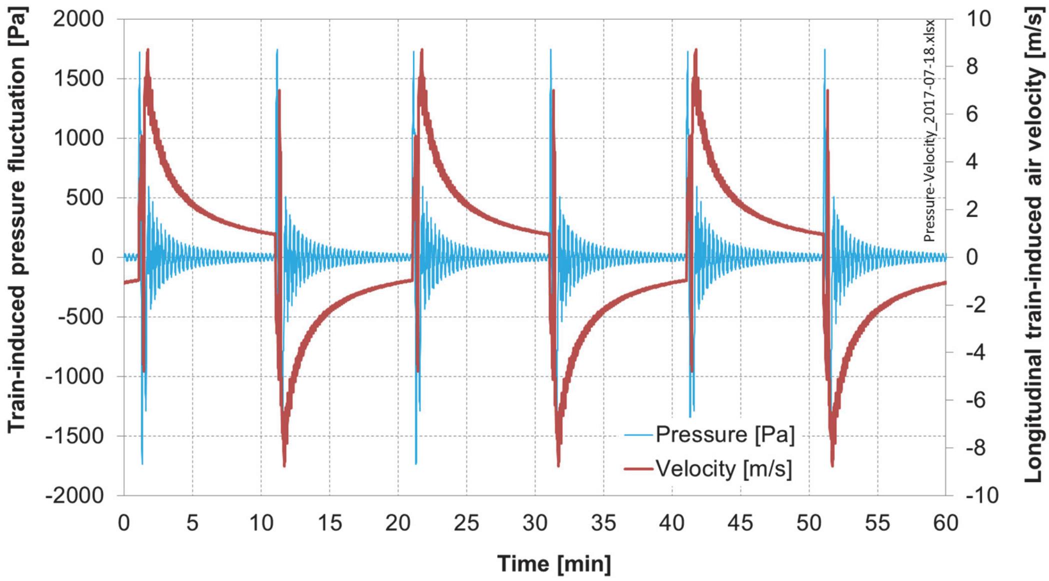
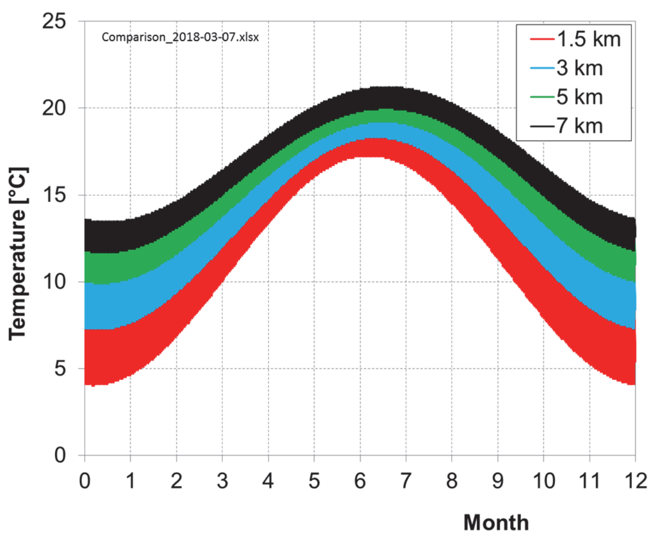


Figure 3: Pressure and longitudinal velocity of air in middle of tunnel (bi-directional traffic with 20 min headway for each direction)

The pressure patterns obtained with THERMOTUN as shown in Figure 3 are used as input for the computation scheme according to Figure 2. Here, the train-induced pressures are superposed with the thermal draught pressures and other meteorological pressures, if any. Two exemplifying results showing the averaged tunnel temperatures resulting from THERMO are shown in Figure 4 and Figure 5:

- Figure 4 shows the impact of tunnel length on the tunnel air temperature. As a general rule, the longer the tunnel is, the higher the temperature. In shorter tunnels, the daily and yearly oscillations of the temperature cover a larger range than in the longer tunnels.
- Figure 5 shows the impact of tunnel slope on the tunnel air temperature. Steeper tunnels lead to higher temperatures and the daily and yearly oscillation of the temperatures cover a larger range.



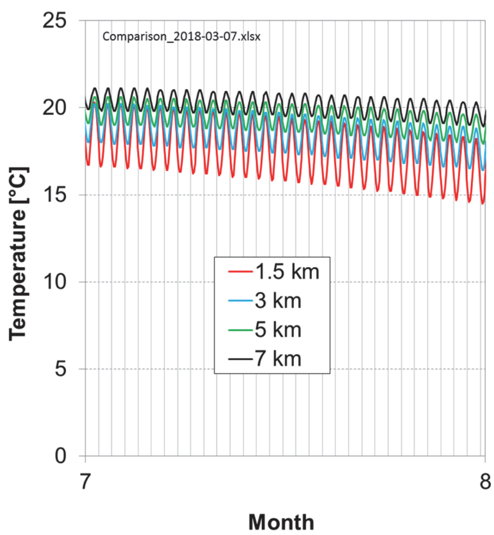


Figure 4: Average tunnel temperature for different lengths (left: 1 year; right: August only)

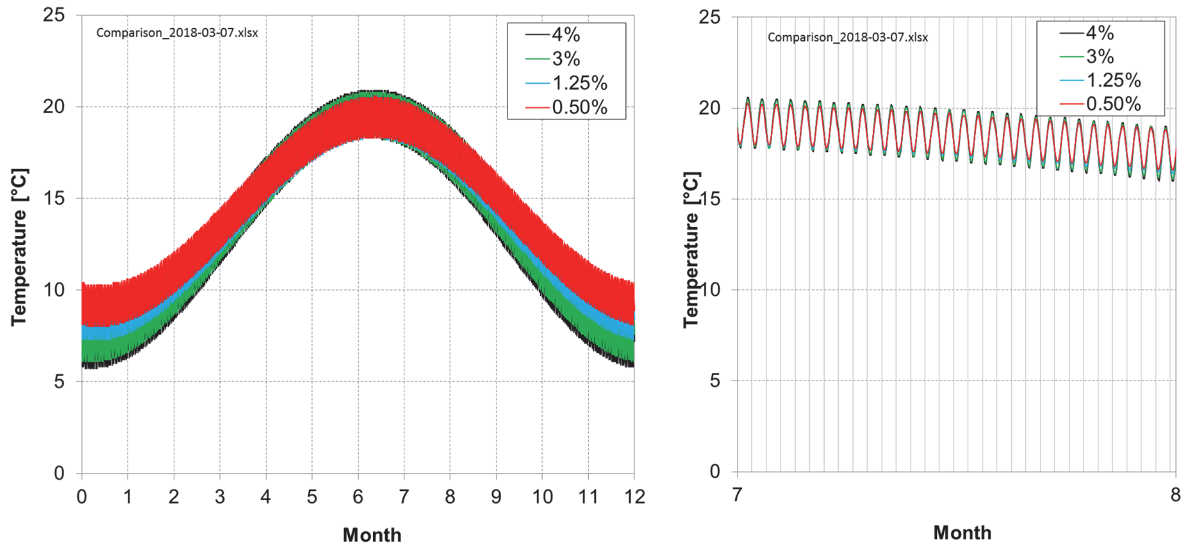


Figure 5: Average tunnel temperature for different slopes (left: 1 year; right: August only)

7.2. Resulting natural flow of air

For the statistical analysis, the flow velocities are taken at fixed time steps. In order to reduce the impact of velocity fluctuations during the immediate passage of a train, the flow velocity prevailing immediately before train entry is monitored for the statistical evaluation.

According to Figure 6, the shortest tunnel of the analysis (1.5 km) exhibits a downflow of air for approximately 40% of the operation time. With an increasing length of tunnels, the proportion of operation time with natural downflow of air decreases. The tunnel gradient supports extreme up- or downwards directed air velocities, however, the slope has no considerable impact on the frequency of up- or downflow.

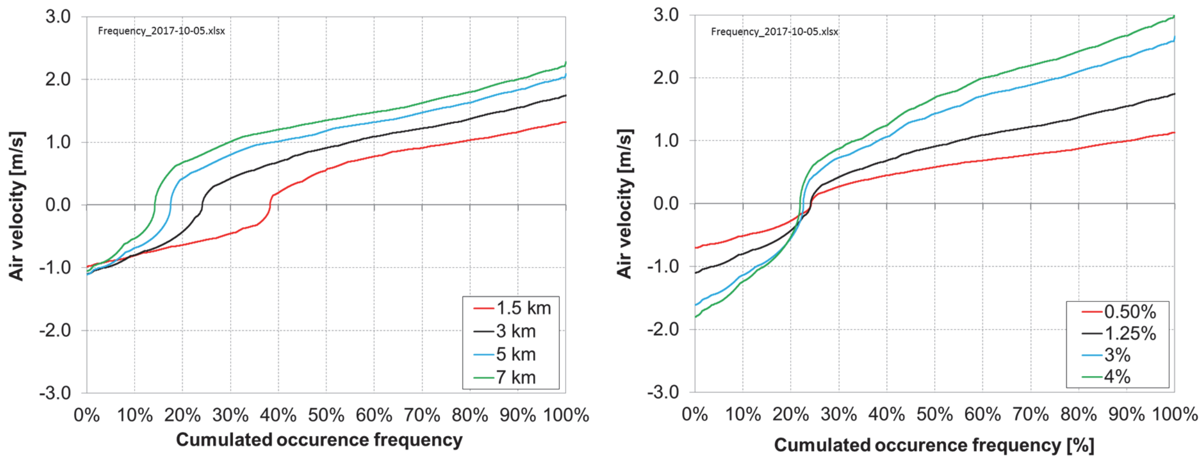


Figure 6: Occurrence frequency of natural air flow for different tunnel lengths and slopes (left: variable tunnel length; right: variable tunnel inclination)

In addition to the results for different lengths and slopes of the tunnel as shown in Figure 6, further parameters were analysed. Together, the consequences of these variations from the reference case on the natural flow in the tunnels are summarized in Table 4.

Table 4: Impact of varying tunnel parameters on natural flow (Parameter range of Table 2)

Variation of parameter	**Impact on downflow (thermal draught to lower portal)**
Increasing length of tunnel	Decreasing proportion of downflow; more extreme velocities
Increasing slope of tunnel	Almost no influence on proportion of downflow; more extreme velocities due to increase of "driving height" for draught
Increasing free cross-sectional area of tunnel	Slight increase of proportion of downflow; slightly more extreme velocities due to smaller flow resistance
Increasing ground / rock overburden	Decreasing proportion of downflow; almost no impact on velocities; Higher temperature due to higher overburden
Traffic "2 tracks up- and downhill" to "downhill only" to "uphill only"	Increasing proportion of downflow; almost no impact on velocities; "2 tracks up- and downhill" leads to lowest air-exchange and highest tunnel temperatures on average
Longer headway	Slight increase of proportion of downflow; no impact on velocity; "Longer headway" means less heat release from trains
"Traffic" to "No traffic"	Increasing proportion of downflow; no impact on velocity; "No traffic" means no heat release from trains
"20 h" or "24 h" operation	No significant impact
Modelling of ground / wall properties	Adiabatic walls: almost 50 % of operation natural downflow; "Isothermal wall" (wall at average annual outside temperature) about 30 % of operation with downflow; "Axisymmetric shells": about 25 % of operation time with natural downflow.

8. CONCLUSIONS AND SUMMARY

For the statistical distribution of natural air flows in rail tunnels prior to an incident and for the range of parameters investigated in this study, the following is noted:

- Short tunnels with small rock/ground overburden are likely to experience downflow.
- Longer and steeper tunnels experience higher natural flow velocities.
- The ground modelling (adiabatic, isothermal, etc.) has an impact on the flow statics.
- Fires in tunnels with natural ventilation include for substantial parts of operation time the risk of flow reversal (up to about 40 % of yearly operation time).
- Flow reversal as additional risk of fire incidents in inclined tunnels without mechanical ventilation should be considered as part of the fire safety assessment.

9. ACKNOWLEDGEMENT

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10. REFERENCES

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