Sprint – a design tool for fire ventilation

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A new one-dimensional time-dependent computer model for analysing fire scenarios in tunnels is presented. The new model is able to handle arbitrary ventilation systems. An important feature is its ability to handle gravity-driven smoke propagation arising from thermal stratification.

The new model was implemented in the computer code ‘Sprint’. The validation was based on results from full-size fire tests and from additional flow measurements. ‘Sprint’ 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 design review work.

The application to existing tunnels, e.g. Gotschna and la Vue-des-Alpes, illustrates the ability of the code to handle real-life situations. Using the 1-D code, the short calculation time allows for the simulation of many different scenarios (parametric studies) in a reasonable time. ‘Sprint’ has been used not only for safety studies, but also for the design of optimised control routines for fire ventilation.

NOMENCLATURE

A	[m^2]	area
D_h	[m]	hydraulic diameter
g	[m/s^2]	gravity constant
k	[-]	factor
p	[Pa]	pressure
Q	[W]	heat flux
T	[K]	temperature
t	[s]	time
u	[m/s]	velocity
x	[m]	axial distance
a	[W/m^{2}K]	heat transfer coefficient
e	[-]	emissivity
l	[-]	wall friction coefficient
r	[kg/m^3]	density of air
s	[W/m^{2}K^4]	Stefan-Boltzmann constant

Indices

sm	smoke
tun	tunnel
V	ventilation
wall	wall
0	initial condition

INTRODUCTION

In the past, ventilation systems were mainly designed 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 decreasing vehicle motor vehicle emissions, coupled with an increasing concern for safety, as well as for the economic and energetic aspects of ventilation, are dramatically changing this situation.

The one-dimensional time-dependent model ‘Rabbit’ (1) was presented one year ago. The code allowed for the analysis of smoke propagation in tunnels with longitudinal ventilation. Included were sub-models for the gravity-driven flow of a hot smoke layer in the upper part of the tunnel as well as for the behaviour of the vehicles in the tunnel, for a time-varying fire size and for the use of jet fans. The chimney-effect due to a constant gradient of the tunnel tube has been included as well.

During the past year there was a strong discussion on the dimensioning of tunnel ventilation systems using solely smoke extraction or smoke extraction in combination with jet fans. The control of the longitudinal velocity in the vicinity of the fire is being discussed ever since. Therefore, there is a strong need for a computer models allowing for simulation of fire scenarios for arbitrary ventilation systems. The calculations have to be fast and straight forward, allowing the simulation of a large number of different scenarios in a reasonable time (2).

To model these scenarios, we expanded the flow model used in ‘Rabbit’ to include transversal ventilation systems. The new code is called ‘Sprint’ (Smoke PRopagation IN Tunnels).

The code has been verified using the detailed data of the Memorial Tunnel Fire Ventilation Test Program. ‘Sprint’ has been in use since mid 1999. We did calculations of fire scenarios for the refurbishment of the Montblanc tunnel in France/Italy, for a retrofit of the tunnels la-Vue-des-Alpes in Switzerland and the Elbe tunnel in Germany as well as design work for the new Gotschna tunnel in Switzerland.

FIRE SCENARIOS

During the first few minutes following a fire or accident, the airflow is mainly influenced by the traffic movement (3). The vehicles moving 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 portals do not prevent the traffic from entering the tunnel, vehicles stop only when they reach the halted vehicles inside the tunnel or if they are alarmed by the smoke. For long tunnels, there are traffic lights at regular intervals. This option has been included in the code as well.

The meteorological pressure difference is another major influence on the airflow. Tunnels with a high coverage may have a meteorological pressure difference between the tunnel portals of several hundred Pascals. For the Montblanc tunnel with a coverage of 2000 m, a pressure difference of 800 Pa and more has been observed on exceptional occasions. Wind pressure is of minor importance.

Most tunnels have a different interior temperature compared with the ambience. The temperature difference causes a chimney effect, even before a fire has started. While vehicles are moving in the tunnel, this effect can barely be observed, but it can cause velocities of several meters per second when the traffic is stopped.

The fire load is not constant during a fire incident. In ‘Sprint’, for dimensioning purposes, either constant fire loads or standard fire loads are being used. For the simulation of test cases, a fire load is implemented in the code that has been derived from measured data, i.e. the public bus fire with a maximum heat release rate of 28 MW (4).

The start-up of large axial fans caused delays during some recent fire tests. In ‘Sprint’ a function for the start-up of axial fans is included. Using several ventilation stages, the start-up behaviour of large axial fans can be modelled in detail.

NUMERICAL MODEL: ‘SPRINT’

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 tunnel is defined as a single tube with constant cross-section. It consists of several sections. Traffic, one- or bi-directional, can be specified in terms of velocity, number of vehicles and percentage of trucks. The fire is modelled as a heat and smoke source. Smoke concentrations are given as a percentage of the smoke concentration of a stoichiometric fuel fire.

The equations describing the flow can be found in the literature on tunnel aerodynamics (e.g. (5),(6)). Here, only the equation for the tunnel without traffic is given:

$$\frac{dp}{dx} = -l\,\frac{1}{D_h}\cdot\frac{r}{2}u^2 - k_V\,ru\frac{du}{dx} - r\,\frac{du}{dt} \qquad \text{(eq.1)}$$

Due to the boundary layer of the tunnel flow, k_V is introduced as an empirical factor taking into account the boundary layer, and the axial momentum of supply and exhaust flow (5). It can be shown that this term is generally not negligible.

The tunnel is divided into a hot smoke layer that covers the upper part of the tunnel and a cool layer of tunnel air underneath (1). Heat is transferred to the tunnel walls by means of convection and radiation.

$$Q_{wall} = \frac{4A_{tun}}{D_h}\cdot\Delta x\cdot\left[a\left(T_{sm}-T_{wall}\right)+e\,s\left(T_{sm}^4-T_{wall}^4\right)\right] \qquad \text{(eq.2)}$$

For each time step the mean flow in the tunnel is calculated from continuity and momentum equation. The velocity of the smoke front u_{sm} is then calculated by superposition of the mean flow velocity in the tunnel and the front velocity due to the gravity current. The front velocity is driven by the temperature difference between hot smoke layer and the colder tunnel air underneath. This can be expressed as

$$u_{sm} = k\cdot\sqrt{gD_h\,\frac{T_{sm}-T_0}{2\cdot T_{sm}}}. \qquad \text{(eq.3)}$$

Equation 3 represents a more general form of the expression given in (1). The factor k can be chosen for different tunnel cross-sections as well as for a pre-set disturbance of the smoke layer. The upper limit for k is $1/\sqrt{2}$ without dissipation (7). Values for k derived from experiments are in the range of 0.5 to 0.67. The velocity of the smoke front is only weakly affected by the grade of the tunnel tube, as shown by lock-exchange experiments over a wide range of inclinations (8).

As long as the front is very close to the fire, it is very hot and travels at high velocities. With increasing distance from the fire, the smoke is cooled down and the front velocity becomes very small. These effects are reproduced by the model.

MODEL VALIDATION

Memorial Tunnel Data

The model implemented in 'Sprint' was validated against the results from the Memorial Tunnel Fire Ventilation Test Program (9). With the length of 853 m and an grade of 3.2% the Memorial tunnel is representative for a number of alpine tunnels. For the fire tests, the tunnel was equipped with data acquisition and instrumentation.

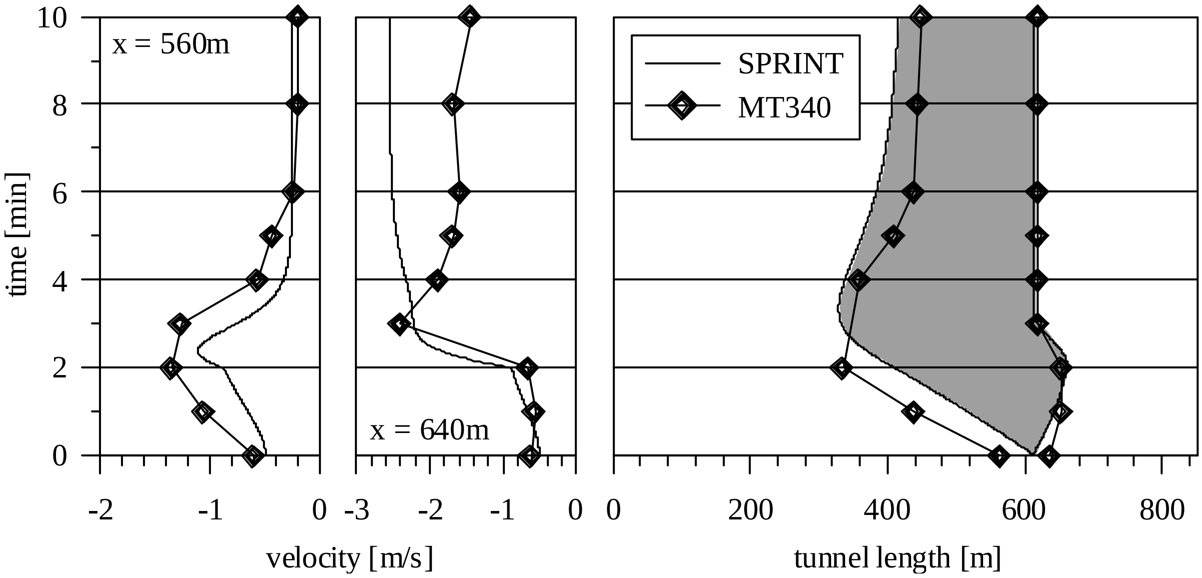

Figure 1: Flow velocities and smoke propagation versus time during test 340B: partial transverse ventilation with oversized exhaust port.

The experiment shown in the following figures is test 340B: 'partial transversal ventilation with single port extraction'. The fire size is stated to be 20 MW, i.e. it is about 7 MW during the first three minutes of the test and rises to constant 18 MW during the following 10 min. The volume flow rate of the smoke extraction is 286 m^3/s. It is switched on two minutes after ignition.

The first two graphs in figure 1 give the flow velocity versus time at locations upstream and downstream of the fire. The diamonds represent mean flow velocities, derived from bulk flow rates given in the test report. At the point left from the fire (x = 560 m), the bulk flow is influenced by the fire immediately after ignition. This is due to the travelling smoke front and the expansion of the heated air in the vicinity of the fire. On the right side of the fire, the flow is affected only two minutes after ignition, when the smoke extraction is started.

On the left hand side from the fire, the simulation shows excellent agreement with the data. On the right hand side, the agreement is less favourable, but the overall behaviour has been predicted well in the simulation. According to the right diagram of figure 1, the smoke spreading shows good agreement with the experimental findings.

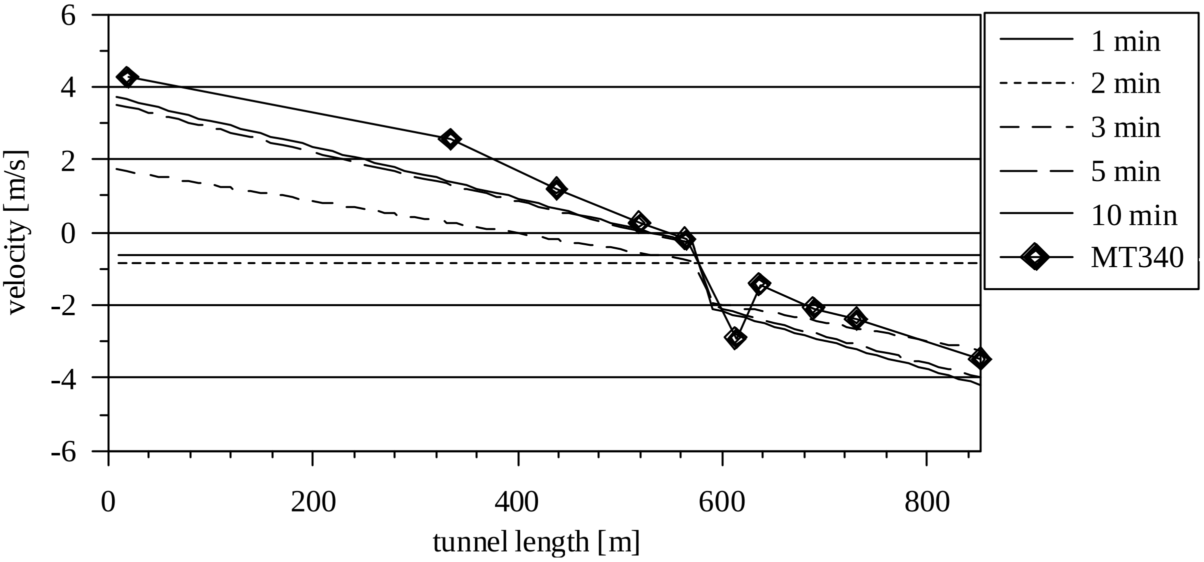

Figure 2: **Flow velocity versus tunnel length. Test 340B at 10 min from ignition.**

Figure 2 shows the longitudinal flow velocity versus the tunnel length. The diamonds correspond to the measurements taken 10 min from ignition. The lines show the calculated velocity for different times from ignition. In the vicinity of the fire, the measurements give a high longitudinal velocity. This is caused by the expansion due to the temperature rise. The expansion is not modelled. Therefore, the change in longitudinal velocity is not visible in the simulation. Nevertheless, the overall behaviour of the tunnel air is visible in the simulation.

Again, the experimental findings are very well represented in the model. The calculated flow velocities tend to be too low. This might be caused by the equipment for data acquisition, which is concentrated in the right hand part of the tunnel. All these components generated additional set-up dependent discrete pressure losses, which in detail were not assessable for the simulations. Especially, the distribution of these losses over the tunnel length is difficult to assess. The distribution becomes important in the case of transversal ventilation due to the varying airflow velocity. In the calculation, the pressure losses due to the installed equipment have assumed to be uniformly distributed over the entire length of the tunnel.

According to figure 2, the predictions of the velocities near the fire have proven to be the most inaccurate. The largest discrepancy is observed at x = 640 m. However for design purposes, also at this location a reasonable prediction was obtained, figure 1.

Montblanc Tunnel Measurements

A further validation was made by a comparison of ‘Sprint’-calculations with measurements of the longitudinal velocity made in the Montblanc tunnel in November 1999. The evaluation of meteorological pressure difference between the tunnel portals gave a meteorological pressure of 250 Pa from Italy to France during the measurements. This includes the chimney effect of about 60 to 65 Pa from France to Italy caused by the inherent difference in temperature between the warmer tunnel air and the ambient air outside the tunnel. Longitudinal velocities from measurement and calculation are given in table 1.

Table 1: Flow velocity in the Montblanc tunnel

	French portal		Italian portal	
France ? Italy	Meas.	‘Sprint’	Meas.	‘Sprint’
Without ventilation (extractor open)	-2 m/s	-2.5 m/s	-4.3 m/s	-4.1 m/s
With French extractor	7 m/s	6.7 m/s	-4.6 m/s	-4.2 m/s
State of ventilation I	0 m/s	0.2 m/s	- 4.5 m/s	-4.4 m/s
State of ventilation II	8.5 m/s	8.7 m/s	-	-2.2 m/s

The comparison of changes in longitudinal velocity due to different ventilation regimes is entirely satisfactory.

Conclusions

The results of the validation were entirely satisfactory. The main experimental findings were reasonably well reproduced by ‘Sprint’, from both a qualitative and 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 ‘Sprint’ is applicable for design and review work.

The application of ‘Sprint’ shows the major advantage of one-dimensional simulations versus complex CFD-codes. The calculation time for the simulation of 10 min of the fire test 340B required less than ten seconds on a standard personal computer. Therefore, multiple simulations with a variety of boundary conditions or ventilation regimes are possible in a reasonable amount of time.

APPLICATION

The Gotschna Tunnel

The new code was used for verifying the safety concept in a tunnel that is currently under construction, the Gotschna tunnel. The tunnel consists of a single tube with bi-directional traffic. It will be equipped with a semi-transversal ventilation for normal conditions with an intermediate ceiling and a separate exhaust duct with dampers for smoke extraction. The main data concerning the tunnel are:

Length	4202 m	
Section	44.2 m^2	
Grade	4.00 %	on 209 m
	4.78 %	on 3797 m
	2.11 %	on 196 m

The goal of the study was to compare a smoke extraction in combination with jet fans with a smoke extraction with increased volume flow without jet fans.

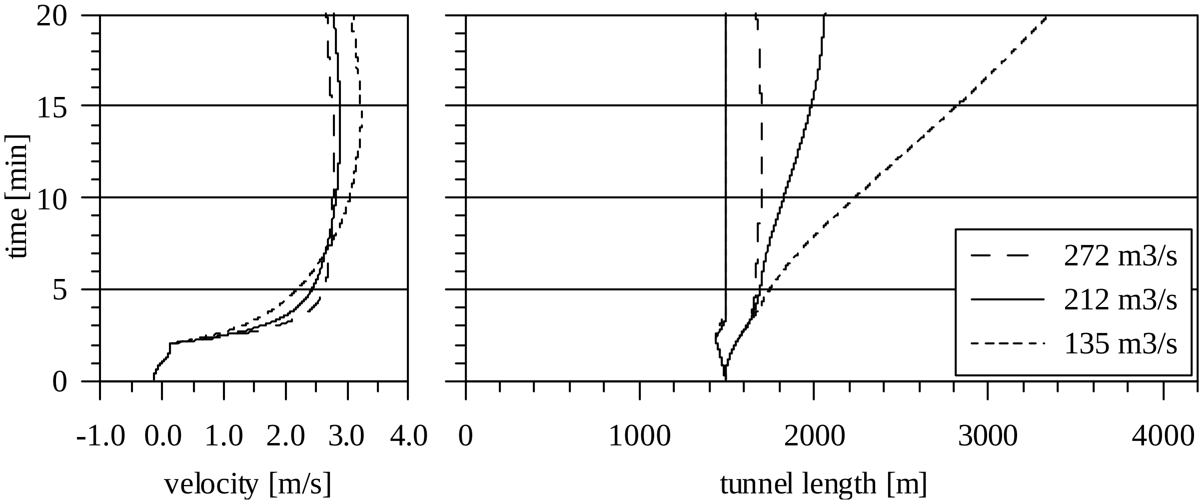

Figure 3: Flow velocity at fire location and smoke propagation in the Gotschna tunnel, different smoke extraction flow rates

The fire scenario shown in figure 3 is a fire of a public bus 1500 m from the lower tunnel portal. The fire starts at t = 0. Three minutes from ignition, the fire is detected and the fire ventilation started. The traffic regime is 500 vehicles per hour in each direction, an average traffic in the tunnel. The vehicles travel with 60 km/h uphill and 80 km/h downhill. The flow velocity at the fire location is shown in the left graph of figure 3. In the right graph, the two smoke fronts are shown. The graph demonstrates that with a smoke extraction of 135 m^3/s the smoke spreading cannot be limited. The very high smoke extraction of 272 m^3/s prevents the smoke from leaving the fire section. The recommended extraction flow rate was 212 m^3/s, a flow rate which can be realised with only slight alterations in the design of ventilation ducts and buildings of the Gotschna tunnel.

The computations showed that the use of jet fans to limit the longitudinal flow velocity in a fire scenario requires careful operation. In any case, it should be studied if an increased extraction flow rate could make additional means for controlling longitudinal flow obsolete.

La Vue-des-Alpes

The goal of a study undertaken for the tunnel la Vue-des-Alpes was to improve of smoke extraction using the existing equipment. One question concerned the possibility to use jet fans for a control of the longitudinal flow velocity in a real fire scenario. The main data concerning the tunnel are:

Length	3250 m
Section	49 m^2
Grade	2.45 %

The tunnel will be equipped with a semi-transversal ventilation with an intermediate ceiling and dampers for smoke extraction. In case of fire, several dampers in the vicinity of the fire are opened. This gives a local smoke extraction over a length of about 300 m.

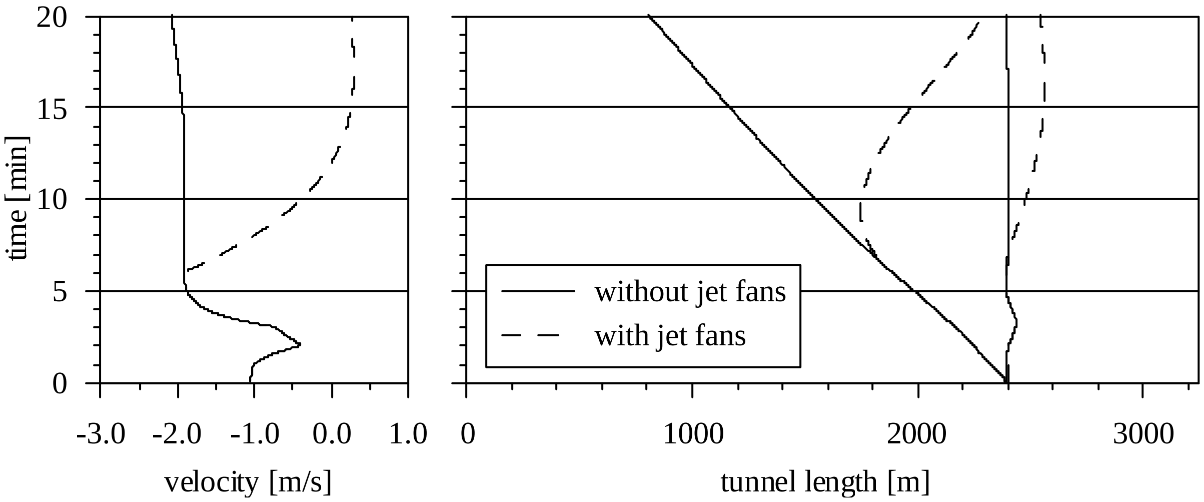

Figure 4: **Flow velocity at fire location and smoke propagation in the tunnel la Vue-des-Alpes (public bus fire)**

The fire scenario shown in figure 4 is a fire of a public bus 2400 m from the lower tunnel portal. The fire starts at t = 0. There is a meteorological pressure difference of 30 Pa between the right and the left runnel portal. Two minutes from ignition the fire is detected and the traffic stopped. One minute later, the smoke extraction with 160 m^3/s is started. The traffic regime is an average traffic in the tunnel, 500 vehicles per hour in each direction travelling with 70 km/h uphill and 80 km/h downhill. In the left graph of figure 4 the flow velocity at the fire location is shown. In the right graph the two smoke fronts are shown.

The solid lines mark the smoke fronts in the case without jet fans. The extraction of 160 m^3/s is not sufficient to limit the smoke propagation against the meteorological pressure difference. But the solid line in the left diagram shows, that three minutes from fire detection the longitudinal flow in the tunnel has reached a somewhat steady state. Therefore four minutes from the fire detection, several jet fans can be switched on to limit the longitudinal flow (marked by the dashed lines in figure 4). The smoke front propagating along the tunnel can be stopped and the smoke can be controlled.

However, in a real case it is very difficult to obtain sufficient information about the flow in the tunnel. Jet fans used for the control of longitudinal flow must not be immersed in smoke. This would completely mix the smoke over the tunnel cross-section and block a possible escape route for the tunnel users. On the other hand the flow measurements must be verified for plausibility. In the presence of heat, there might be different velocities on the upper and lower part of the tunnel (smoke front velocity). The question arises if the flow has reached a steady state four minutes after switching on traffic lights. A single truck moving with 60 km/h in a tunnel has the same thrust as two small jet fans.

Consequently, it was found a very difficult task to devise a velocity control algorithm, although the improvement in terms of smoke control is clearly visible from the simulations. The computations showed that the use of jet fans to limit longitudinal flow velocity in a fire scenario requires extensive studies during the set-up of the control routine. For the tunnel la Vue-des-Alpes, an increased flow rate for the smoke extraction was not feasible. It was decided to install additional jet fans and to work on the control routines.

CONCLUSIONS

Refined analysis of ventilation systems is called for in order to increase safety without using extensive economic resources. 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 CFD simulations are called for.

A new model for analysing fire scenarios with arbitrary ventilation systems 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 jet fans, the tunnel wall friction, inlet and outlet pressure losses at the portals, the meteorological pressure differences and the influence of transversal ventilation on the momentum of the tunnel air. 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 model was implemented in a new computer code ‘Sprint’. The validation was based on results from the Memorial Fire Ventilation Test Program (9) as well as measurements at the Montblanc tunnel. ‘Sprint’ was able to reproduce the main experimental findings and gave rise to both qualitatively and quantitatively agreement with the experimental results.

The results of the validation effort and practical application of ‘Sprint’ were entirely satisfactory. The key features observed in case of a fire were reasonably well reproduced by the code. It was concluded that the new model is suitable for design and review work.

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