OPTIMISATION OF VENTILATION IN THE CASE OF A FIRE IN ROAD TUNNELS

Stosch R.\textsuperscript{1}, Wehner M.\textsuperscript{1}, Brandt R.\textsuperscript{2}
HBI HAERTER AG, Tunnel Ventilation
Heidenheim\textsuperscript{1}, D and Zurich\textsuperscript{2}, CH

ABSTRACT
The control of the tunnel ventilation in a 2.7 km long dual bore tunnel in the event of a fire has been optimised. In particular, the conditions for the evacuation phase of self-rescue are addressed. Besides the requirement for smoke control in the affected tunnel with the fire, a fixed plan is normally defined for the ventilation of the unaffected tunnel during an emergency. However, as shown in this paper, the optimal ventilation depends on the detailed aerodynamic aspects prior to the incident. The objective is to ensure that the unaffected tunnel is at a higher pressure than the affected tunnel and to prevent a short circuit of smoke at the portal.

On the basis of extensive calculations of the non-stationary scenarios, the optimal jet fan settings were determined by analysing the distributions of velocities and pressures in the two adjacent tunnels. The present ventilation settings were examined and optimal setting derived. Optimal conditions in the unaffected tunnel can be obtained rapidly adopting a two-step procedure. It is shown that traffic conditions in the unaffected tunnel immediately prior to the outbreak of the fire also have an effect on the optimum jet fan setting.

1. INTRODUCTION
There are several philosophies on how a longitudinal ventilation system shall operate in the case of a tunnel fire. In tunnels with unidirectional traffic the common strategy is to maintain the direction of the traffic induced airflow. Upstream of the fire the incoming vehicles come to a halt due to heat and the spread of smoke. In order to keep the stationary vehicles in a smoke free zone, a minimal air flow velocity (e.g. the critical velocity) should be established and maintained.

Devising models of ventilation control for dual bore road tunnels with unidirectional traffic demonstrates the difficulty in achieving and maintaining the three fundamental requirements for tunnel ventilation during the initial evacuation phase of self-rescue. Usually a fixed and relatively simple control setting is opted for. In order to satisfy all requirements it may be necessary to adapt the initial ventilation settings. The design of control concepts should consider both free flowing and slow moving traffic. However, most studies are restricted to the free flowing traffic in the unaffected tunnel. As shown in this paper, slow moving traffic in the unaffected tunnel should also be considered. Moreover, results of the present (original) and optimised control settings are presented for a 2.7 km long tunnel with unidirectional traffic and longitudinal ventilation using jet fans.

2. VENTILATION STRATEGY FOR FIRE IN UNI-DIRECTIONAL TUNNELS
During a fire the tunnel ventilation strategy must take into account two distinct phases: evacuation and fire-fighting. During the evacuation phase of self-rescue the tunnel users are escaping from the fire zone. The tunnel ventilation must ensure optimal conditions in order to protect the people fleeing from smoke and heat.

To achieve this three fundamental conditions should be satisfied:

- controlling smoke in the affected tunnel
- building up higher pressure in the unaffected tunnel than in the affected tunnel in order to keep the escape routes free of smoke
• avoiding a short circuit of air flow at the portals and thereby preventing that smoke exiting the affected tunnel enters the unaffected tunnel

During the fire-fighting phase the ventilation is used to aid the fire brigade. Figure 1 shows the recommended ventilation setting during the evacuation phase in a dual bore tunnel with longitudinal ventilation and unidirectional free flowing traffic. The smoke is pushed through the tunnel to the exit portal in the same direction as the traffic flow with sufficient longitudinal air velocity, as recommended in various national and international guidelines [1],[3],[2],[4]. To avoid a back-flow of smoke, which is often termed “back-layering”, a minimum velocity (i.e. the critical velocity) must be achieved. The computation of this velocity is given in [7]. It is typically in the range of 2.3 m/s to 3.6 m/s [3]. However, the airflow velocity required causes turbulence and affects the smoke stratification downstream of the fire. This phenomenon becomes more evident at higher air velocities. The smoke stratification is also influenced by the longitudinal slope of the tunnel and in particular by the vehicles. By comparison, the Austrian guideline RVS requires an air velocity of 1.0 m/s to 1.5 m/s [2], but does not aim at avoiding back-layering but maintaining stratification.

With slow moving or congested traffic, it is important to keep the smoke stratification intact during the evacuation phase as people may be on both sides of the fire. This means that the longitudinal air flow velocity should be kept relatively low and no jet fans should operate in the smoke zone. This is the recommended ventilation setting for the affected tunnel during the evacuation phase of a fire.

To keep the escape and rescue routes free of smoke, higher pressure is built up in the unaffected tunnel. The pressure difference between the affected and unaffected tunnel should not exceed a certain level so that it is still possible to open cross passage doors enabling the tunnel users to escape [3].

Finally the third condition requires the air flow in the unaffected tunnel to be reversed as quickly as possible in order to avoid a short circuit at the portals [3].

In order to work out a suitable control strategy first of all the priority of two of the conditions, avoiding an air flow short circuit and building up higher pressure, has to be determined on the basis of the specific tunnel conditions. Initial examination of this example has shown that it is not possible to fulfil both conditions concurrently. Hence a two step control strategy is adopted. At first avoiding an air flow short circuit takes priority in this particular case. In the first few minutes after the fire is detected the ventilation control is set to avoid an air flow short circuit. The effects of ventilation on events and pressure distribution are not very pronounced in this period. Afterwards the ventilation control is set to fulfil the required build up of higher pressure to reach the optimum pressure drop over the cross passages.

Figure 1: Longitudinal ventilation system in the case of fire in the downhill tunnel
3. DESCRIPTION OF THE TUNNEL
The tunnel consists of two 2.7 km long bores each with unidirectional traffic in two lanes. The longitudinal incline is a constant 1.1 %. The principal geometric and traffic data are as follows:

- 57 m$^2$ cross sectional area
- 7.8 m hydraulic diameter
- 520 m height above sea level
- 43400 veh/24h number of vehicles passing through both tunnel bores
- 14 % proportion of heavy goods vehicles
- 80 km/h recommended travel speed
- 9 cross passage connections leading to the adjacent tunnel, fitted with fire doors
- 18 jet fans (35 kW electric power) in the downhill tunnel and 14 jet fans in the uphill tunnel

4. METHOD USED

4.1. Influences on smoke propagation
The spread of smoke in a road tunnel depends on a series of parameters. Most of these remain constant during a fire, for instance tunnel geometry, location of the fire, position of the jet fans. Other parameters are not constant, such as the heat release rate, number of vehicles, fire detection time.

Some of the parameters, which have a strong influence over smoke propagation, are considered in the following section.

**Fire detection time**
The fire detection time should be as short as possible in order to allow quick intervention. A period of three minutes from the start of fire to its detection is usual and realistic. This potential time delay is considered in the ventilation control strategy.

**Traffic conditions (free flowing or slow moving traffic)**
The traffic conditions immediately before and after the fire starts affects the flow velocity due to the piston effect. Therefore the airflow is affected by the direction of traffic, the volume of traffic, the velocity of vehicles, the proportion of heavy goods traffic and the behaviour of drivers after the fire starts. It is assumed that vehicles moving ahead, away from the fire are not affected and leave the tunnel with a constant travel speed. Vehicles moving towards the fire cannot pass its location due to stationary vehicles, heat and smoke. Before the portals are closed to incoming traffic, the number of vehicles moving in the direction of the fire falls only relatively slowly until stationary vehicles fill the tunnel between its entrance and the fire. Moving vehicles continue to push tunnel air forward.

**Location of the fire and tunnel length**
Depending on the location of the fire, the evolution of flow velocity with time may be completely different. If the fire is close to the entrance portal, the piston effect of vehicles entering its portal is reduced. If the fire is close to the exit portal, the piston effect of vehicles is greater because of the longer distance covered.

**Meteorological pressure differences**
Two meteorological effects can influence airflow in a tunnel. One is wind pressure at the portal and the other is the atmospheric pressure difference between the tunnel portals (“barometric barrier”). Both wind and atmospheric pressure can lead to a considerable airflow inside a tunnel. Atmospheric pressure differences are more relevant to longer mountain tunnels.
Tunnel gradient and fire heat release rate

A fire may lead to high temperature differences and thus cause an airflow towards the upper portal due to the stack effect. The importance of this airflow depends on the size of the fire and the slope of the tunnel.

4.2. Scenarios investigated

A fire causes the following sequence of events in the affected tunnel as illustrated in Figure 2.

![Figure 2: Time dependent traffic distribution and smoke propagation from the start of the fire](image)

The vehicles moving forward, away from the fire are not affected and leave the tunnel with a constant travel velocity. The vehicles moving towards the fire cannot pass it due to the stationary vehicles. They are also hindered by the smoke and heat. If the traffic lights at the portal do not prevent traffic from entering the tunnel, vehicles only stop once they reach the stationary ones inside the tunnel or if they get alarmed by the smoke. Figure 2 shows curves of the position of the vehicles and the extent of smoke propagation with respect to the length of the tunnel. The vertical axis represents the elapsed time since the start of the fire. The broken line to the right of the fire represents the position of the last vehicle leaving the tunnel. The thin broken line to the left of the fire shows the extent of the congested traffic inside the tunnel. A few minutes after the start of the fire, the entrance portals are closed. This is indicated by the thin line running to the right showing the position of the last incoming vehicle, which stops and then forms the rear end of the congested traffic. After this point, all vehicles in the tunnel are stationary. The vehicle distribution at two different times is illustrated. Before the fire detection and hence the portal closure, the number of vehicles moving towards the fire falls only relatively slowly until stationary vehicles fill the tunnel from the entrance to the fire. These vehicles continue to push the tunnel air forward.

4.3. General introduction to the simulation program used

The simulation program “SPRINT – Smoke PRopagation IN Tunnels” has been used to simulate fire scenarios. This program is a tool for design and review work used to examine the dimensioning and the control of the tunnel ventilation. It is described in articles [5] and [6]. The following parameters are taken into account in the program “SPRINT”: tunnel geometry, traffic piston effects, the build up of congestion in front of the fire, the stack effect due to heat release rate, the spread of smoke due to the basic air flow in the tunnel and the front velocity of smoke. The time dependent distributions of pressures, velocities, smoke concentrations and temperatures over the length of the tunnel are computed. The effects taken into account are the piston and drag effect of the vehicles, the thrust from the jet fans, the friction losses, the inlet and outlet losses and meteorological influences.
Moreover, the fire is modelled as a heat and smoke source with either constant intensity or a prescribed evolution with time.

5. RESULTS

5.1. Present concept of a ventilation control

The present concept for ventilation control for free flowing traffic has been to operate all the jet fans in the same direction as the traffic flow in affected tunnel. In the unaffected tunnel one group of jet fans was set in the same direction as the traffic flow and the other groups set to reverse mode against the direction of traffic. This setting is appropriate if there is free flowing traffic in both the affected and unaffected tunnel. It is also appropriate for slow moving traffic in the unaffected tunnel.

In the unaffected tunnel the air direction is reversed and the air exits the lower situated entrance portal. Fresh air flows into the tunnel via the upper portal.

5.2. Optimised concept of a ventilation control

For the unaffected tunnel a two-step control strategy is implemented in order to firstly reverse the air flow and secondly to build up an adequate higher pressure with respect to the affected tunnel. In the scenarios examined, a pressure difference between the two tunnels of 100 Pa maximum is envisaged.

Compared to the present concept the settings in the affected tunnel are also revised. The jet fans close to the fire are not switched on as they merely causes turbulence. A different setting is selected if there is slow moving traffic in the affected tunnel.

5.3. Two examples of fire scenarios

The results of the study are illustrated by two representative cases for a fire in the downhill tunnel. In the first scenario the fire is located 300 m from the entrance portal. The traffic is free flowing traffic and a wind pressure of 25 Pa acts on the lower portal, see results in Figure 3. In the second scenario the fire is located 2000 m from the entrance portal. The traffic is slow moving and a wind pressure of 10 Pa acts on the upper portal, see results in Figure 4.

The course of events is as follows: $t = 0$ min is when the fire starts at the specified location. Three minutes later ($t = 3$ min) the fire is detected, both entrance portals are closed to traffic and the fire ventilation plan is initiated. A further two minutes later ($t = 5$ min) the ventilation settings in the unaffected tunnel are changed to achieve the best possible conditions. The end of the simulation is at $t = 20$ min.

The co-ordinate at $X = 0$ m represents the position of the uphill portal in all graphs. The co-ordinate at $X = 2700$ m represents the downhill portal.

The positions of the cross passages between the tunnels are added to the graphs as an orientation aid when determining the pressure differences between the two tunnels.

In the affected tunnel the smoke is driven downstream towards the exit portal using ventilation control. By quickly adjusting the control setting air flow is initially reversed in the unaffected tunnel. Two minutes after the fire is detected (five minutes after fire started) the setting is adapted to also create a higher pressure in the affected tunnel in order to achieve the optimum pressure drop between the tunnels at the cross passages.

In the case of free flowing traffic Figure 3 shows the results of the non-stationary calculations for the present and optimised settings. The variations of the pressure with time to the ambient pressure ($\Delta p$) are shown for two representative times (4 min and 6 min after fire started). The pressure distributions are shown for both ventilation settings (present and optimised) and for both tunnels. In the first few minutes applying the present scheme, the pressure distribution is
not ideal as the pressure in the affected tunnel is higher than in the unaffected tunnel (at \( t = 4 \) min). Using the optimised settings the situation improves. The pressure in the unaffected tunnel is higher than in the affected tunnel at the position of the cross passages. Therefore the requirement to keep the escape routes free of smoke is fulfilled and the conditions are improved for those fleeing.

The variation of the tunnel air velocities with time is shown in separate graphs. The air flow velocity is drawn on the abscissa and the vertical axis represents the elapsed time since the start of the fire.

For slow moving traffic in the affected tunnel Figure 4 shows the corresponding results applying the present and the optimised settings. The velocity in the affected tunnel is disadvantageous with the present setting as the air flow velocity is reversed at \( t = 7 \) min. The situation is improved considerably when applying the optimised settings. The air flow velocity remains in the direction of the traffic flow at a low velocity as desired.

In order to fulfil the three fundamental requirements listed in section 2, an optimised control strategy has been implemented. This distinguishes between free flowing and slow moving traffic in the affected tunnel as well as in the unaffected tunnel.

With respect to the potential occurrence of a flow short circuit at the portal, the air flow velocities are unfavourable at the time of the onset of the fire. This is due to the piston effect of the vehicles and cannot be influenced within the first few minutes of the fire.
The tunnel ventilation and the closure of the entrance portals to traffic is initiated at the time of the fire detection e.g. three minutes after the onset of the fire. During this period the pressure difference between the two tunnels is rather unfavourable. The pressure in the affected tunnel is higher than in the unaffected tunnel, allowing smoke to spread into the unaffected tunnel via the opened doors in the cross passages.

Congestion in front of the fire in the affected tunnel and the resulting decrease in vehicle velocity reduces the air velocity. The rate of decrease in velocity depends on the location of the fire. Prior to the fire detection the traffic flows undisturbed in the unaffected tunnel.

The pressure difference between the tunnels changes once the tunnel ventilation starts. A considerable improvement is achieved by using the two-step adjustment to optimise ventilation control of the unaffected tunnel.
A comparison of the consequences of the traffic conditions in the unaffected tunnel is shown in Figure 5. The effect of free flowing and slow moving traffic in the unaffected tunnel is very distinct when the same settings are used in both cases for the tunnel ventilation. Having free flowing traffic in the unaffected tunnel, the pressure difference between the tunnels is satisfactory. However if slow moving traffic prevails in the unaffected tunnel, the pressure difference increases and may exceed the acceptable limits with limited zones, as shown in Figure 5 at t = 4 min.

A completely different picture results from the comparison between free flowing and slow moving traffic in the unaffected tunnel when having slow moving traffic in the affected tunnel, as shown in Figure 6. In this case the pressure difference between the tunnels is limited and not optimal in all areas. In this scenario the pressure difference is much less favourable at t= 4 min. The conditions then change with time to reach almost the ideal conditions later on.

6. CONCLUSIONS

By means of simulation models it is possible to derive the optimum settings for the tunnel ventilation in the case of a fire. When designing the ventilation control strategies, all traffic scenarios prior to the onset of the fire including slow moving and free flowing traffic for the affected tunnel and the unaffected tunnel should be considered. This enhances the complexity of the control system and requires an input from the traffic management system. Nevertheless, it is the only viable procedure in order to ensure optimal conditions for the evacuation phase of self rescue.

7. REFERENCES

[1] PIARC - World Road Association, "Fire and Smoke Control in Road Tunnels", PIARC Committee on Road Tunnels (C5), 05.05.B, 1999
[4] Lüftung der Strassenbahn; Systemwahl, Dimensionierung und Betrieb; Bundesamt für Strassen; Schweizerische Richtlinie Bereich Tunnel und Elektromechanik, Entwurf vom Dezember 2003