# Ventilation Strategies in Case of Fire in Longitudinally Ventilated Two-Way Tunnels

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*Abstract*

There are recommendations on how a longitudinal ventilation system should be operated in case of a tunnel fire. In tunnels with uni-directional traffic, the common strategy is to maintain the traffic induced airflow. The strategy is to avoid back-layering of smoke by maintaining a minimum flow velocity. In tunnels with bi-directional traffic, the situation is more complex as vehicles may be halted on both sides of the fire.

This paper reviews some national guidelines and the new PIARC-report for fire-ventilation strategies in two-way tunnels.

A survey amongst ventilation specialists, who are familiar with the contents of the guidelines, lead to surprisingly different answers on how to ventilate for a given fire scenario. It was concluded that it is hard to prescribe one specific approach.

One section of the paper concentrates on the main influences on the smoke propagation. The emphasis is placed on the vehicle motion before and after ignition, tunnel length, fire location and tunnel inclination (to cater for the stack effect). It is argued that a regulation of the flow velocity in case of a fire is a difficult task. In many cases, it will hardly be possible to fulfil the recommendations.

Calculations of the smoke propagation for different ventilation strategies under equivalent conditions are shown. A comparison of the smoke propagation and the flow velocities in these cases leads to the choice of an optimal ventilation strategy for this particular fire scenario. Finally, a viable approach for the definition of a tunnel dependent ventilation strategy is described. In a tunnel with bi-directional traffic, it appears impossible to handle all possible fire scenarios. Nevertheless, the safety of the tunnel users is increased, if possible fire scenarios are considered carefully during the ventilation-design phase. This allows to prescribe an automatic control routine that can handle most real fires.

## Introduction

There are several recommendations on how a longitudinal ventilation system should be operated in case of a tunnel fire [1,2,3,4,5]. In tunnels with uni-directional traffic, the common strategy is to maintain the traffic induced airflow. Upstream of the fire, the incoming vehicles are halted due to heat and smoke. In order to keep the halted vehicles in a smoke-free zone, a minimal flow velocity (critical velocity) should be established and maintained. However, this paper is devoted to tunnels with bi-directional traffic, and tunnels with uni-directional traffic will therefore not be pursued any further.

In tunnels with bi-directional traffic, the situation is more complex as cars may be halted on both sides of the fire. Using a longitudinal ventilation system, it is not possible to prevent that some people are in or under the smoke.

## Recommendations for fire ventilation in two-way tunnels

The new PIARC-Report emphasises the importance of keeping the smoke stratification intact during the evacuation phase [1]:

- The longitudinal airflow should be kept ‘quite small’.
- In the smoke zone, no jet fans should operate.
- A flow reversal due to the ventilation should be avoided, even if the fire is located near a portal.

When the evacuation phase is concluded, fire fighting must be facilitated by proper smoke handling. One requirement is to ensure a smoke free access from one side of the fire (no back-layering).
The new French recommendation [2] gives a more specific value for the flow velocity during the evacuation phase. With bi-directional traffic two phases are compulsory: in the evacuation phase, the flow velocity should be as low as possible in order to maintain stratification and enable evacuation of users on both sides of the fire. In the fire-fighting phase, it may be necessary to reach the design velocity (usually the critical velocity).
The Austrian recommendation [3] states that in order to chose the optimal ventilation strategy, one needs to consider parameters such as the fire location, the traffic (volume, velocity and main direction), the airflow velocity and the location of the jet fans. The flow velocity in the tunnel should be reduced to 1.0-1.5 m/s so that the emergency exits are kept free from smoke.
The German RABT [5] recommends that in order to keep the stratification, the airflow should not forcibly be reversed and the flow velocity should not exceed 2 m/s. The ventilation should not be switched off until the fire fighters arrive at the location.
These recommendations imply that:

- the fire has a minimum heat-release rate giving rise to a stratified layer of smoke,
- the spread of smoke is limited and there is no change in the flow direction,
- the control of a predefined flow velocity in the tunnel is possible.

## Defining a ventilation strategy - a survey

A survey amongst ventilation experts was held in order to determine how a ventilation system should be operated for three fire scenarios. The answers lead to a variety of strategies.

The length of the tunnel was proposed to be 2 km. The presence of emergency exits was not specified. The traffic volume was 600 vehicles from left to right, and 300 from right to left. The travel speed of the vehicles was 60 km/h. The inclination of the tunnel and the location of the fire were varied:

| | Inclination<br>Left - Right | Location<br>from Left Portal |
|---|---|---|
| A | 0 | 500 m |
| B | 0 | 1500 m |
| C | 5% downwards | 1500 m |

Table 1: The fire scenarios in the survey for a 20 MW fire

The answers on "how to ventilate" during the evacuation phase in these scenarios were:

A: No airflow, no jet fans, preserve stratification.

B: 1.5 m/s longitudinal airflow, maintain stratification, avoid flow reversal.

C: No back-layering – higher velocity to keep the smoke on one side of the fire.

D: 1.0 to 1.5 m/s; keep stratification, in case ‘c’ reverse flow downhill – nearer portal.

E: Stop all fans.

F: ‘a’, ‘b’: keep fans off, ‘c’: critical velocity downwards.

It was agreed that the parameters which should be taken into account include: traffic density, initial airflow, number of cars in the tunnel, tunnel length, number and location of fans, turning cars, the heat release rate of the fire, smoke dilution and control of jet fans. In reality, however, it is very difficult when not impossible, to obtain reliable real-time information on most of these parameters.

It is very hard to prescribe one specific approach. The problem is how to ensure the low velocity during a fire. Basing the control routine on a prescribed velocity is not a viable approach as the closed loop control of the jet fans would be very difficult.

## Influences on smoke propagation

Smoke dispersion in a road tunnel depends on a series of parameters. Most of these parameters remain constant during a fire. Examples are:

- the location of a fire inside the tunnel,
- the tunnel geometry: length, inclination, cross-section,
- barometric pressure differences between the portals,
- wind pressure on one portal (might though change during the fire),
- the installed ventilation capacity and the position of the fans.

However, other parameters vary during the incident.

- The size of the fire may vary rapidly. The heat-release rate is essential for the critical velocity and for the buoyancy forces (if there is any inclination of the tunnel).
- The number of cars in the tunnel, their travel velocity and the number of halted cars inside the tunnel influence the airflow. These parameters change dramatically during the first minutes, depending directly on the location of the accident, the tunnel length, traffic volume and the traffic-control system.
- The fire-detection time is of particular importance. It determines the number of vehicles that are inside the tunnel.

Therefore, it is essential to consider a number of scenarios in order to find a tunnel-specific strategy for two-way tunnels with longitudinal ventilation. Especially the fire-detection time is a parameter that is difficult to estimate. This parameter is of importance, as the fire scenario has to be classified from a few measured parameters (flow velocity, fire location, traffic...) and the best ventilation strategy chosen accordingly.

In the next section, we discuss some of these factors which strongly influence smoke propagation. The following factors have to be considered to elaborate on a ventilation strategy: traffic volume and dominant direction, fire-detection time, fire location, tunnel length, inclination and atmospheric pressure difference between the portals.

**Traffic**

An often neglected factor is the traffic situation just before and after the onset of the fire. The traffic influences the flow velocity due to the piston effect. Therefore the airflow is influenced by the main direction of the traffic, the traffic volume, the travel velocity of the vehicles, the proportion of heavy traffic and the behaviour of the drivers after the onset of the fire (traffic control).

It is important to have an idea of the variation of traffic with time in order to identify the impact of incidents involving a fire in a tunnel [6]. The vehicles moving ahead away from the accident are not affected and leave the tunnel at constant velocity. Vehicles moving towards the accident cannot pass the fire location due to halted vehicles, heat and smoke. As long as there is no red traffic light at the portals, the number of vehicles moving in the direction of the fire drops relatively slowly until the halted cars occupy the tunnel between the fire and the entrance. The moving vehicles continue to push the tunnel air forward.

Figure 1 shows the flow velocity over time in a 2000 m long tunnel with bi-directional traffic. The tunnel has no inclination. The calculations are based on a one-dimensional simulation of the unsteady processes, including smoke propagation due to the gravity-driven flow of a hot smoke layer under the ceiling. It gives no indication on whether or not the smoke remains stratified adjacent to the ceiling. The results show merely the position of smoke fronts on both sides of the fire. The model used for the calculations shown in this paper is described in [7].

The results show flow velocities and positions of the smoke limits over time for various traffic scenarios. The solid lines represent a scenario with a traffic volume of 600 veh/h from left to right and 300 veh/h in the opposite direction. The fire starts at t=0. In these examples, the fire is not detected and the ventilation remains switched off.

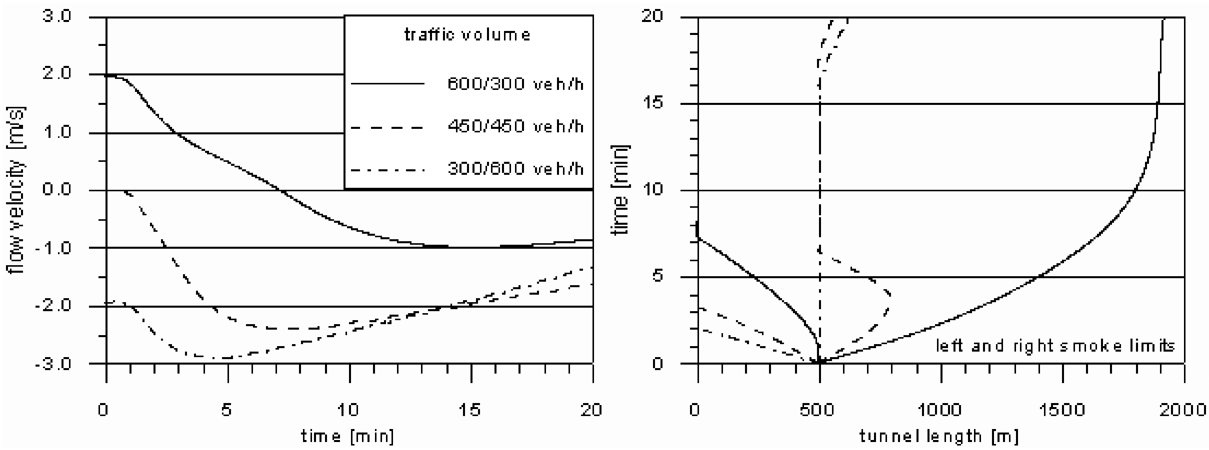

Figure 1: Flow velocity and smoke limits for a 20 MW fire located at x = 500 m, the vehicle speed was 60 km/h and the traffic distributions varied.

During the first minute after ignition, the flow velocity is insignificantly influenced by the fire. When the vehicles that have already passed the fire leave the tunnel, the influence of the fire location becomes visible (see Figure 2). As the smoke spreads inside the tunnel, the part of the tunnel where vehicles are moving decreases. This causes further changes in the flow velocity. The smoke propagation in these three scenarios is rather different. The solid line shows a smoke propagation where only 100 m of the tunnel remain smoke free during 20 min from ignition. The traffic volume and traffic main direction determine the initial flow velocity and the initial smoke propagation. The traffic causes changes in flow velocity or even a flow reversal after 2 to 7 min. Then, the smoke might already have propagated over several hundred meters.
After the detection of a tunnel fire, we assume that traffic lights inhibit further vehicles from entering the tunnel. Hence, the number of vehicles that are in the tunnel is a function of the traffic volume, the tunnel length and the fire detection time. This is shown in Table 2 for a constant traffic volume of 900 veh/h and a travel velocity of 60 km/h.

| Tunnel length | 300 m | 1000 m | 2000 m | 3000 m |
|---|---|---|---|---|
| Vehicles trapped in tunnel at the begin of the fire | 3 | 8 | 15 | 23 |
| Entering vehicles per minute | 15 | 15 | 15 | 15 |

Table 2: Number of vehicles trapped in the tunnel after the fire started.
If the fire-detection time is short and the traffic lights at the portals inhibit further vehicles from entering the tunnel, the number of people involved is minimised.

**Fire location and tunnel length**
Calculations for the same 2000 m long tunnel with bi-directional traffic (Figure 2) show that depending on fire location, the time evolution of the flow velocity may be completely different. In the calculated scenario, the flow is reversed, if the fire location is close to the left portal (x<500 m); whereas with the fire located near the other portal, the airflow is further enhanced for some time. The vehicles can only move between the entrance portal and the fire location. If the fire location is close to one portal, the piston effect of the vehicles that enter this portal is fairly reduced. Therefore, the traffic tends to push the smoke to the nearer portal. The broken lines

in the right diagram show no back-layering even though the flow velocity is below the critical velocity. This is due assumptions for modelling of the flow in the vicinity of the fire. In reality, a small zone with back-layering has to be expected in these cases.

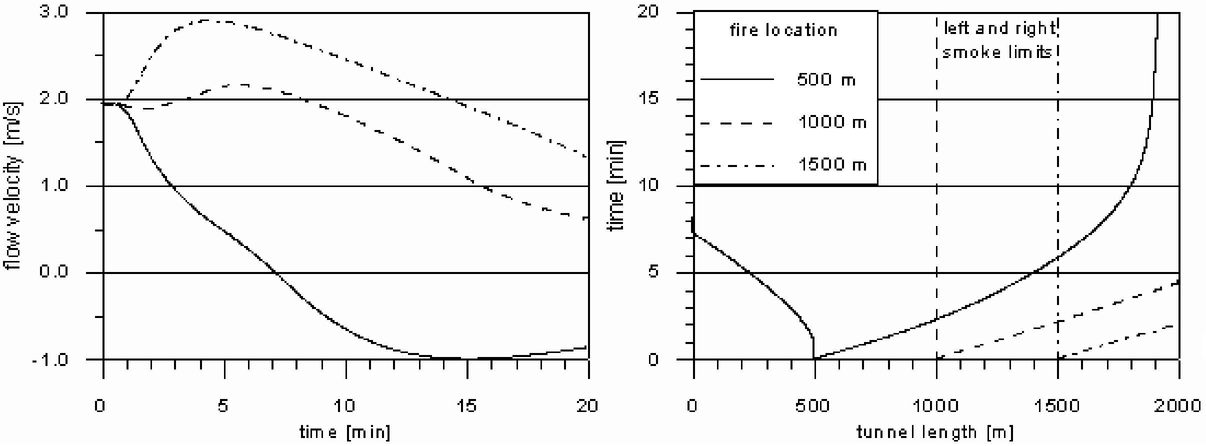


Figure 2: Flow velocity and smoke limits for a fire in a 2000 m tunnel with two-way traffic at 60 km/h, three fire locations and a traffic distribution of 600/300 veh/h.

The piston effect of the traffic remains important for several minutes after the traffic lights prevent further vehicles from entering the tunnel. A generally valid statement about which side of the tunnel will be filled with smoke is therefore not possible. In order to select an optimised ventilation strategy, the expected time variation of the airflow has to be investigated for each tunnel and for several traffic and fire scenarios.

**Tunnel inclination**

Buoyancy forces can mostly be neglected for tunnel ventilation under normal operating conditions. A fire may lead to high temperature differences and thus to an airflow towards the upper portal. The importance of this airflow depends on the size of the fire and the inclination of the tunnel.

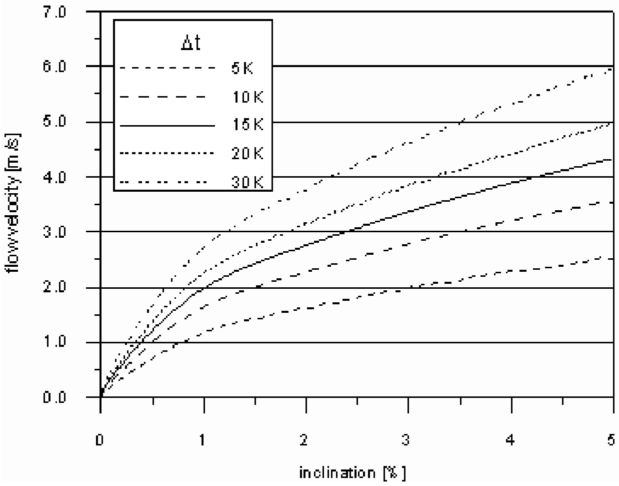


Figure 3: Flow velocity in a 2000 m tunnel versus tunnel inclination as a function of the temperature difference Δt.

In the literature there is only little information about smoke propagation in tunnels with considerable slopes. Figure 3 shows theoretical values for the longitudinal airflow depending on the difference between the average temperature of the tunnel air and the temperature of the surroundings outside the tunnel Δt. Note that this parameter depends on the tunnel length, and the values plotted refer to a 2000 m long tunnel without traffic and insignificant atmospheric pressure difference between the portals. Figure 4 shows a simulation of a fire scenario in a 2000 m two-way tunnel for different inclinations of the tunnel tube. It is assumed that the fire is not detected and vehicles continue to enter the tunnel. 15 min after ignition, the left part of the tunnel is filled with vehicles that have come to a halt. 7 min later, the right part of the tunnel is filled with vehicles as well. Without inclination, the flow velocity in the tube decreases rather slowly (compare the dashed line in Figure 2). With a downward inclination of 2%, smokes starts to move to the left side of the fire about 10 min after ignition. Flow reversal occurs only a little later. With a downward inclination of 4%, the smoke starts to propagate to the left of the fire about 5 min after ignition.

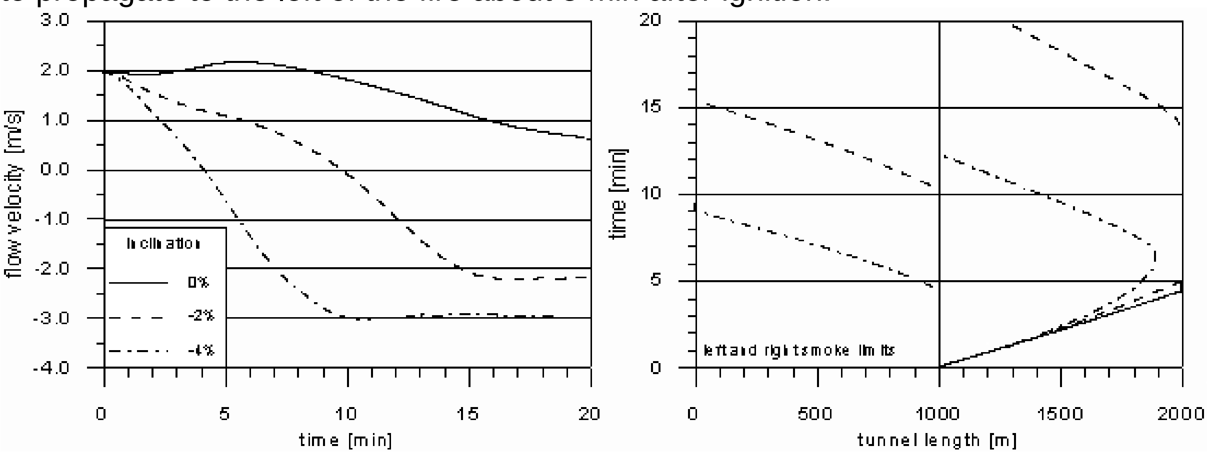


Figure 4: Flow velocity and smoke limits for a 20 MW fire, two-way traffic, 600/300 veh/h at 60 km/h, fire location at x=1000 m.

The velocity generated by the stack effect is at the same order of magnitude as the critical velocity. Therefore, only when considering the stack effect is it possible to analyse the fire ventilation of tunnels with inclinations exceeding 1-2%.

**Meteorological pressure difference**

Two meteorological effects can influence the airflow in a tunnel:

- Wind pressure at the portal
- An atmospheric pressure difference between tunnel portals (‘barometric barrier’)
- Stack effect due to a temperature difference between tunnel and ambient air without fire

Wind pressure can lead to a considerable airflow inside a tunnel depending on the wind force and the orientation of the portal towards the wind direction. On the other hand, atmospheric pressure differences have mainly relevance for longer tunnels in the mountains.

The amount of the wind pressure on a portal is about 60% of the dynamic pressure, if the wind direction is normal to the portal. When estimating the wind pressure that has to be taken into account, we analyse the wind velocities. A wind velocity of 2 m/s normal to a portal results in a wind pressure of 1.4 Pa which leads to a air flow velocity of about 0.7 m/s inside a two-lane tunnel which is 2000 m long. A typical wind-velocity distribution is shown in Figure 5.

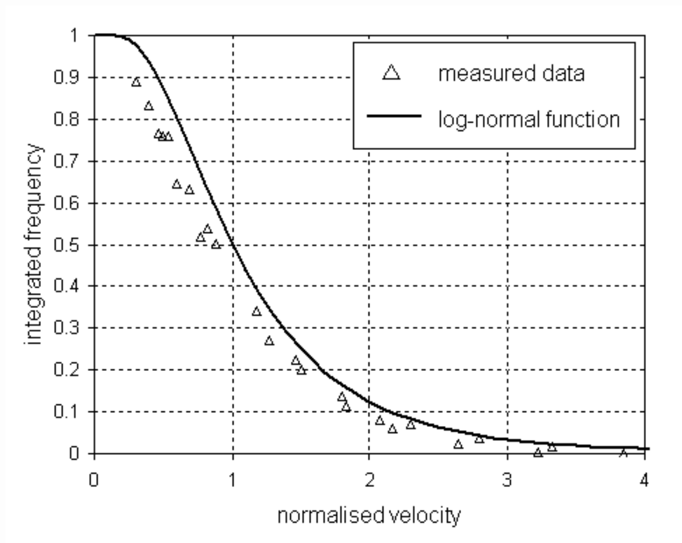


Figure 5: Typical distribution of wind velocities, normalised with the average velocity [8].

Only about 12% of the wind velocities are more than twice the average velocity. Therefore, the likelihood of having extreme wind pressure concurrent with a tunnel fire is rather low.

We described some of the influences on the airflow during the first few minutes after a fire starts in the tunnel. The time scales during which the flow velocity is changed by these effects are at the same order of magnitude as the time jet fans need to change the velocity. We come to the conclusion that a closed-loop control of a prescribed flow velocity by means of jet fans is not feasible in most tunnels. The number of jet fans used in a fire scenario has to be determined during the definition of the ventilation strategy. The probability of different fire scenarios has to be taken into account.

A tunnel fire should be detected as quickly as possible (at the most two minutes after a strong rise of heat and smoke production). The fire location can be detected by means of a linear heat sensor.

## An example fire scenario

As an example, we consider one of the fire scenarios that are shown in Figure 1. The tunnel is 2000 m long and has no inclination. Initially, 600 veh/h travel from left to right and 300 veh/h from right to left. All vehicles travel at a speed of 60 km/h. A 10 MW fire starts at x=500 m. Two minutes later, the fire is detected, traffic lights at the portals switch to red and the ventilation starts. Figure 6 shows results of a one-dimensional simulation of the smoke propagation. The velocities for different ventilation strategies are shown in the left diagram and corresponding smoke limits to these strategies in the right diagram.

Due to the piston effect, the simulation starts with an initial flow velocity of 1.9 m/s. The velocity drops when the lanes are partially blocked by the fire. Two minutes after ignition, traffic lights at the portals inhibit further vehicles from entering the tunnel. 1.5 minutes later, all vehicles in the tunnel are at rest. This fact is seen in Figure 6 (left) as a bend in the velocity-time function. Without ventilation, the flow velocity decreases slowly. For both directions, 4 jet fans are sufficient to rise the flow velocity to reach the critical velocity. 3.5 min after ignition, there are about 42 vehicles in the tunnel (25 left and 17 right of the fire). A flow velocity of 1.2 m/s can be reached with 1 jet fan in operation.

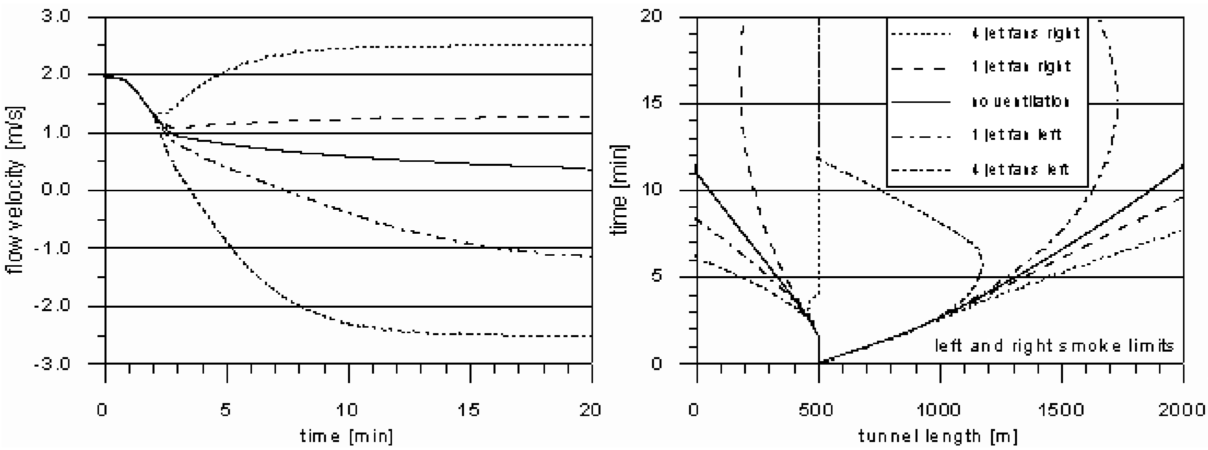

Figure 6: Flow velocity and smoke limits for a fire in a 2000 m tunnel, 600/300 veh/h at 60 km/h and different ventilation strategies.

Smoke spreads on both sides of the fire due to the gravity-driven flow of the hot smoke layer under the ceiling. Without ventilation, the entire tunnel is filled with smoke 11 min after ignition. With 4 jet fans blowing to the right, smoke reaches the right portal 8 min after ignition. Three minutes earlier that without ventilation. On the other hand, the left part of the tunnel remains free from smoke. With 4 jet fans blowing to the left, the smoke propagation to the right is stopped after 700 m and the flow is reversed. 6 min after ignition, the left smoke front reaches the portal. With one jet fan blowing to the left, the average air flow is reversed 7 min after ignition. The left smoke front reaches the portal one minute later. The right smoke front does not reach the portal, but it comes as close as 300 m from it.
In our opinion, the best ventilation strategy in this case would be to use one jet fan blowing to the right. The flow velocity is kept at 1.2 m/s and there is no flow reversal. Compared to using no ventilation, the propagation of the right smoke front is only a little accelerated. The smoke front reaches the portal about 9-10 min after ignition. The left smoke front is stopped 300 m away from the fire. As the flow velocity is small, a smoke stratification is probably maintained. The use of only a few jet fans keeps the flow velocity from reversing. On the other hand, due to the low velocity, smoke stratification is only insignificantly disturbed. For the choice of the best ventilation strategy, various fire scenarios have to be considered. The simulation shown in Figure 6 is just one of them.

## A matrix of fire ventilation strategies

The matrix of possible fire-ventilation strategies depends on the geometric boundary conditions like inclination profile, tunnel cross-section, the number and position of jet fans. On the other hand, the matrix depends on the information that can be obtained and feed to the control routine, such as fire location, flow velocity, traffic volume and other parameters.
As an example, we consider tunnel that is divided into three sections of equal size by the fire detection system. Two groups of jet fans are installed in section 1 and two groups in section 3 (Figure 7). The fire detection gives the tunnel section that is involved in the fire. The exact position of a fire remains unknown. One velocity measurement is installed in the tunnel. A matrix of possible ventilation strategies is given in Table 3.

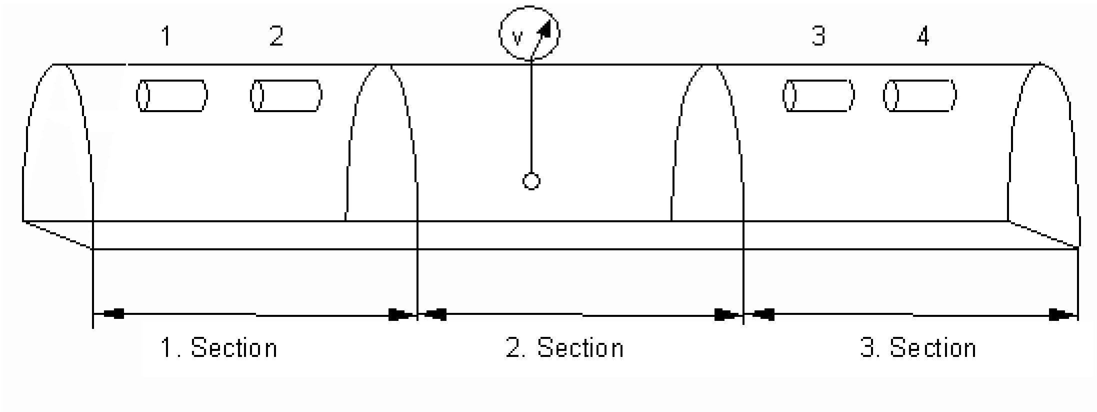


Figure 7: Tunnel scheme.

| | Flow velocity < 0 | Flow velocity ~ 0 | Flow velocity > 0 |
|---|---|---|---|
| Fire in section 1 | | | |
| Fire in section 2 | | | |
| Fire in section 3 | | | |

Table 3: A simple matrix of nine ventilation strategies.

In most tunnels with low traffic volume, the number of vehicles is not measured. Therefore, the traffic volume and traffic main direction is not considered, when the ventilation strategy is chosen. Furthermore, the time between ignition and fire detection and the fire size are not considered. Obviously, it is not possible to measure this parameter. The choice of a ventilation strategy cannot be determined by a parameter that is not measured. As these parameters are nevertheless needed to determine the ventilation strategy, they have to be estimated during the design phase of the ventilation control routine. The fire scenarios have to be weighted with their probability in order to define the ventilation strategies of the matrix. The ventilation strategy has to cover the most and the most likely scenarios.

## Outlook

Research work is needed in order to improve the existing models for smoke propagation in tunnels. Models that can be used to design tunnel ventilation should be fast, reliable and easy to use. These models have to predict the smoke propagation. Simulations of tunnel fires have to take the main external influences on the smoke propagation (time-varying traffic, stack effect, ventilation etc.) into account. One-dimensional and zone models have limitations due to a simplified analysis, especially close to the fire. However, in order to define a matrix of ventilation strategies, numerous simulations have to be performed. Therefore, for ventilation design, one-dimensional or zone models appear more advantageous than complex CFD-models.

## Conclusions

Considerations of the influences on smoke propagation and simulations of various fire scenarios lead to the following conclusions:

- The fire-detection time should be kept as small as possible. After fire detection, traffic lights should inhibit further vehicles from entering the tunnel and thereby minimise the number of people involved.
- Depending on the location of the fire, the piston effect may lead to flow reversal during the first few minutes after the ignition of a tunnel fire.
- Depending on the heat-production rate of the fire and on the inclination of the tunnel tube, the stack effect may lead to a flow reversal during the first few minutes after the ignition of a tunnel fire.
- In order to chose the best ventilation strategy in case of a tunnel fire, the momentary flow direction, the fire location, the inclination of the tube, a number of fire sizes and a traffic volumes should be taken into account.
- This leads to a tunnel-specific matrix of probable fire scenarios with a need of an individual treatment of each, which need to be considered in the control routine.
- In a tunnel with bi-directional traffic, it appears impossible to control all fire scenarios. There is always a risk of choosing the wrong ventilation strategy. Nevertheless, the safety of the tunnel users is increased if possible fire scenarios are considered carefully during the ventilation-design phase. This allows to set an automatic control routine that can handle most real fires.

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## Key Words

Tunnel, Fire, Smoke, Ventilation, Control, Jet Fan, Longitudinal Ventilation, Fire Scenario, Temperature