OPTIMAL SMOKE EXTRACTION BY CONTROLING THE LONGITUDINAL FLOW VELOCITY USING A PUNCTUAL AIR SUPPLY OR EXTRACTION

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ABSTRACT

The 2,7 km long Saukopf-tunnel in Weinheim (Germany) is operated with bidirectional traffic and ventilated using a transverse ventilation system. This incorporates a continuous smoke extraction that enables to extract the smoke over the half or the entire tunnel length. In addition, the vitiated tunnel air can be extracted from the middle of the tunnel using the point extraction that can also perform smoke extraction. Due to the enforcement of the new German guideline on tunnel equipment of road tunnels (RABT-2003 [1]), the ventilation system has to be upgraded in order to cater for the more onerous requirements for the fire case. The distributed smoke extraction is to be replaced with localised smoke extraction using remote controlled dampers. Furthermore during the smoke extraction, a control of the longitudinal flow is recommended.

In this tunnel with bidirectional traffic, the most efficient smoke extraction is obtained, if the smoke is extracted such that air flows equally from both sides of the fire towards the extraction point situated above the fire. In order to enable a regulation of the longitudinal flow, new ventilation systems typically use jet fans. However due to civil constraints, this would be difficult to realize for this tunnel and consequently alternatives have been considered. One method is to enable air supply as well as extraction at the current middle extraction point. Furthermore, when smoke is extracted in one half of the tunnel, fresh air could be supplied in the other half. With these means, the flow velocity at the location of the fire can be influenced favourably.

In the present work, the theoretical framework for the control of the flow velocity using a punctual air supply or exhaust is developed. The analysis is tested by conducting one-dimensional non-stationary calculations with the in-house computer program SPRINT. Using a scenario approach, the concept for the control routines has been simulated, evaluated and optimised.

NOMENCLATURE

A	Cross section	[m²]
a	Coefficient equation (6)	[-]
b	Coefficient equation (6)	[m/s]
c	Coefficient equation (6)	[m²/s²]
c_w	Drag coefficient	[-]
D_h	Hydraulic diameter of the tunnel	[m]
L	Length of tunnel or tunnel section	[m]
n_{veh}	Number of vehicles	[-]
$Q_{Control}$	Flow rate at central fan building	[m³/s]
Q_{Fire}	Flow rate extracted at fire location	[m³/s]
$Q_{Supply,Distr.}$	Distributed supply-air rate	[m³/s]
u	Velocity	[m/s]
Δt	Time step of control routine	[s]

Greek letters

λ	Wall friction coefficient	[-]
ζ	Pressure-loss coefficient	[-]

Indices

i	Existing value
I/O	Portal Inlet/Outlet
j	Tunnel Section according Figure 4
s	Target value
T	Tunnel
veh	Vehicle

1. INTRODUCTION

Partly as a consequence of the tunnel fires in Mont-Blanc, Tauern and Gotthard, the last couple of years have focused on methods to improve the level of safety in road tunnels. One of the important aspects is the efficiency of the smoke extraction. This paper relates to the planned upgrading of the tunnel ventilation system of the Saukopf-tunnel.

In order to improve the efficiency of the smoke extraction, the distributed slots are to be replaced by remote controlled dampers situated every 50 m in the false ceiling that separates the tunnel from the extraction duct. Another significant conclusion of the recent Mont-Blanc fire, was that only if the longitudinal flow can be controlled is an efficient smoke extraction possible, which therefore has obtained due attention by upgrading the ventilation system of the Saukopf-tunnel.

It is normally not possible to install a sufficiently high extraction rate to adequately outbalance the forces due to stack effects, atmospheric influences etc. Consequently, the longitudinal flow has to be controlled using mechanical ventilation. This is typically done by means of jet fans. However, as this would cause considerably impact on the civil works and subsequent costs, alternative solutions were considered for the Saukopf-tunnel. The present paper describes the use of punctual air supply/extraction at the middle of the tunnel and its automatic regulation in order to control the longitudinal flow in the tunnel during a fire.

2. TUNNEL SPECIFICATION OF THE SAUKOPF-TUNNEL

The Saukopf-tunnel is part of the main road B 38a. It has been in use since 1999 as a two-way traffic tunnel. The main specifications of the single bore tunnel are as follows:

– Length	2'715 m
– Gradient	1,78 % from west to east
– Height above sea level	150 m
– Number of bores	1
– Traffic	19'000 vehicles/day; 6% trucks, bidirectional
– Escape routes	parallel rescue tunnel planned
– Control centre	unmanned, fully automatic

3. MODIFICATION OF THE VENTILATION SYSTEM

Original ventilation system

Figure 1 illustrates the existing transverse ventilation system and the central extraction that can be used in case of a fire in the Saukopf-tunnel.

Two ventilation ducts are situated above the traffic compartment. The smaller duct (4,5 m²) is used exclusively to supply fresh-air. Secondary pipes inside the tunnel wall lead fresh-air to outlets situated about 1 m above the road surface. The larger duct (8,2 m²) is used either to supply fresh-air or in the event of fire to extract smoke by reversal of the direction of flow. For this purpose, slots are located in the false ceiling every 10 m. Longitudinally, the tunnel is subdivided into two ventilation sections. Each section has a dedicated fan building situated at the portals. The fan building in the middle of the tunnel, the central fan building, serves as a central extraction unit.

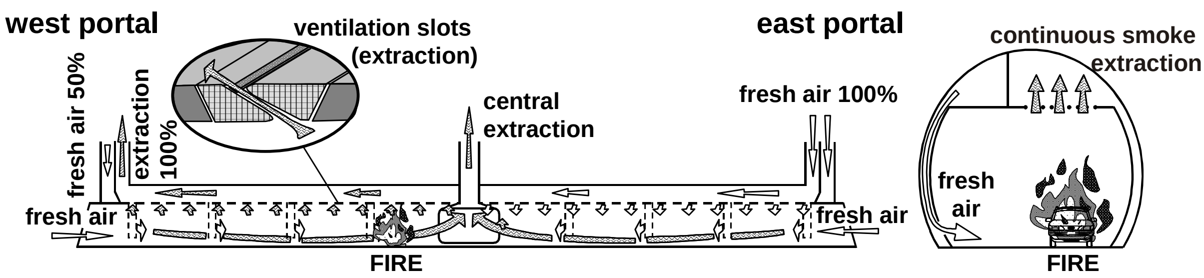

Figure 1: Existing ventilation concept of the Saukopf-tunnel in occurrence of a fire

At the portals, each of the two fan buildings contain one fresh-air fan with a 1,80 m impeller-diameter providing 52 m³/s (west) and 55 m³/s (east) fresh-air supply and one reversible fan with 2,24 m impeller-diameter providing either a fresh-air supply of 104 m³/s (west) and 110 m³/s (east) or an air extraction of 106 m³/s (west) and 112 m³/s (east). The central fan building incorporates two extraction fans with impeller-diameters of 3,15 m giving a maximum extraction capacity of 275 m³/s each. All fans are equipped with electro-mechanical blade pitch-angle adjustment in order to vary the airflow rate during operation.

Upgraded ventilation system

Having completed the planned upgrading of the ventilation system, Figure 2 shows the operation principle in case of fire. The separating wall in the exhaust duct near the central extraction unit will be removed in order to join both sections of the extraction ducts and hence enable extraction from both portal fan-buildings simultaneously. This duct then operates exclusively for smoke-extraction purposes and no longer for fresh-air supply. The slots originally situated in the false ceiling at distances of 10 m are to be sealed and remote controlled dampers installed at distances of 50 m.

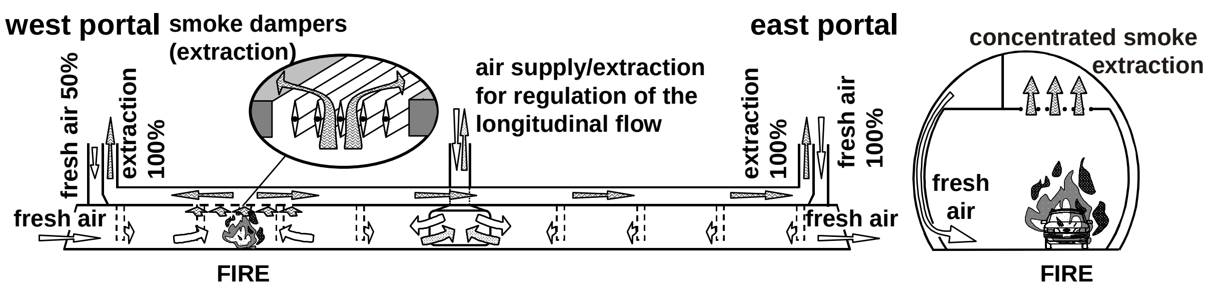

Figure 2: Planned ventilation system of the Saukopf-tunnel in occurrence of a fire

The reversible air extraction/supply fans at the portals then only operate in extraction mode. Moreover, the fans in the central fan building, which originally only operated in extraction mode, will be reversible so that fresh-air supply as well as air extraction is possible.

If the fire is close to the central fan building, then the fans located here will be used for smoke extraction. Otherwise, the remote controlled dampers, which are situated in the duct, near the fire are opened over a length of 200 m. Consequently, the concentrated smoke extraction is realised in the vicinity of the fire benefiting from the axial fans at both portals. Furthermore, fresh-air is supplied via the secondary fresh-air supply tubes integrated in the tunnel walls. In the tunnel section containing the fire, the fresh-air supply rate is reduced to about 50 %, in order to minimise fanning the fire but still ensuring a minimal fresh-air supply to the fleeing persons. Finally, the fans in the central fan building are used either in extraction or supply mode in order to control the velocity of the longitudinal flow in the tunnel.

4. THE REASON TO CONTROL THE LONGITUDINAL FLOW VELOCITY DURING SMOKE EXTRACTION

The upgraded ventilation system requires a new designated control concept for the fire ventilation. In order to test the envisaged parameters for the control system, various fire scenarios have been simulated. The computations of the one-dimensional flow, smoke and temperatures are conducted using the simulation program SPRINT (Smoke Propagation IN Tunnels). SPRINT was developed in order to assess effects of fires and has been validated with the experimental data from the Memorial-Tunnel Fire Tests. Furthermore, it was employed in order to develop the current ventilation concept of the newly refurbished Mont-Blanc tunnel. SPRINT computes the physical impact of significant parameters such as traffic, tunnel construction, ventilation system, traffic management etc. The stack effects due to the fire and natural temperature differences as well as atmospheric pressures are considered. More details about the computer model including validation cases can be found in [2] and [3].

As an illustration for this paper, selected 30 MW fire scenarios are described. The ventilation system after being upgraded and hence including the remote controlled dampers is considered. As a definition, the fire ignites at the time equals zero (t = 0). Prior to the ignition, a total of 1’950 vehicles per hour drive trough the tunnel of which 30 % drive eastwards (1’300 veh./h direction west→east and 650 veh./h direction east→west). A travel speed of 70 km/h and six percent heavy goods vehicles is assumed. As a result of the asymmetric traffic distribution, the piston effect of the vehicles causes a longitudinal velocity of 2 m/s, which ensures an adequate fresh-air supply. Consequently, during normal operation, no mechanical ventilation operates.

At the time equal zero (t=0 min), a fire breaks out 300 m from the west portal. In this case, the heat-release rate immediately increases from 0 to 30 MW and then remains constant at 30 MW. As a result of the fire, it is assumed that no vehicles pass the fire but come to a halt here. A lane occupation of 150 pcu[1]/km is assumed for the vehicles driving towards the fire and coming to a halt. Furthermore, it is assumed that vehicles come to a halt when encountering heavy smoke. On the other hand, vehicles that have passed the location of the fire drive out of the tunnel unhindered.

Three minutes after the ignition (t=3 min), the automatic linear heat detector, detects and locates the fire. As an automatic and immediate response, the traffic signs and bars close the entries of the tunnel. Furthermore, the automatic fire ventilation program is initiated.

In the vicinity of the fire, at 200 m to 400 m from the portal, five dampers open and 180 m³/s is extracted. Furthermore, in the western section 26 m³/s (= 50 % of the maximal available 52 m³/s) and in the eastern section the maximum 55 m³/s of fresh-air is supplied along the side wall and uniformly distributed over the length of each section. At the central fan building, 90 m³/s of fresh-air is introduced. 17 min of the fire ventilation is simulated i.e. until t=20 min.

Two wind and temperature scenarios are illustrated here. In the first case, balanced conditions are assumed i.e. no external wind forces and initially same temperatures inside the tunnel as outside, see Figure 3, 1a). In the other scenario (Figure 3, 1b), a resulting wind pressure of 10 Pa acts on the west portal and a natural higher temperature of the tunnel air than the ambient air of 10 K causes a natural stack effect. In scenario 1b the combined effect of these forces results in a pressure of 28 Pa assisting the flow from west to east. In the diagrams, the transient smoke spread, the longitudinal flow velocity at four positions (150, 300, 450 and 2'000 m) and the pressure difference due to the stack effect is shown. Furthermore, the maximum number of halted vehicles is sketched.

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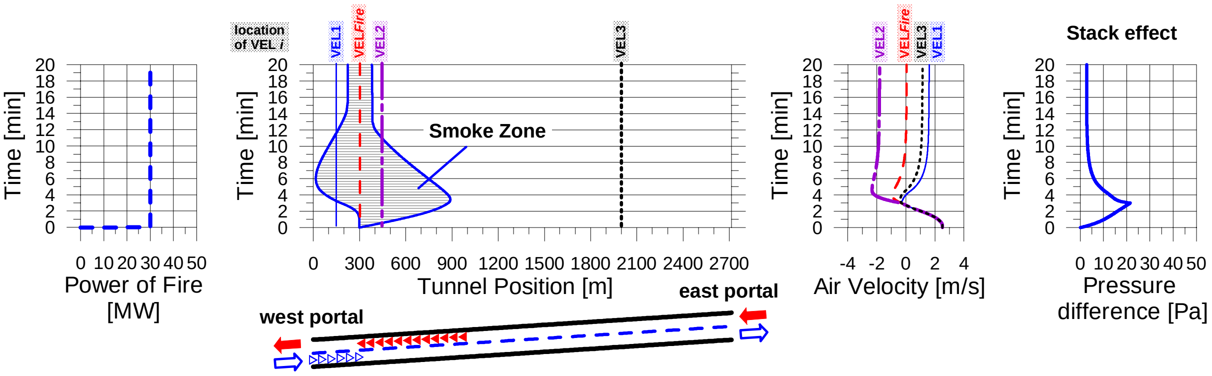
[1] pcu = passenger car units: one passenger car equals one pcu and one truck corresponds to two pcus.

1a) No wind pressure, No temperature difference



1b) 10 Pa wind pressure of west portal, +10 K temperature in the tunnel

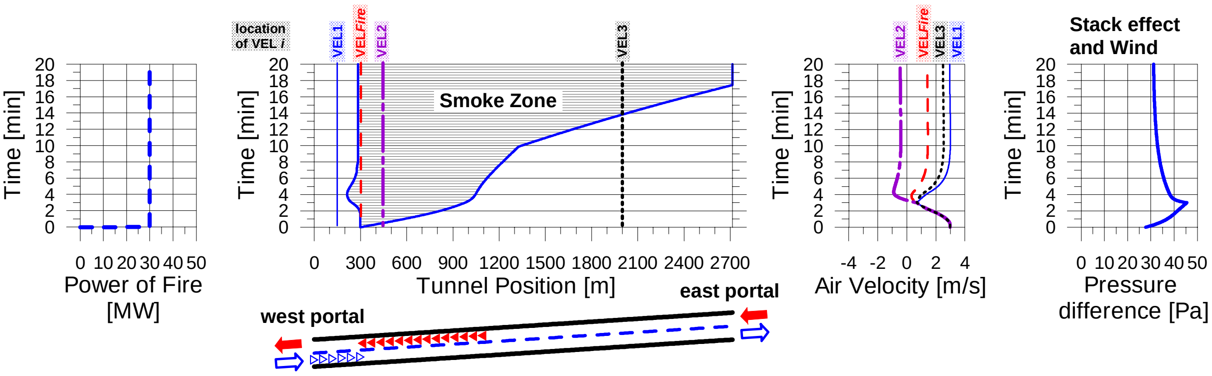


Figure 3: Two scenarios of a 30 MW fire located at 300 m from the west portal and with predefined settings of the ventilation system. 1a (top) is without external wind and temperature forces. 1b (bottom) is with external wind forces and a higher tunnel temperature than outside. ▷ = maximum number of vehicles entering west portal and brought to a halt by the fire or smoke. ◀ = maximum number of vehicles entering east portal and brought to a halt by the fire or smoke.

As seen in Figure 3 scenario 1a, the smoke extraction is close to ideal. Flow comes from both sides towards the extraction point and the flow velocity at the fire is close to zero. Smoke that has past the extraction point during the first minutes of the scenario is driven back and finally being extracted.

Applying the same settings for the ventilation system as in scenario 1a, a very disadvantageous smoke spread arises in scenario 1b, because of the different thermo-meteorological conditions. The asymmetric flows on both sides of the fire cause some of the smoke to pass the extraction point. Eventually, the entire tunnel section from the fire point to the east portal is filled with smoke. Due to the cooling of the smoke, it must be assumed that in the section near the eastern portal, the entire tunnel cross section is filled with smoke. Moreover, beyond the central fan unit, the longitudinal velocity is increased from about 0 m/s to about 2 m/s (VEL3), which causes the egress conditions to deteriorate rapidly. The smoke flows faster than many people can escape.

When comparing scenarios 1a and 1b, it can be concluded that it is impossible to obtain a satisfactory smoke extraction with fixed settings of the ventilation system. In order to cater for several conditions, two approaches are possible:

Option 1: for each extraction section (i.e. each damper) have several parameter settings at disposition depending e.g. on the longitudinal velocity at the time of fire detection.

Option 2: use the ventilation system to regulate the longitudinal flow and hence respond to time-dependent changes e.g. in heat-release rate and external forces.

The second option was chosen for the Saukopf-tunnel, as the influence from the traffic at the time of fire detection can be a dominating factor. In this case, the net effect of the external forces cannot be established.

5. REGULATION OF THE LONGITUDINAL FLOW VELOCITY

By controlling the longitudinal velocity, the smoke spread is minimised and the smoke extraction optimised. For this tunnel with bidirectional traffic, the flow should stream at about the same speeds from both sides towards the extraction point located above the fire. The smoke extraction is dimensioned in order to ensure a minimum velocity of 1,5 m/s towards the fire for any foreseeable situation.

In new tunnels, the control of the longitudinal velocity is normally achieved using jet fans. However, for the upgrading of the Saukopf-tunnel, this would have caused rather expensive civil works and in order to optimise the costs, alternatives were sought. The solution was to use the installed semi-transversal ventilation system injecting longitudinally distributed fresh air at the sides together with the central fan unit. The fans at the central fan unit are to be modified in order to be able to select between punctual fresh-air supply and air extraction at the middle of the tunnel.

6. THEORY

Figure 4 shows the theoretical model. The example depicts a fire in the left hand (western) tunnel section. For the analysis, the tunnel is subdivided into three sections (indices 1, 2 and 3). Section 1 extends from the left hand (west) portal to the fire; section 2 is from the fire to the central fan unit (in extraction or supply mode) and section 3 from the central fan unit to the right hand (eastern) portal.

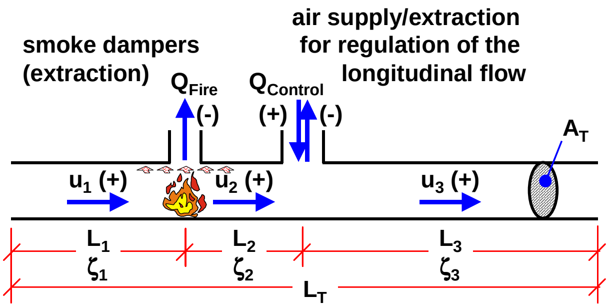


Figure 4: Illustration of model used for the theory applied in order to regulate the longitudinal flow using the central fan unit (supply or extraction).

L_j denotes the length and ζ_j the resistance coefficients (j=1, 2, 3). The values of the resistance coefficients (ζ_j) also incorporate the entrance and exit losses as well as the resistances caused by the halted vehicles according to equation (1).

$$\zeta_j = \zeta_{I/O} + \frac{\lambda \cdot L_j}{D_h} + \frac{n_{veh,j} \cdot (c_w \cdot A)_{veh}}{A_T} \qquad j = 1, 2, 3 \tag{1}$$

As an approximation, the model assumes that one lane of section 1 and 2 are fully occupied with vehicles, whereas section 3 contains no halted vehicles. The trucks are integrated in the term $(c_w \cdot A)_{veh}$.

The smoke extraction rate, Q_{Fire}, is modelled as being punctual, although in reality it is distributed over a distance of 200 m. In the equation, the value of Q_{Fire} is negative. The value of the flow rate at the central fan unit, $Q_{Control}$, which is used to control the longitudinal flow velocity in the tunnel, is positive in case of fresh-air supply and negative by flow extraction.

The feature with distributed fresh-air supply along the side walls is not modelled explicitly. However, as seen in Figure 6, the control model is very robust also with this simplification.

The objective to have identical flow rates from both sides towards the fire gives equation (2).

$$u_{1s} = -u_{2s}; \qquad u_{1s} > 0 \tag{2}$$

The model is formulated mathematically in equations (3) to (5). Equation (3) represents a pressure balance for the entire tunnel: the first three parts are the stationary terms and the succeeding three terms the non-stationary components required during the time Δt in order to change the velocity from the initial value (subscript '*i*') to the desired value (subscript '*s*'). Losses due to abrupt velocity gradients between the sections are ignored as well as variations in the fluid density. Equations 3 and 4 reflect the continuity between the sections (1 to 2 and 2 to 3).

$$\begin{aligned} &-\frac{\zeta_1}{2}\left(u_{1s}|u_{1s}|-u_{1i}|u_{1i}|\right)-\frac{\zeta_2}{2}\left(u_{2s}|u_{2s}|-u_{2i}|u_{2i}|\right)-\frac{\zeta_3}{2}\left(u_{3s}|u_{3s}|-u_{3i}|u_{3i}|\right)\\ &-\frac{L_1}{\Delta t}\left(u_{1s}-u_{1i}\right)-\frac{L_2}{\Delta t}\left(u_{2s}-u_{2i}\right)-\frac{L_3}{\Delta t}\left(u_{3s}-u_{3i}\right)=0 \end{aligned} \tag{3}$$

$$u_1 \cdot A_T + Q_{Fire} = u_2 \cdot A_T \tag{4}$$

$$u_2 \cdot A_T + Q_{Control} = u_3 \cdot A_T \tag{5}$$

Equation (3) can be reformulated to a quadratic equation as follows:

$$\begin{aligned} &a \cdot u_{3s} \cdot |u_{3s}| + b \cdot u_{3s} + c = 0 \qquad \text{mit} \qquad a = -\frac{\zeta_3}{2}; \qquad b = -\frac{L_3}{\Delta t};\\ &c = -\frac{\zeta_1}{2}\left(u_{1s}|u_{1s}|-u_{1i}|u_{1i}|\right)-\frac{\zeta_2}{2}\left(u_{2s}|u_{2s}|-u_{2i}|u_{2i}|\right)+\frac{\zeta_3}{2}u_{3i}|u_{3i}|-\frac{L_1}{\Delta t}\left(u_{1s}-u_{1i}\right)-\frac{L_2}{\Delta t}\left(u_{2s}-u_{2i}\right)+\frac{L_3}{\Delta t}u_{3i} \end{aligned} \tag{6}$$

Theoretically, equation (6) has four possible solutions. However, only one solution satisfies the sign of u_{3s}.

$$u_{3s} \geq 0: \qquad u_{3s\,1/2} = \frac{-b \pm \sqrt{b^2 - 4 \cdot a \cdot c}}{2 \cdot a} \qquad u_{3s} \leq 0: \qquad u_{3s\,3/4} = \frac{+b \mp \sqrt{b^2 + 4 \cdot a \cdot c}}{2 \cdot a} \tag{7}$$

In the computation, it is assumed that the measured flow velocity is not perturbed by smoke, which in practise means that the anemometer in the section that is not influenced by the fire is used. Furthermore, the measured value has to be corrected due to the distributed fresh-air supply, $Q_{Supply,Distr}$, in order to obtain u_{3i} according to equation (8). The values for the extraction rate at the fire, Q_{Fire}, and the flow rate at the central fan unit, $Q_{Control}$, are measured at the fans. However in order to derive the value of Q_{Fire}, the measurement at the fan has to be corrected for the leakage of the ducts and the closed dampers.

$$u_{3i} = u_{3Measurement} - \frac{1}{A_T} \sum_{Fire\ Location}^{Measurement\ Location} Q_{Supply,Distr.} \tag{8}$$

Using equations (2) and (4) as well as the value of Q_{Fire}, the values of u_{1s} and u_{2s} can be computed. The value of u_{3s} is derived using equation (7). Finally, from equation (5), the flow rate at the central fan unit, $Q_{Control}$, to use in the succeeding time step is determined.

7. RESULTS

Controlling scenario 1b (10 Pa portal pressure and 10 K higher tunnel temperature)

It is recalled that the initially decided fixed settings of the ventilation system resulted in an unsatisfactory smoke extraction, if an external wind pressure of 10 Pa acts on the west portal and the tunnel temperature is 10 K higher than ambient (scenario 1b). In Figure 5 (scenario 1c), scenario 1b is repeated applying the described control procedures. At the time of the fire detection (t=3 min), the fixed settings of the ventilation system are initially applied. The regulation of the longitudinal flow does not begin until one minute later (t=4 min), as the disturbances caused by the driving vehicles are too severe to obtain reliable flow measurements that reflect the physics of the system. During the regulation, time steps of 20 s were chosen. Running averages over 10 s of the measured flow velocities were applied.

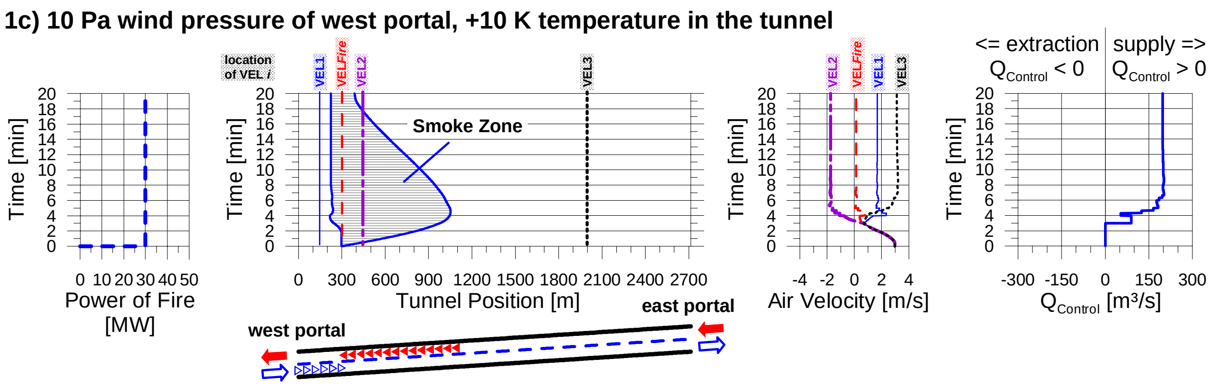


Figure 5: Scenario 1c: A 30 MW fire 300 m from the west portal in Saukopf-tunnel employing a regulation of the longitudinal flow using the central fan unit in extraction or supply mode. The same scenario though without the control of the longitudinal flow is illustrated in Figure 3.

Employing the regulation for about 1 min is adequate to stabilize the longitudinal flow at the location of the fire and hence obtain an ideal smoke extraction. The disadvantageous conditions shown in scenario 1b (Figure 3) have been outbalanced and the smoke is limited to the extraction region. In this case, a fresh-air supply of about 200 m³/s by the central fan unit is required.

Influence by the distributed fresh-air supply

In the theoretical model, the influence by the distributed fresh-air supply was initially omitted. However, as shown in Figure 6, the applied regulation is nevertheless very robust and can also cater for this phenomenon. Scenario 1b was re-analysed with three different fresh-air supply rates: a) with the envisaged 50% in the western section with the fire and 100% in the eastern section; b) no fresh-air in the eastern section but still 100% in the western section and c) without any distributed fresh-air supply in either section.

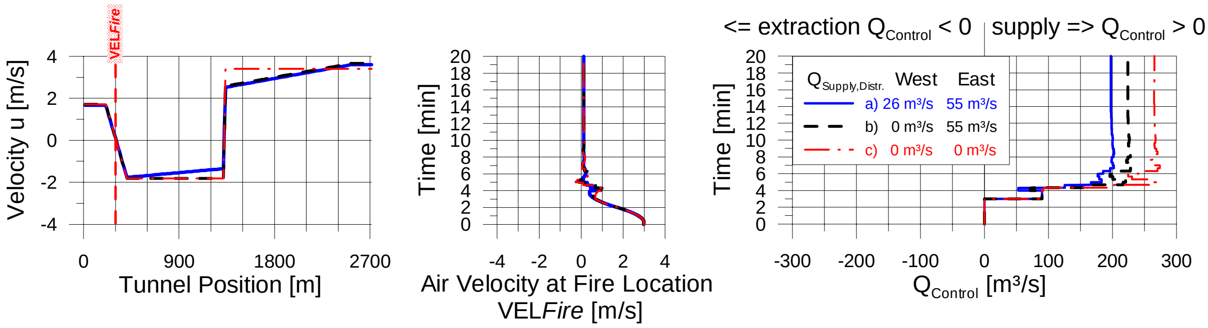


Figure 6: Influence of distributed fresh-air supply on the flow rate $Q_{Control}$ used to regulate the longitudinal velocity

As seen in Figure 6, the velocity distributions are very similar. Depending on the distributed fresh-air supply, the flow rate at the central fan unit, $Q_{Control}$, varies from 200 m³/s to 265 m³/s. As expected, the distributed fresh-air supply is beneficial, as it reduces the flow rate required by the central fan unit.

Realistic fire developments and the influence of other external factors

So far it was assumed that the fire immediately after ignition reaches its maximum heat-release rate of 30 MW, as this is the most critical assumption for the ventilation system. However, in order to test the robustness of the control routines, a slower increase and later a reduction of the heat-release rate were examined. Consequently, the public-bus fire from the EUREKA Firetun project [4] was assumed. Furthermore, other external parameters e.g. the wind pressure at the portals could change. In order to examine this phenomenon, a sudden portal-pressure increase of 50 Pa at the time t=10 min was assumed. Initially there are no pressures acting on the portals and no temperature difference to the ambient, as in scenario 1a.

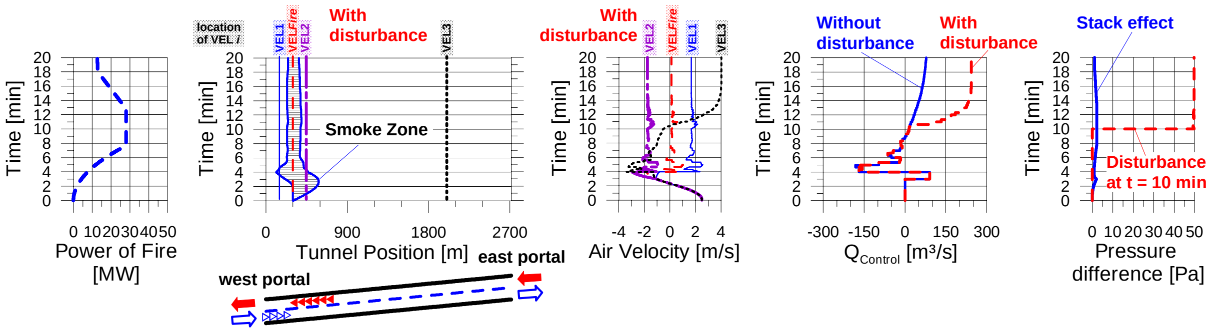


Figure 7: Realistic fire (public bus, EUREKA) and influence from large external disturbance

Figure 7 shows the time-dependent development of the heat-release rate of the fire (power of fire), the smoke development, the longitudinal air velocities, the flow rate at the central fan unit ($Q_{Control}$), and the pressure differences due to stack effect and wind. Finally, the extent of halted vehicles is also illustrated.

In comparison with scenario 1a: the slower development of the fire results in less smoke spread. The variation in heat-release rate is well mastered by the control routine and the stack effect is maintained low due to the high extraction rate of smoke and air at high temperatures. Furthermore, the sudden increase in portal pressure of 50 Pa is quickly i.e. within 1,5 min encountered for. Due to the control routine applied, no visible change of the smoke spread is caused by this large external disturbance.

8. CONCLUSIONS

The principal conclusions from the current study may be summarised as follows:

1. The computation of several scenarios using a model of the non-stationary, one-dimensional flow field is beneficial when testing the functionality of a tunnel ventilation system for the fire case and for the optimisation of the control procedures.

2. Fixed settings of the fans for the fire case can be problematic in particular for tunnels with higher longitudinal slopes or large variations in external forces due to atmospheric conditions e.g. wind or ambient temperature.

3. The control of the longitudinal flow in a tunnel using punctual air supply or extraction near the middle of the tunnel is very efficient. The desired longitudinal velocity, which is necessary in order to obtain an optimal smoke extraction, is quickly reached. Due to the outbalancing of the unfavourable external forces, an efficient smoke extraction is achieved.

4. The theoretical framework for the model for the control routines can be kept simple as long as all significant physical parameters are duly considered.

5. Using the described approach, the control algorithm is robust against variation with time of important influencing parameters such as heat-release rate and external forces (e.g. wind).

6. The parameters used for the control routines are object-specific and with respect to stability to be optimised individually.

7. For the control of the longitudinal flow, a distributed fresh-air supply at the tunnel side wall is advantageous.

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