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THE PREDICTION OF SMOKE PROPAGATION DUE TO TUNNEL FIRES

Ingo Riess and Marco Bettelini
HBI Haerter AG, Zürich, Switzerland

ABSTRACT

A new one-dimensional time-dependent model for analysing fire scenarios in tunnels with longitudinal ventilation is presented. An important feature of the model is its ability to handle the stack effect and gravity-driven smoke propagation due to the strong thermal stratification in the tunnel. The new model was implemented in the computer code 'Rabbit'. The validation was based on results from the Memorial Tunnel Fire Ventilation Test Program [5]. 'Rabbit' was able to reproduce in a qualitatively and quantitatively correct way the main experimental findings. It was concluded that the model is suitable for design and review work.

The application to an existing tunnel, the Pierre Pertuis, illustrates the ability of the code to handle real-life situations. The results also demonstrate that for tunnel inclinations in excess of 1-2% the stack effect plays a prominent role in case of fire. Only when this is properly accounted for can dangerous situations, such as flow reversal and smoke spread over halted vehicles and escaping persons, be analysed to the extent required by modern safety standards.

Nomenclature

A [m²] area

c_p [W/kgK] heat capacity

c_w [-] drag coefficient

D_h [m] hydraulic diameter

g [m/s^2] gravity constant

i [-] inclination

k [-] wall loss factor of jet fan

L [m] tunnel length

n [-] number of

Δp [Pa] pressure difference

Q [W] heat flux

T [K] temperature

t [s] time

u [m/s] velocity

x [m] axial distance

α [W/m^{2}K] heat conduction coefficient

ε [-] emissivity

λ [-] wall friction coefficient

ρ [kg/m^3] density of air

σ [W/m^{2}K^4] Stefan-Boltzmann constant

ζ_E [-] portal entry losses (=0.6)

ζ_O [-] other discrete losses

Indices

air tunnel air

b fire

f smoke front

jf jet fans

m average

sm smoke

tun tunnel

veh vehicles

0 initial condition

1. INTRODUCTION

In the past, ventilation systems were designed and dimensioned on the basis of the fresh air required for maintaining an acceptable air quality in the tunnel, notably sufficiently low concentrations of pollutants and sufficient visibility. The power installed was therefore typically determined by situations with congested traffic or nearly equilibrated traffic in the two directions. The comparatively large ventilation systems had adequate capacity to handle a possible fire and little attention was paid in order to study this aspect in detail. In the case of longitudinal ventilation, power reserves sufficient for achieving a prescribed axial velocity (e.g. 4 m/s in the German RABT [1]) were typically specified. Such prescriptions always imply relatively large global safety margins for adverse conditions, such as atmospheric counter-pressure, heavy traffic or fires at "critical" locations.

The steadily decreasing motor vehicle emissions, coupled with an increasing concern for safety as well as for financial and energetic aspects of ventilation, are now dramatically changing this situation. Fire and smoke control are increasingly emerging as limiting factors resulting in less powerful ventilation systems. Therefore refined analysis is called for. Recent investigations emphasise the importance of the critical velocity required in order to avoid smoke propagation against the flow driven by the ventilation ('back-layering'). This is emerging as the determining parameter for dimensioning the ventilation, which leads to significantly smaller systems compared to the past giving rise to significant financial and energetic benefits. On the other hand, the reduced safety margins require a careful and detailed analysis of all parameters controlling smoke propagation, such as atmospheric pressure difference between the tunnel portals, traffic, fire location and tunnel inclination. The steady-state treatment of the problem, which was common practice in the past, must be supplemented by a time-dependent analysis, even at the design stage. This can be best illustrated considering a relatively short tunnel. If the detection and reaction times are too long, the tunnel might already be filled with smoke prior to switching on the ventilation. In this case, a ventilation becomes useless.

The physics of fire development and smoke propagation, promoted by recent full-size and small-scale experiments as well as numerical simulation, is reasonably well understood. The challenge is now to implement this knowledge in the analysis and dimensioning of ventilation systems. A viable approach is to implement the vast body of empirical and analytical information in an 'expert' computer code that then can be used for the design and analysis of the ventilation system. Such tools allow a detailed analysis of each individual tunnel and the development of suitable ventilation systems at minimum cost. Moreover, a complete simulation of accident scenarios enables us to identify possible hazards for tunnel users and subsequently to improve the emergency procedures.

The present paper considers the main factors controlling smoke propagation in a tunnel and their impact on design and dimensioning of longitudinal ventilation systems. The focus is on the correct modelling of all relevant physical aspects at the design and review stage. The computer code 'Rabbit', developed for this purpose by the authors, is described in some detail. A validation against available large-scale experimental data is included. The final part of the paper is devoted to the discussion of practical applications on the basis of a real-life case, the Pierre Pertuis, which is a road tunnel located in the Swiss Jura.

2. FIRE SCENARIOS IN TUNNEL

It is important to have a representation of the variation of traffic with time in order to identify the impact of accidents involving a fire in a tunnel. The vehicles moving ahead away from the accident are not affected and leave the tunnel with constant velocity. All vehicles moving towards the accident cannot pass the location of the fire due to the halted vehicles. They are also inhibited from the smoke and heat development. As long as the traffic lights at the portal does not prevent the traffic from entering the tunnel, vehicles stop only if they reach the halted vehicles inside the tunnel or are alarmed by the smoke.

Figure 1 shows curves of the position of the vehicles and the limits of smoke propagation over the length of the tunnel. The ordinate represents the time elapsed 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 traffic lights at the entrance portal switch to red. This is indicated with the thin line running to the right showing the position of the last incoming vehicle, which halts and then forms the end of the congested traffic. After this time, all vehicles in the tunnel have come to a halt. The vehicle distribution at two different times is illustrated by means of different colours.

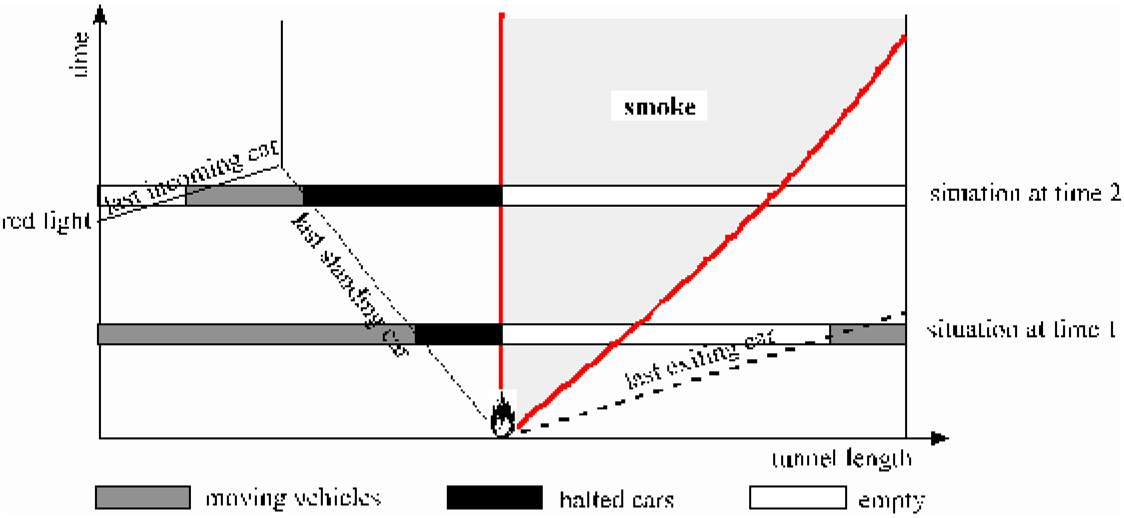

Figure 1: Time dependent traffic distribution and smoke propagation from the start of the fire [4]

As long as there is no red traffic light at the portal, 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. These vehicles continue to push the tunnel air forward.

This representation can also be used for the more general case of bi-directional traffic, where the same patterns apply for each traffic direction. This traffic pattern and the flow model described in Section 3 have been implemented in the computer code 'Rabbit'.

3. NUMERICAL MODEL: 'RABBIT'

The unsteady flow field in the tunnel is well described by means of a one-dimensional time-dependent model, based on the governing equations describing the conservation of mass, axial momentum and energy, as well as the additional relations for smoke propagation. The flow variables of primary interest are the air velocity and temperature, as well as the extent of the zone partially filled with smoke. The tunnel has a constant cross-section and inclination. Traffic, uni- or bi-directional, can be specified in terms of velocity, number and type of vehicles (in particular for the heavy-duty vehicles). The fire is modelled as a heat source, with either of constant intensity, or has a prescribed evolution in time. Here we use the heat-release rate evaluated from a fire of a public bus during the FIRETUN experiments [2]. The effects taken into account are the piston and drag effect of the vehicles, the thrust from the jet fans, the tunnel-wall friction, the inlet and outlet losses and a meteorological pressure difference between the portals. The 'stack effect' is accounted for based on the computed average air temperature in the tunnel. The current version of the code is restricted to longitudinal ventilation systems, with an arbitrary number of user-specified jet fans.

The single most important parameter in safety analysis is the extent of the smoke-filled area. As evidenced by various tests, e.g. [5], the hot combustion products initially spread along the upper part of the tunnel section. Values of the visibility and temperature at vehicle and person height remain initially unchanged. With increasing time and distance from the fire, the stratification is progressively lost and the entire tunnel section is filled with smoke. Note, however, that even 10 to 15 minutes after ignition, when visual observations indicate a homogeneous smoke distribution, temperature and velocity measurements still show a very pronounced stratification. This is in the numerical model taken into account, as it computes temperature and speed for the upper and lower layers. This information, generally excluded from one-dimensional models, is necessary in order to predict the smoke propagation correctly, which is a result of both passive convection and gravity-driven propagation. Moreover, explicit computation of the stratification is necessary for a realistic evaluation of the convective and radiative heat-transfer rates.

The simulation is started from an arbitrary initial state, typically zero speed and temperature difference. 'Rabbit' initially computes the steady-state situation prior to ignition, as it results from the specified undisturbed traffic situation and given operation of the ventilation. After ignition, which occurs at a user-defined location, the evolution of the main variables in time is computed. This forms the basis for assessing and improving the ventilation system. After fire detection and alarm, current tunnel- safety systems automatically start an emergency procedure. This consists of an installation-dependent sequence of steps aimed at reducing the risk for the persons in the tunnel and easing rescue, which affects among others the ventilation and traffic control. Important steps in this emergency sequence are included in 'Rabbit', which allows for a quite realistic simulation of a fire scenario. As an example, in the programme the traffic light can be switched to red at the tunnel entrances at the time of the fire detection (which is generally a recommended measure in a tunnel safety procedure).

The air motion is computed by means of the conservation of momentum

$$\frac{\partial u_{air}}{\partial t} = \frac{1}{\rho} \cdot \frac{\Sigma \Delta p}{L} \quad (1)$$

where $\Sigma\Delta p$ denotes the sum of all pressure effects present:

pressure difference caused by the vehicles

$$\Delta p_{veh} = n_{veh} \frac{\rho}{2} c_w \frac{A_{veh}}{A_{tun}} \left(u_{veh} - u_{air}\right)^2, \quad (2)$$

tunnel wall friction, entry and exit losses and other discrete losses

$$\Delta p_{friction} = \frac{\rho}{2} u_{air}^2 \left(\zeta_E + \lambda \frac{L}{D_h} + 1.0 + \zeta_O \right), \quad (3)$$

effect on pressure by jet fans

$$\Delta p_{jf} = n_{jf} \rho \left(u_{jf} - u_{air}\right) \frac{A_{jf} u_{jf}}{A_{tun} k_{jf}}, \quad (4)$$

stack effect due to the average temperature in the tunnel T_m

$$\Delta p_{stack} = iL \cdot \rho g \frac{T_m - T_0}{T_m}, \quad (5)$$

the portal pressure difference is given by Δp_{meteo}.

For the calculation of the air temperature, the tunnel is divided into elements, for which the energy equation is solved. The fire is modelled as a heat source. Energy transport occurs through advection in the axial direction, with the mean flow velocity, and heat convection as well as radiation to the tunnel wall. A sketch of the thermal model is given in Figure 2.

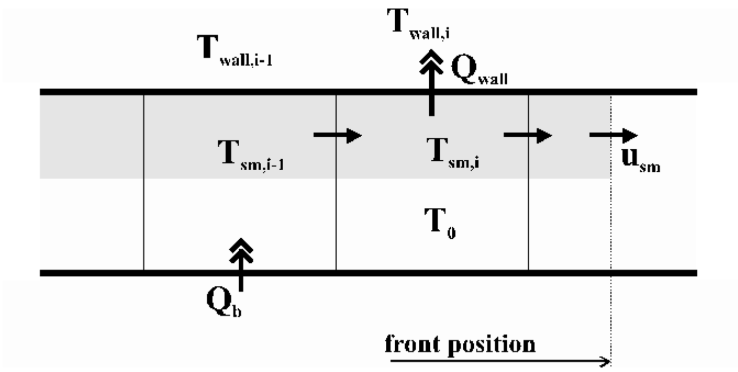

Figure 2: Model for the propagation of the smoke layer.

Ambient temperature is assumed for the lower layer. Heat transfer from the upper to the lower half of the tunnel is neglected. Advective energy transport occurs therefore only in the upper part of the tunnel, where the higher temperatures are observed. Convective and radiative heat transfer to the wall is also limited to the upper layer. This is a reasonable approximation, since the primary parameter of interest is the average temperature for the entire tunnel rather than the temperature distribution in the tunnel. The heat-transfer rate to the tunnel wall is computed using

$$Q_{wall} = \frac{4A_{tun}}{D_h} \cdot \Delta x \cdot \left(\alpha \left(T_{sm} - T_{wall} \right) + \varepsilon\sigma \left(T_{sm}^4 - T_{wall}^4 \right) \right) \quad (6)$$

For each time step, the average temperature of the smoke layer between the fire and the smoke front $T_{sm,m}$ is calculated. Subsequently, the velocity of the smoke front is calculated as the sum of the mean flow velocity in the tunnel u_{air} and the front velocity due to the gravity current u_{sm}. The front velocity is driven by the temperature difference between the hot smoke layer and the colder tunnel air underneath. According to Fanneløp [3] this can be expressed as

$$u_{sm} = 0.67 \cdot \sqrt{g D_h \frac{T_{sm,m} - T_0}{2 \cdot T_{sm,m}}}. \quad (7)$$

It is a common assumption that the fire represents a strong heat source. Hot smoke is produced, which rises to the tunnel ceiling due to its low density. A smoke layer is formed, which spreads along the ceiling. As long as the front is very close to the fire, it is very hot and travels with high velocity. Further away from the fire, it is cooled down by heat conduction and radiation to the tunnel wall. At some distance from the fire, the smoke is cooled and the value of u_{sm} becomes very small. These effects are represented in the model.

4. MODEL VALIDATION

The model was validated against the results from the Memorial Tunnel Fire Ventilation Test Program [5]. With a length of 853 m, a cross-sectional area of 60.4 m^2 and an inclination of 3.2%, the Memorial Tunnel is representative for a number of alpine tunnels. The test program consisted of a series of full-scale fire tests, with intensities in the range of 10 to 100 MW, conducted in an abandoned road tunnel. Several ventilation systems were evaluated with respect to their capacity of managing smoke and heat propagation. The energy was released through the ignition of oil contained in four steel pans. The energy-release rate is proportional to the free oil surface and essentially constant in time. Two fire tests, with intensities of 20 and 50 MW, were performed for the natural ventilation case, i.e. without the use of mechanical ventilation. Additionally, a total of 15 tests with longitudinal ventilation were performed focusing on smoke and heat management.

The Memorial Tunnel was extensively equipped with data-acquisition and instrumentation. Moreover, fan rooms were installed in the upper part of both portals. All these components generated additional set-up dependent discrete pressure losses, which are accounted for in the model with the coefficient ζ_O, Eq. (3). The value of this parameter was determined on the basis of the experimental values for the tunnel airflow as a function of the number of operating jet fans (between 2 and 15), which were available for the fire sizes with heat rates between 10 and 100 MW. The analysis showed that the value of ζ_O is proportional with the heat rate. It took the value of about 6 for a heat rate of 10 MW and about 15 for rates between 20 and 50 MW. In no case was a the model parameters tuned in order improve the agreement with the Memorial Tunnel data.

Firstly, the results for the naturally ventilated case, tests 501 (20 MW) and 502 (50 MW) are discussed. The results for the higher fire intensity are illustrated in Figure 3. Initially smoke propagated in both directions. After 2 minutes in the 20 MW case, smoke was flowing out of the lower portal (downwards). A more limited motion downwards was observed at the higher energy-release rates. At steady state, which occurs after about 15 minutes from ignition, the natural airflow generated by the fire was sufficient to prevent the smoke from entering the tunnel section downwards of the fire. ‘Rabbit’ was able to reproduce these effects correctly. In the 20 MW case, the smoke did not quite flow out of the lower portal at intermediate times, but arrived as close as 3 m from it. The downwards propagation in the 50 MW case was much weaker. As observed in the experiment, the rate of smoke movement towards the higher portal (upwards) increased with increasing fire size. The average smoke speed increased from 2.9 m/s (20 MW) to 3.9 m/s (50 MW), which was in reasonable agreement with the values obtained in the experiments: 2.2 and 4.0 m/s.

Another fundamental information for safety work is the asymptotic average airspeed. In this case, it is reached after roughly 10 to 15 minutes. The predicted results for both cases, 1.7 resp. 2.3 m/s, are in excellent agreement with the experimental values, 1.6 resp. 2.2 m/s.

In spite of the large uncertainties, the results obtained with ‘Rabbit’ are surprisingly good. Both front velocity, driven by the thermal stratification, and the average velocity, largely determined by the stack effect, are well reproduced. In particular, both parameters respond very well to changes in the fire intensity.

The experiments with longitudinal ventilation focussed on smoke management, in particular on the verification of semi-empirical correlation for the critical velocity, i.e. the smallest velocity, which prevents back-layering. A qualitative comparison between prediction and experiment was carried out for the tests 615B (100 MW, 6 fans), 611 (50 MW, 5 fans) and 624B (50 MW, 6 fans). In all cases, the ventilation was started 2 minutes after ignition. The results, in particular concerning smoke propagation and the impact of the ventilation system, confirmed the predictive capabilities of the new model.

The overall results of this validation were entirely satisfactory. The main experimental findings were reasonably well reproduced by ‘Rabbit’, from both a qualitative as well as a quantitative point of view. In particular, the velocity induced by the stack effect and the gravity-driven spread of the smoke cloud are modelled to give plausible results. Consequently, it was concluded that the new model 'Rabbit' is applicable for design and review work.

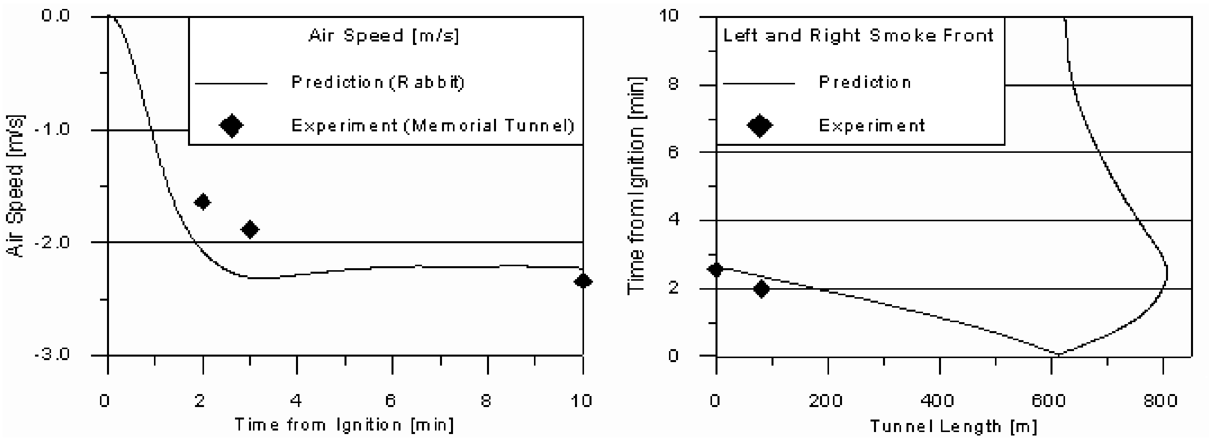

Figure 3: Memorial Tunnel test number 502: natural ventilation with fire intensity 50 MW.

5. APPLICATION

The Pierre Pertuis Tunnel

The new code was applied in order to verify the safety concepts in an existing tunnel, the Pierre Pertuis, which is a part of the A16, in the Swiss Jura. The tunnel consists of two tubes with uni-directional traffic. The main data concerning this tunnel are:

- Length 2114 m
- Section 54.8 m
- Average inclination 3.5%
- Maximum inclination 4.9%
- Peak traffic 930 veh/h
- Average traffic 270 veh/h

- Heavy vehicles 10%

The tunnel is longitudinally ventilated, with eight 33 kW jet fans (diameter 1000 mm) in each tube that are grouped in pairs. Since the fan group close to the fire might not work and in any case should not be operated during a fire, it must be assumed that only 6 jet fans are available in case of fire.

From a safety point of view, three main questions need to be answered:

- Is the installed ventilation power sufficient to prevent back-layering?
- What is the best fire ventilation concept?
- How does the fire ventilation perform in the rare case of bi-directional traffic in one tunnel tube?

The safety concept was evaluated in the case of uni- and bi-directional traffic [6]. However, we have here limited ourselves to extent on the result for the predominant condition: the uni-directional traffic.

Tunnel Inclination

Firstly, we illustrate the influence of the tunnel inclination on the critical velocity and on the air velocity in the tunnel. The critical velocity, computed according to [5], is plotted in Figure 4 for tunnel inclinations up to 6% and fire intensities up to 100 MW. The values are in the range from 1.5 m/s for smaller fires to 3-3.5 m/s for very large fires and high inclinations. For comparison, Figure 5 shows the velocity generated in the tunnel by a given temperature difference, say, between 5 and 30 K. Note that this parameter depends on the tunnel length, and the values plotted refer to the length of the Pierre Pertuis tunnel for a situation without traffic and vanishing atmospheric pressure difference between the portals. The speed 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 such as Pierre Pertuis with inclinations exceeding 1-2%.

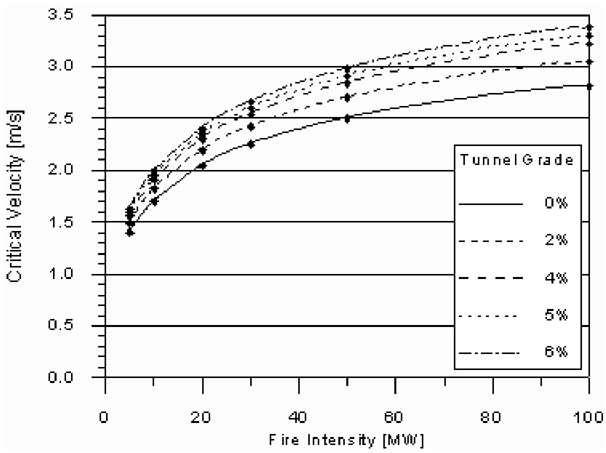

Figure 4: Critical velocity vs. fire intensity and tunnel inclination (grade).

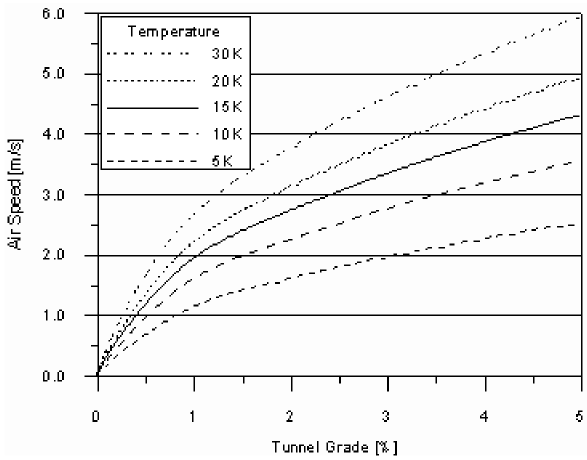

Figure 5: Air speed vs. tunnel inclination (grade) and mean temperature in the tunnel.

Fire Scenario in the Pierre Pertuis Tunnel

The analysis of a fire scenario in the Pierre Pertuis is presented as a typical design application of 'Rabbit'. We assume uni-directional traffic, with an average volume of 270 veh/h. The tunnel parameters are given above. For the safety of the persons in the tunnel, it is important that the tunnel section behind the accident, where the vehicles have come to a halt, is kept free from smoke, at least until all passengers are evacuated. With a positive inclination, the piston effect from the vehicles prior to the accident and the stack effect act in the same direction and flow reversal cannot occur. Therefore, the potentially critical downwards-directed tube is considered here. The fire is assumed to take place in the middle of the tunnel at the time 0 s, with a constant intensity of 20 MW. Three sets of results are presented in Figure 6:

- Ventilation not activated
- 6 jet fans activated 3 minutes after ignition
- Ventilation not activated, stack effect and front velocity not included

In the ventilated case, it is further assumed that 3 minutes after ignition, a traffic light at the tunnel portal prevents vehicles from entering the tunnel.

All results are identical at times prior to ignition ($t \leq 0$ s). This traffic situation generates a steady-state air speed of 3.3 m/s. In the unventilated case this value diminishes rapidly after ignition, due to the stack effect. Flow reversal is observed after 6-7 minutes, after which most of the tunnel is filled with smoke. A new steady-state situation is reached after about 15 minutes, in which the left-hand part of the tunnel (where the vehicles are halted) is filled with smoke, while the right-hand side is free from smoke. Without ventilation the final velocity is slightly higher than 3 m/s, which now works against the initial direction of the traffic. This is clearly a potentially dangerous situation, which has to be corrected with a fire ventilation.

The fire ventilation, started in this case 3 minutes after ignition, is able to prevent flow reversal by maintaining the air speed at about 3 m/s. As seen in the lower part of Figure 6, the left-hand part of the tunnel is now free from smoke. Consequently, the persons trapped in the tunnel can escape the fire and leave the tunnel through the left portal and rescue is not hindered by bad visibility. The proposed ventilation system is therefore very well suited for this case.

The importance of the stack effect is illustrated by the third result represented in Figure 6. The unventilated case was computed without taking the stack effect into account. With this approximation, the resulting axial velocity diminishes monotonically to zero over very long time scales. Correspondingly, one finds that smoke would be confined to the right-hand part of the tunnel. Hence it is of paramount importance to include the stack effect in such models, as the dangerous situation with flow reversal would otherwise not have been predicted.

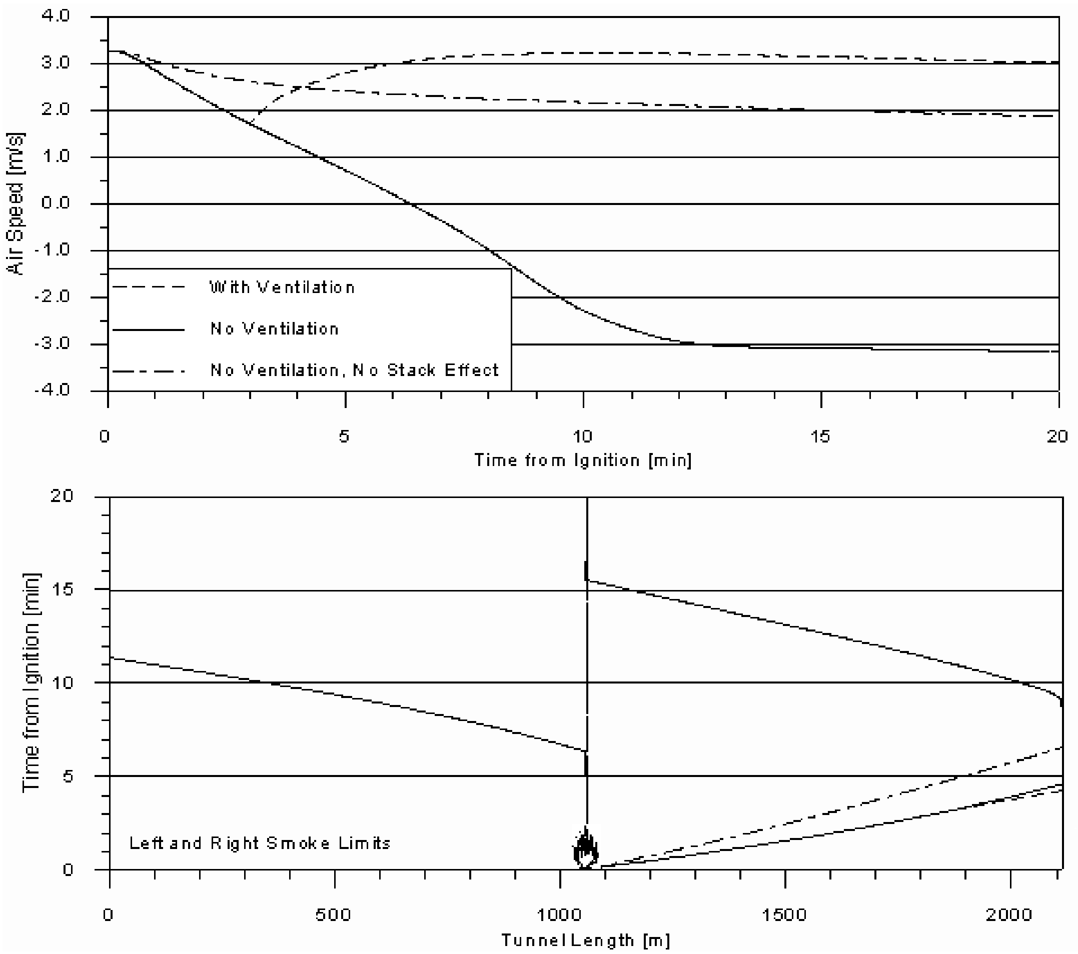

Figure 6: Air speed and smoke limits for a 20 MW fire in the Pierre Pertuis tunnel (uni-directional traffic, 270 veh/h; vehicle motion from left to right).

6. CONCLUSIONS

Modern ventilation systems are smaller than in the past. This is due to diminishing motor-vehicle emissions as well as to an urge to reduce investment and running costs. Refined analysis of ventilation systems is called for in order to minimise safety margins without endangering tunnel users. In particular, detailed analysis of fire scenarios need to be carried out in a routine manner in the design phase with particular attention to smoke propagation. For this purpose, substantially faster models than the comprehensive CFD simulations are called for.

A new model for analysing fire scenarios in tunnels with longitudinal ventilation has been presented. The model is based on the one-dimensional time-dependent momentum and energy equations. The effects taken into account are the piston and drag effect of the vehicles, the thrust from the jet fans, the tunnel wall friction, the inlet and outlet pressure losses and the meteorological pressure difference between the portals. The temperature distribution in the tunnel is computed, which allows to take the stack effect into account. Additionally, gravity-driven smoke propagation due to the strong thermal stratification in the tunnel is accounted for using an adequately accurate engineering model.

The new model was implemented in a new computer code, ‘Rabbit’. The validation was based on results from the Memorial Tunnel Fire Ventilation Test Program [5]. ‘Rabbit’ was able to reproduce the main experimental findings and gave rise to both qualitatively and quantitatively agreement with the experimental results. It is important to mention that none of the model parameters was tuned in order to achieve this excellent agreement with the validation data.

The application to an existing tunnel, the Pierre Pertuis, illustrated the code's ability to handle real-life situations. In case of fire, the results also showed that for tunnel inclinations in excess of 1-2% the stack effect plays a prominent role. If this is not properly accounted for, dangerous situations, such as flow reversal and smoke propagation over halted vehicles and escaping persons, cannot be analysed to the extent required by modern safety standards.

The overall results of the validation effort and practical application of ‘Rabbit’ were entirely satisfactory. The key features observed in case of fire were reasonably well reproduced by the code, from both a qualitative as well as a quantitative point of view. In particular, the modelling of the major parameters affecting smoke propagation appears to be adequately accurate. It was concluded that the new model is suitable for design and review work.

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