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## POSSIBILITY OF FIRE ACCIDENT ANALYSIS IN ROAD TUNNELS

### ABSTRACT

The basic aim of this treatise is to research the relevant features of the control and management of fire event in road tunnels. The simulation of 200 meters long cut out of the road tunnel is performed with the computer code FDS (Fire Dynamics Simulator) which is based on the computational fluid dynamics. FDS is used to simulate fire dynamics behavior in three different scenarios: natural ventilation, forced ventilation with axial ventilators and vertical smoke extraction.

It is believed that the present research, the methodology applied and its findings should promote and improve safety and reliability of fire safety in road tunnels and to cope with the complex contemporary logistic demands of safety and reliability in the transportation of passengers and goods.

### KEY WORDS

traffic safety, fire safety, road tunnel, fire modelling, computational fluid dynamics, numerical methods

### 1. INTRODUCTION

Accidental combustion and fire modelling are attractive research topics both from the academic and from the technical point of view. In fact, while many physical phenomena related to fires are still very far from being completely translated into formulas, their full understanding is highly desirable in order to prevent fires and, more important, to plan safety procedures and rescuing operations in case of fire. In particular, fire modelling in enclosures (such as railway or road tunnels) is a challenging research area with immediate practical benefits on the safety of people. Since closed analytical solutions are possible only in very simple cases, and experiments are often hazardous, recent developments received substantial contributions from the tools of computational fluid dynamics. On the other hand, theoretical approaches allow writing of improved algorithms for CFD codes, and

experiments provide a large amount of information useful in tuning the code parameters.

Longitudinal ventilation systems are characterized, if compared with more elaborated systems, by significantly lower investment, maintenance and exploitation costs. Their use has become more and more widespread recently, in particular because of the significant reduction of motor vehicle emissions [13].

The described fire model presents the behaviour of fire and smoke in a road tunnel. The most interesting is the effect of air supply and exhaust system on smoke movement. Does the ventilating system accelerate or choke fire and what is the optimum? The correct procedure for ventilators operation in case of fire accident plays the most important role to ensure the longest possible evacuation time. This is important information for planning of people evacuation.

### 2. RECENT FIRE ACCIDENTS

During the last five years many accidents occurred in tunnels with catastrophic results. The 11.6-km long Mont Blanc Tunnel was opened for traffic in 1965. At the time of the accident, its ventilation and safety concept thus corresponded to the design standards of 40 years ago. As in the case of all longer transalpine tunnels, the Mont Blanc tunnel is operated on a bi-directional basis. Seventeen fires have occurred in the tunnel since 1965, five of which required the fire brigade on the scene. In four of these cases, a heated-up engine was determined as the cause of the fire. There was not a single incidence of fire spreading to the neighbouring vehicles. On 24 March 1999, a refrigerator lorry carrying 9 tons of margarine and 12 tons of flour caught fire. It was coming from France and it stopped at the 6700-m station. A fully-fledged fire soon developed, which spread to involve 23 lorries and 10 cars. There were 39 fatalities among people [10].



Two months later, another terrible fire occurred in the 6400m-long Tauern Tunnel on 29 May, 1999. This tunnel is also operated bi-directionally. It is fitted with 30 emergency call bays set 212 m apart, 61 fire extinguishing bays every 106 m and a total of seven breakdown bays every 750 m. In 1998, this tunnel had to cope with 5.55 million vehicles. Including almost 1.05 million lorries (~19%). This corresponds to an average daily frequency of 15.000 vehicles, including 2800 lorries in both directions. At the time of the accident, there was a construction site in the tunnel with signal lights regulating traffic, which was confined to a single lane. A lorry travelling from the south drove into the end of the tailback at high speed and pushed four cars under the lorry stopped in front of them. This incident cost eight lives and resulted in the lorry catching fire. As a result, the flames spread to a lorry carrying a variety of goods. Its load included aerosols containing hair spray. Altogether, 14 lorries and 26 cars were destroyed by the fire. Apart from 12 dead, 49 other persons were injured.

The most recent fire catastrophes with fatal results occurred on 6 August 2001 in the 8.3 km-long single tube Gleinalm Tunnel in Austria and on 24 October 2001 in the nearly 17 km–again single tube – Gotthard Tunnel in Switzerland. In both cases the origin of the fire was head-on collision in the tunnels with bi-directional traffic. In the first case a car hit an oncoming mini bus because the driver was diverted by a squabble between his two children on the rear seats. Both vehicles caught fire immediately and five persons of the mini bus lost their lives. In the Gotthard Tunnel the accident started probably because of severe alcohol abuse of a truck driver. That truck driver lost control of his vehicle, drove snaky and crashed into an oncoming HGV (Heavy Goods Vehicle) truck. Both trucks immediately developed fire. The fire grew extremely fast causing tremendous masses of smoke because of the highly energetic fire loads. One truck was loaded with tyres, the other with plastic material. At the end 11 tunnel users died and 13 trucks, 4 vans as well as 6 cars burnt down. The false ceiling that separates the ventilation canals from the traffic space collapsed over a section of 200 to 250 m. For the re-opening of the tunnel 2 months after the fire the ventilation system was improved by enlargement of the extraction openings in the false ceiling. These openings are equipped with remote controlled louvers. It is one of the tragic aspects

linked with this accident that these improvements on the ventilation system had been already started before the fire occurred, but had not been finished yet at the time of the accident [10].

### 3. PHYSICAL BACKGROUND: HEAT AND SMOKE IN TUNNEL FIRES

From the point of view of tunnel safety the main parameters characterizing tunnel fires are the heat-release rate and the rate of smoke production. Depending on the ventilation system adopted, smoke-management procedures or smoke-extraction operations are required. Ventilation design is therefore based on appropriate information on smoke dynamics, either from experiments or computer simulations. The “EUREKA 499” test series, a joint European effort, was carried out during 1991 and 1992 in an abandoned mining tunnel in Repparfjord (Finnmark, Norway) (EUREKA 499 Report, 1996). The 25 tests involved both standardized fires (consisting of wood elements and heptane containers) and real-life fires (road and rail vehicles) with peak heat-release rates up to 150 MW. The results form an excellent database for characterizing fires in both road and rail tunnels. The experimentally observed heat-release rates for some road vehicles are presented in Figure 1. It is clearly seen that the nominal heat-release rates assumed in design fires, typically 30 MW for a loaded HGV, can in pick easily be exceeded 3 to 4 times, but only for relatively short time intervals.

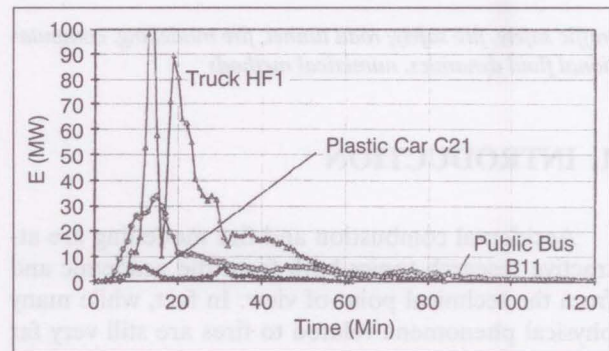


Figure 1 - Estimated heat release rates observed in the EUREKA 499 tests (EUREKA 499 report, 1996) [12]

Typical fires for ventilation system designs have also been defined and listed in Table 1.

Table 1 – Typical design fires for road tunnels ventilation design [12]

| Fire type                     | HRR (Heat release rate) | Smoke release rate        | Growth time | Duration time |
|-------------------------------|-------------------------|---------------------------|-------------|---------------|
| Small fires (cars)            | 5 - 10 MW               | 20 - 30 m <sup>3</sup> /s | 5 - 7 min   | 20 min        |
| HGV fires                     | 20 - 30 MW              | 60 - 80 m <sup>3</sup> /s | 10 min      | 60 min        |
| Large fires (dangerous goods) | 100 - 200 MW            | 300 m <sup>3</sup> /s     | 10 min      | 60 min        |



The experimental evidence with theoretical investigations suggests several important considerations for ventilation design:

Smoke propagation can be extremely fast. As shown by the observations in the EUREKA tests, it can easily reach 4 to 5 m/s even without mechanical ventilation and traffic influence.

Smoke stratification can allow for acceptable visibility over about 500 – 1,000 m and for a time of the order of 5 - 10 min. These values are highly dependent on the particular conditions in the tunnel and shall be considered as favourable.

The tunnel slope is extremely important in the development of a longitudinal airflow towards the higher entrance and therefore for smoke propagation. From this point of view slopes over 2% are to be considered as high.

Longitudinal ventilation using jet fans was shown to be capable of managing smoke and heat resulting from heat releases up to 100 MW and higher. The required longitudinal air velocity to prevent back-layering is typically of the order of 3 - 4 m/s for a 100 MW fire [8].

Adequate quantities of oxygen to support combustion were available from the tunnel air. The possible increase in fire intensity resulting from the initiation of ventilation did not outweigh the benefits [15], [14].

## 4. EXPERIMENTS AND NUMERICAL SIMULATIONS IN ROAD TUNNELS

Experiment and numerical simulations are often used in the tunnel design phase or when testing new materials and other safety and operating systems in a tunnel. There are three basic approaches to making tests; small-scale tests, large-scale tests and computer simulations. Full-scale tests are the most realistic and the results obtained are the most reliable. Small-scale tests are used for specific applications, when testing for example different types of ventilation systems. In the last fifteen years computer simulations are often used parallel with full-scale experiments. The correct assembling of the full-scale experiment is prepared using results of the numerical model and at the same time the computer model is improved and validated with experimental data [13].

### 4.1. Small-scale tests

Dimensional analysis allows devising scaling rules to extrapolate experimental conditions to similar situations with different dimensions. Two major assumptions are common when modelling buoyant smoke propagation in tunnel. The geometry of the structure is reproduced accurately and the Froude number best

represents the dynamics of the phenomenon. The approach maintains the balance of inertial to buoyancy forces, but does not correctly scale many other parameters and processes as fuel bed geometry and near field convection and radiative heat transfer rates.

Small-scale investigations are attractive because the experimental conditions are better controlled and the experimental set-up can be low-cost allowing parametric studies to be performed. The use of results on full scale depends on the accuracy of the scaling model implied and care is required in the design of the experiments to ensure that the relevant processes and phenomena are scaled correctly and the dynamic similarity is retained [13].

### 4.2. Full-scale tests

Full-scale tests are expensive and the characteristic dimensions of the structures tends to prohibit the installation of a comprehensive array of the instrumentation and limit the total number of experiments which can be undertaken. The large-scale tests have provided tantalizing snapshots of the tunnel fire phenomena, but have always fallen short to providing sufficient data to completely validate the functional relationship derived in laboratory tests. Examples of the well-known large-scale tunnel fire tests are: Ofenegg 1965 Svizzera, Futatsugoya 1968-1969, Giappone Amikake 1975, PWRI 1980, Zwenenberg 1974-1975, Austria EUREKA 499 "Firetun" Project 1990-1992, USA Memorial Tunnel 1993-1995, Prova a Fuoco in Galleria Stradale Colli Berici C. N. VV. F GR-DENER-C, Novembre 1999, Italy Tunnel del Monte Bianco November-January 2001-2002, Italy-France.

Fire tests are conceived as controlled fire events with the aim of measuring and recording the evolution of the characteristic thermo-fluid-dynamic parameters for a fire event as the mass burning rate, the temperature field inside the enclosure, the pressure differences induced by the fire event.

A fire test can be designed to test the effectiveness and the reliability of fire detection systems, the real performances of installed ventilation systems, as well as to characterize the indoor air quality and to record on photo-video apparatus the smoke layer evolution. Moreover, fire tests allow the verification of new equipments, materials, devices to detect and localize the fire sources, guide the people employed for fire suppression, first aid, security in localizing the injured and people in danger, evaluate the fire size by mapping the thermal field, perform smoke control, reduce the generation of combustion products, reduce the damage due to thermal effects on the tunnel linings and on the fire source [12].



### 4.3. Computer simulations

Computer simulation based on CFD technology is an important tool in fire research. Based on numerical solution of a system of partial differential equations that governs the involved physics, it offers a possibility to take the fundamentals of the involved sub-processes into better consideration. Due to the limit of the computer resources, the past attempts were based on the conventional relative cheap averaged simulation (RANS - Reynolds-Averaged Navier-Stokes) method, where the instantaneous equations are statistically averaged for solution and thus only the relatively smooth mean field needs to be resolved properly. Since turbulence is a property of flow, the constructed turbulence models in RANS can never be universal. With the parallel computing technology and the rapid growth of the computing power, it is now affordable to refine the consideration of the physics in the computation, for example to upgrade RANS to LES (Large Eddy Simulation). In LES, eddies down to the inertial range are resolved properly [16].

## 5. THEORETICAL MODEL

### 5.1. Thermo-hydrodynamic model

The fluid flow is modelled by solving the basic conservation equations. Those are conservation of mass, conservation of mixture fraction, conservation of momentum and conservation of energy using a form for low Mach number. The approximation involves the filtering out of acoustic waves.

$$\begin{aligned} \frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} &= 0 \\ \frac{\partial}{\partial t} (\rho Z) + \nabla \cdot \rho Z \mathbf{u} &= \nabla \cdot \rho D \nabla Z \\ \rho \left( \frac{\partial \mathbf{u}}{\partial t} + \frac{1}{2} \nabla |\mathbf{u}|^2 - \mathbf{u} \times \omega \right) + \nabla \tilde{p} &= (\rho - \rho_\infty) \mathbf{g} + \nabla \cdot \boldsymbol{\tau} \\ \rho c_p \left( \frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) &= \dot{q}_c^m - \nabla \cdot \mathbf{q}_R + \nabla \cdot k \nabla T \end{aligned}$$

Where  $\rho$  is a density,  $\mathbf{u}$  is a velocity vector,  $Z$  is the mixture fraction,  $T$  the temperature and  $D$  is molecular diffusivity.  $\tilde{p}$  is the perturbation pressure caused by pressure differences,  $\boldsymbol{\tau}$  the viscosity stress tensor and  $k$  thermal conductivity.  $\dot{q}_c^m$  and  $\nabla \cdot \mathbf{q}_R$  are the source terms of chemical reaction and radiation, respectively. The radiation term has a negative sign because it represents a heat sink [1].

Since the model assumes the low-Mach number flows, the pressure  $p_o$  is approximated to be an average value, which filters out the acoustic waves.

$$p_o = \rho T R \sum (Y_i / M_i)$$

$R$  is the general ideal gas constant and  $Y_i$  and  $M_i$  are the species mass fraction and molecular weight. In case of open space (tunnel),  $p_o$  is a constant value.

A very important approximation in the model is the following substitution in the momentum equation

$$\nabla \mathcal{K} \approx \frac{1}{2} \nabla |\mathbf{u}|^2 + \frac{1}{\rho} \nabla \tilde{p}$$

This approximation is equivalent to neglecting the baroclinic torque compared with buoyancy as source of vorticity [1]. The value of  $\mathcal{K}$  is solved by taking the divergence of the momentum equation, using the equation of state and solving the resulting Poisson equation by fast, direct method. The final form of momentum equation becomes

$$\frac{\partial \mathbf{u}}{\partial t} - \mathbf{u} \times \omega + \nabla \mathcal{K} = \frac{1}{\rho} ((\rho - \rho_\infty) \mathbf{g} + \nabla \cdot \boldsymbol{\tau})$$

The effect of the flow field turbulence is modelled using LES (Large Eddy Simulation), in which the large scale eddies are computed directly and the sub-grid scale dissipative processes are modelled. The unknown sub-grid stress tensor  $\boldsymbol{\tau}$  is modelled by Smagorinsky model.

### 5.2. Combustion model

The combustion model is based on the assumption that the combustion is mixing-controlled. This implies that all species of interest can be described in terms of the mixture fraction  $Z$ . Heat from the reaction of fuel and oxygen is released along an infinitely thin sheet where  $Z$  takes on its stoichiometric value as determined by the solution of the transport equation for  $Z$ . The heat release rate per unit area of flame surface is defined using the following equation [1].

$$\dot{q}'' = \Delta H_0 \frac{dY_O}{dZ} \Big|_{Z=Z_f} (\rho D) \nabla Z \cdot \mathbf{n}$$

$\Delta H_0$  is the energy released per unit mass of oxygen consumed,  $Y_O$  is mass fraction of oxygen and  $\mathbf{n}$  is the outward facing unit normal vector. Note that  $dY_O/dZ$  and  $\nabla Z \cdot \mathbf{n}$  are negative.  $\Delta H_0$  should correspond to the amount of oxygen originating outside the fuel. The state relations are calculated for a stoichiometric reaction of  $C_7H_{16}$  (Crude oil), which is proposed by [1], and called Crude oil reaction.

#### 5.2.1. Soot formation

Soot is an important contributor to thermal radiation in fire. In order to calculate the radiation accurately, soot must be considered. Due to the extreme complexity of soot formation process, no very good model is currently available for soot prediction in the combustion of solid fuel, although some significant progress in the soot modelling has been made in the recent years. In this paper soot was considered by as-



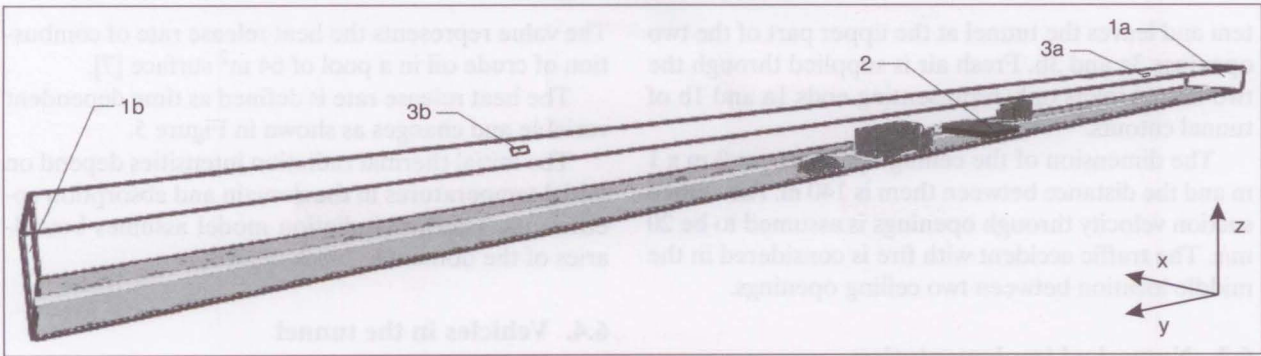


Figure 2 - Geometry of the model

suming a constant soot conversion factor, 11%, chosen with reference to experimental measurements (Alaskan Clean Seas Meso Scale tests - 1994). The soot formation rate was simply assumed to be proportional to the fuel supply rate [7].

## 6. GEOMETRY AND MODEL DEFINITION

### 6.1. Geometry of the model

Figure 2 shows the simplified geometry of the tunnel. Objects are numbered and specified in Table 1. The geometry assumed is a tunnel cut-out, 200 meters long, 10 meters wide and 50 meters high.

Three different simulations have been performed on a very similar geometry. Different boundary conditions have been applied to define different ventilation characteristics. Three simulations performed are listed below:

1. Natural ventilation;
2. Forced ventilation with axial ventilators located on the tunnel ceiling; and
3. Natural ventilation with smoke extraction system.

#### 6.1.1. Natural ventilation

Natural ventilation assumes openings 1a and 1b as open boundary condition in a mathematical model. The heat and mass released from the fire source are extracted from the tunnel by effect of buoyancy only. It is expected to be the worst scenario in the sense of smoke tunnel filling.

#### 6.1.2. Forced ventilation with axial ventilators

The second scenario assumes forced ventilation with axial ventilators on the tunnel ceiling. Real ventilators are not considered in the model, but are modelled as boundary conditions definition on surfaces 1a and 1b representing the ends of the tunnel cutouts. The boundary condition is defined as shown in Figure 3.

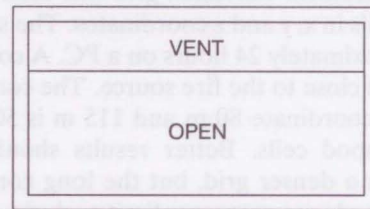


Figure 3 - Tunnel cross-section for boundary condition definition at tunnel ends of tunnel cut out 1a and 1b

Vent in Figure 3 is a boundary condition with a prescribed initial velocity 10 m/s in the direction  $y+$ . The value is assumed to be similar as used in tunnel applications for air movement. The vent height is 1 m. The rest of the surface has an open boundary condition prescribed.

#### 6.1.3. Natural ventilation with forced smoke extraction system

The third model assumes a tunnel with the smoke extraction system. The smoke extraction system is a very new safety system in tunnel applications. The system is activated automatically in case of higher smoke concentration. The ventilating system is located inside the tunnel ceiling as shown in Figure 4. Not all the smoke is extracted through the smoke extraction system.

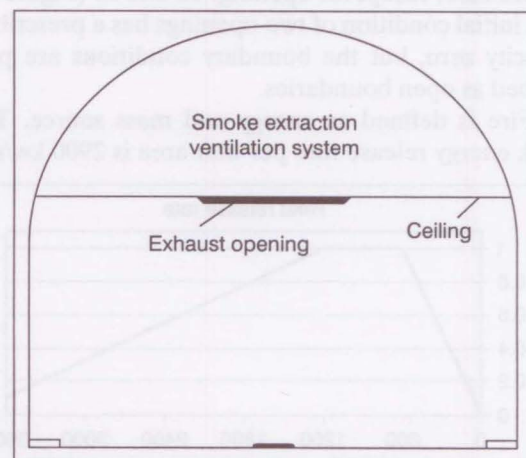


Figure 4 - Cross section of the tunnel with ceiling exhaust openings 3a and 3b



tem and leaves the tunnel at the upper part of the two openings 3a and 3b. Fresh air is supplied through the two tunnel inlets only representing ends 1a and 1b of tunnel cutouts.

The dimension of the ceiling openings are 3 m x 1 m and the distance between them is 140 m. Air-smoke suction velocity through openings is assumed to be 20 m/s. The traffic accident with fire is considered in the middle location between two ceiling openings.

## 6.2. Numerical implementation

A non-uniform Cartesian grid was used with 16 x 225 x 16 cells in x, y and z coordinates. The simulation takes approximately 24 hours on a PC. A compressed grid is used close to the fire source. The compression between y coordinate 80 m and 115 m is 50% of the neighbourhood cells. Better results should be obtained with a denser grid, but the long computation time and hardware resources limit such simulations.

Table 2 – Properties of the modelled elements

| No.  | Name | Properties                                   | Size       | Velocity |
|------|------|--|------------|----------|
| 1a,b | VENT | Open boundary condition <sup>2</sup>         | 10 m x 5 m | variable |
| 2    | Pool | HRRUPA <sup>1</sup> = 2900 kW/m <sup>2</sup> | 8 m x 8 m  | -        |
| 3a,b | VENT | Mass and Hear sink-ventilator <sup>2</sup>   | 2 m x 1 m  | 20 m/s   |

<sup>1</sup> Heat Release Rate per Unit Area

<sup>2</sup> Initial velocity profile may be applied

## 6.3. Initial and boundary condition

Temperatures of the numbered objects surfaces and domain boundaries (Figure 2), assume environmental temperature of 20°C. The velocity components at any domain boundary and within the domain are assumed zero, except for openings 1a and 1b (Figure 2). The initial condition of two openings has a prescribed velocity zero, but the boundary conditions are prescribed as open boundaries.

Fire is defined as energy and mass source. The peak energy release rate per unit area is 2900 kW/m<sup>2</sup>.

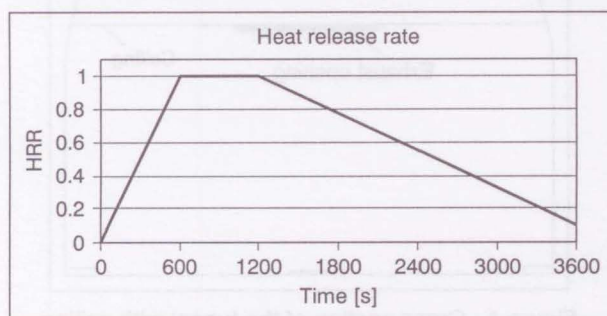


Figure 5 - Assumption of fire heat release rate

The value represents the heat release rate of combustion of crude oil in a pool of 64 m<sup>2</sup> surface [7].

The heat release rate is defined as time dependent variable and changes as shown in Figure 5.

The initial thermal radiation intensities depend on initial temperatures in the domain and absorption coefficients. Thermal radiation model assumes boundaries of the domain as black objects.

## 6.4. Vehicles in the tunnel

Obstacles representing cars are included in the model. Their location is shown in Figure 2. Only three vehicles are introduced in the model and their presence influences the development and the movement of the smoke in the tunnel. Number, type and location of vehicles during the real fire in the tunnel influence the development of fire events a great deal.

## 7. RESULTS

All three scenarios are analyzed and discussed. The analysis of results is focused on the quality, advantages and disadvantages of each ventilation system. The tunnel smoke filling is analyzed as a function of time, which is tightly related with the speed of people evacuation. The analyses of results propose new criteria to define the safety level during tunnel evacuation. It is called tunnel-filling criteria and is defined as a quotient of the total mass of fluids and the mass of combustion products inside the tunnel.

All three ventilation system results are presented with similar diagrams and figures. The first is a tunnel-filling ratio, the second and third are slices of soot concentration and temperature distribution respectively.

### 7.1.1. Natural ventilation model results

As supposed, natural ventilation is the worst regarding smoke extraction during fire event. The following figures show the characteristic dynamics of the fire in the tunnel.

Figure 6 shows that the final amount of smoke in a tunnel depends on the ventilation system. In case of natural ventilation the amount of smoke is around 20 to 22 percent. The remnant mass is the mass of air, it means of nitrogen and oxygen. The concentration of oxygen falls quickly under the level that is required for breathing.

Figures 7 and 8 show two basic parameters used to define the danger level in a tunnel. The temperature level is obviously very high and reaches the highest level under the ceiling. Lower temperatures are present in the lower half of the tunnel also because fresh air is entering from the bottom of the tunnel in-



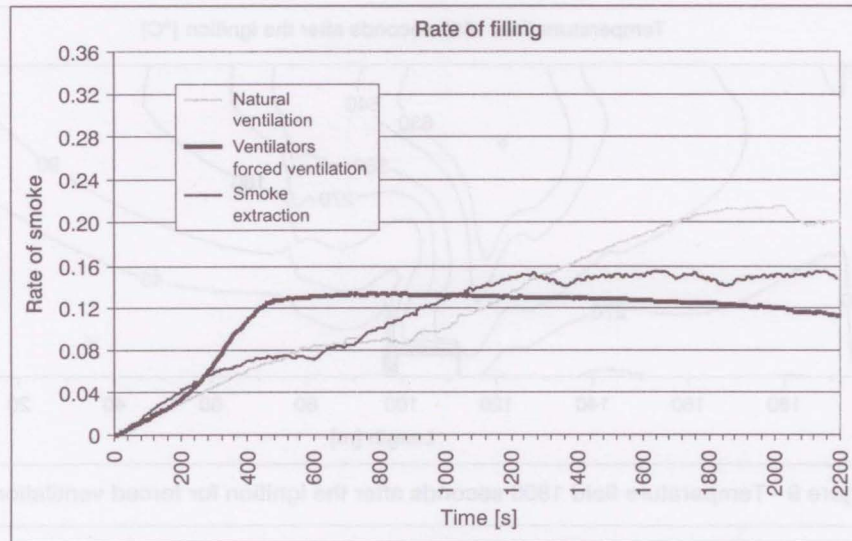


Figure 6 - Rate of smoke filling inside a tunnel

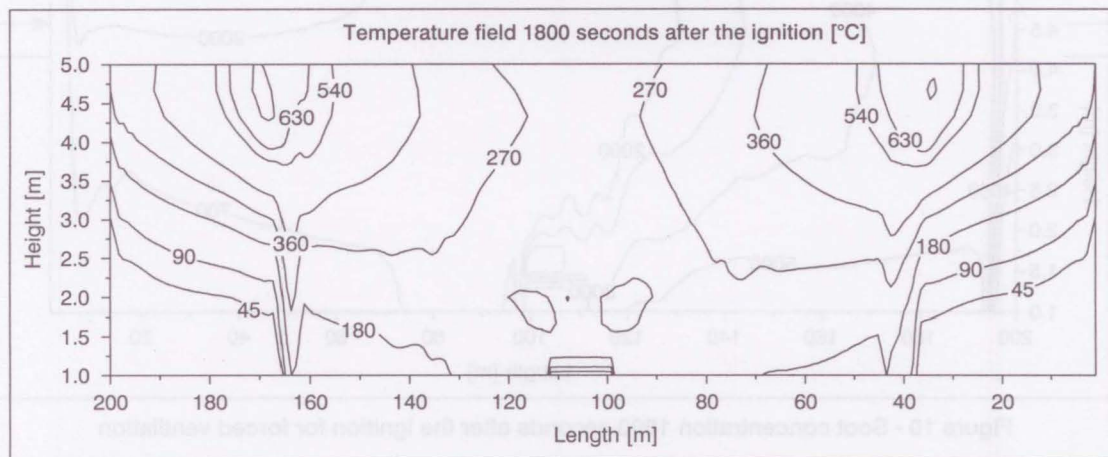


Figure 7 - Temperature field 1800 seconds after the ignition for natural ventilation

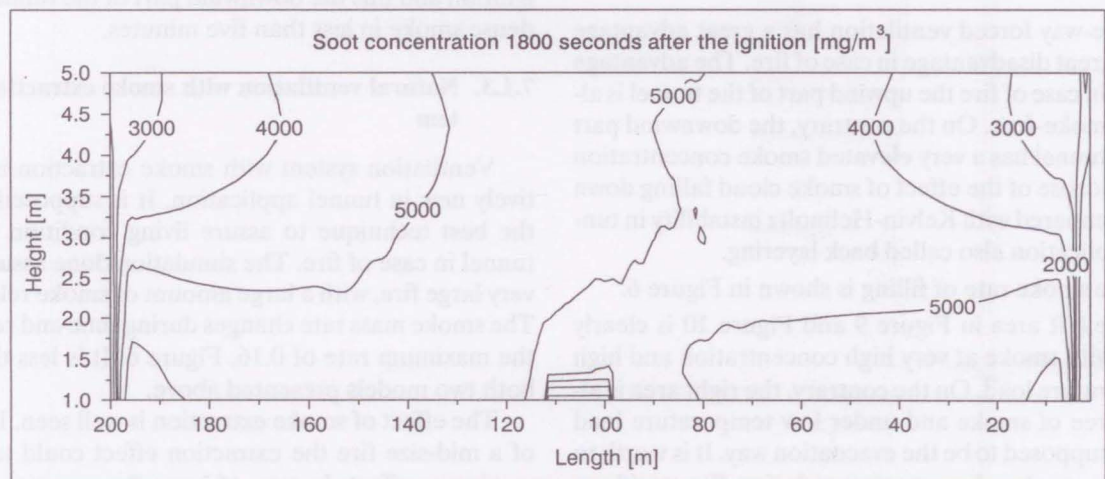


Figure 8 - Soot concentration 1800 seconds after the ignition in case of natural ventilation

lets. After 1200 seconds the heat release rate of the fire decreases and reaches the rate 0.8 of full power, 1800 seconds after the ignition. Soot concentration is very high and after 1800 seconds the environment in

the tunnel is absolutely uninhabitable. The upper limit of soot concentration is around  $100 \text{ mg/m}^3$ . The calculated values exceed this value fifty times and more [7].



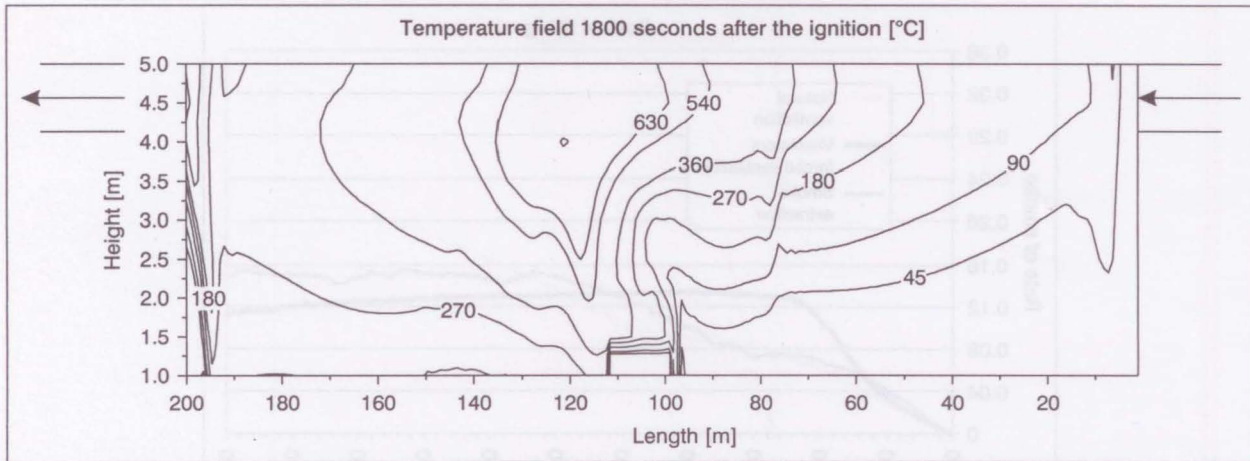


Figure 9 - Temperature field 1800 seconds after the ignition for forced ventilation

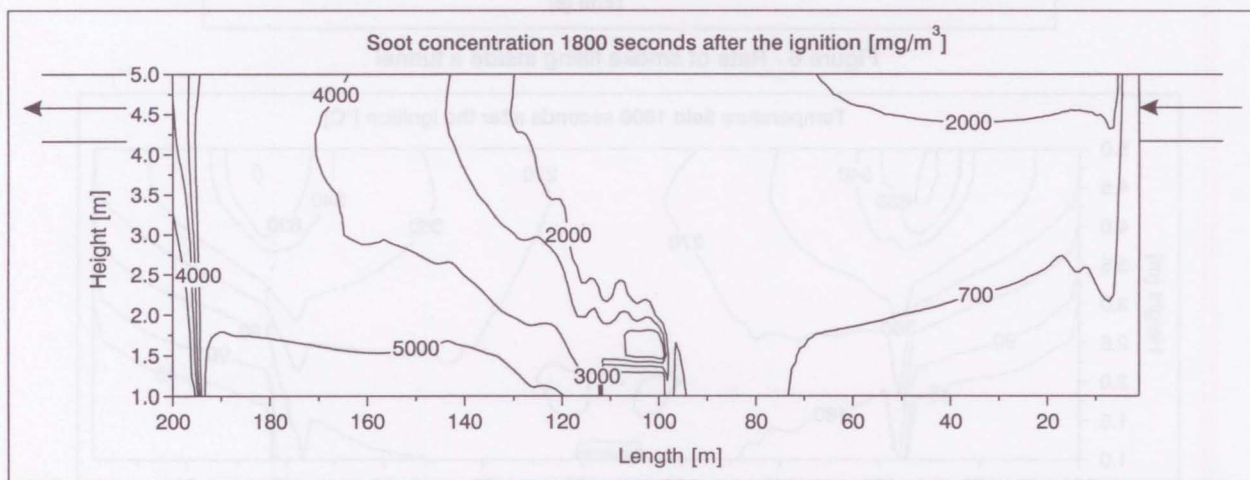


Figure 10 - Soot concentration 1800 seconds after the ignition for forced ventilation

**7.1.2. Forced ventilation using axial ventilators**

One-way forced ventilation has a great advantage and a great disadvantage in case of fire. The advantage is that in case of fire the upwind part of the tunnel is almost smoke-free. On the contrary, the downwind part of the tunnel has a very elevated smoke concentration also because of the effect of smoke cloud falling down also compared with Kelvin-Helmoltz instability in tunnel application also called back layering.

The smoke rate of filling is shown in Figure 6.

The left area in Figure 9 and Figure 10 is clearly filled with smoke at very high concentration and high temperature load. On the contrary, the right area is almost free of smoke and under low temperature load and is supposed to be the evacuation way. It is worth to inform people where to move during fire accident. Drivers and passengers on the left side or the downwind side could be in great trouble. Very dense smoke and high temperature do not allow them to choose the right way. The greatest problem is the velocity of the smoke cloud movement that is assisted by axial ventilators. It is calculated that smoke reaches the left end

of the tunnel cut out (Figure 10) 60 seconds after the ignition and fills the downwind part of the tunnel with dense smoke in less than five minutes.

**7.1.3. Natural ventilation with smoke extraction system**

Ventilation system with smoke extraction is relatively new in tunnel application. It is supposed to be the best technique to assure living condition in the tunnel in case of fire. The simulation done assumed a very large fire, with a large amount of smoke released. The smoke mass rate changes during time and reaches the maximum rate of 0.16, Figure 6. It is less than in both two models presented above.

The effect of smoke extraction is well seen. In case of a mid-size fire the extraction effect could take its maximum effect. In case of large fire, as assumed in the model, the dynamics of smoke changes which affects the quality of the smoke-extraction system.

The main flow streams and vortices formed are presented in Figure 11. Smoke extraction represents an air-smoke sink and changes the normal flow. Details (A) in Figure 11 show the tendency of smoke to



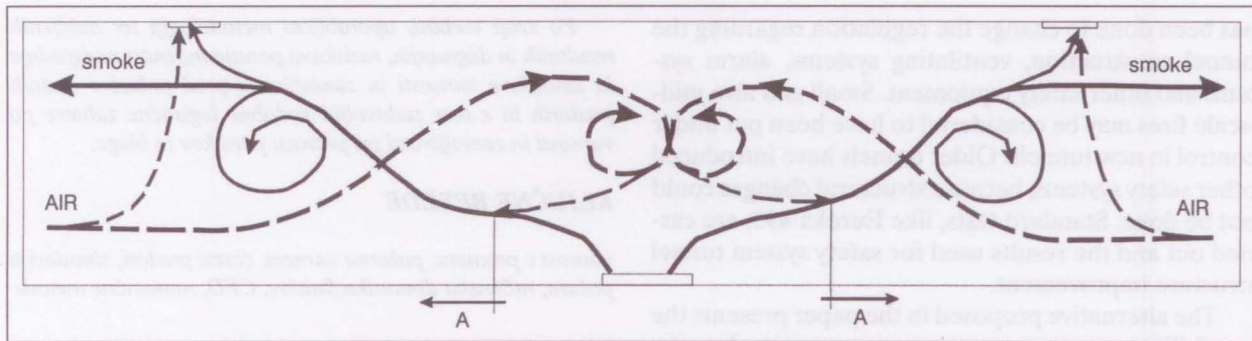


Figure 11 - Schematic view of main flow streams and vortices in case of ceiling smoke extraction

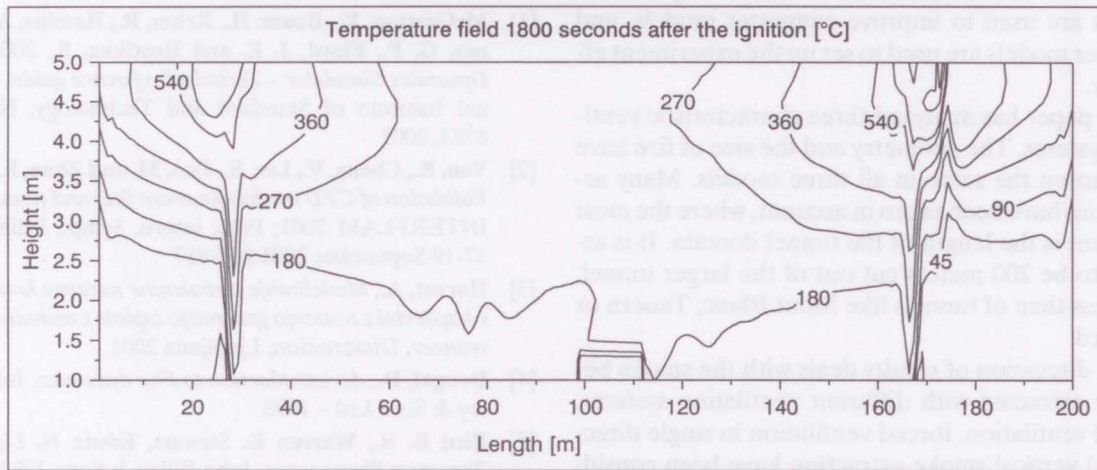


Figure 12 - Temperature field 1800 seconds after the ignition for smoke extraction

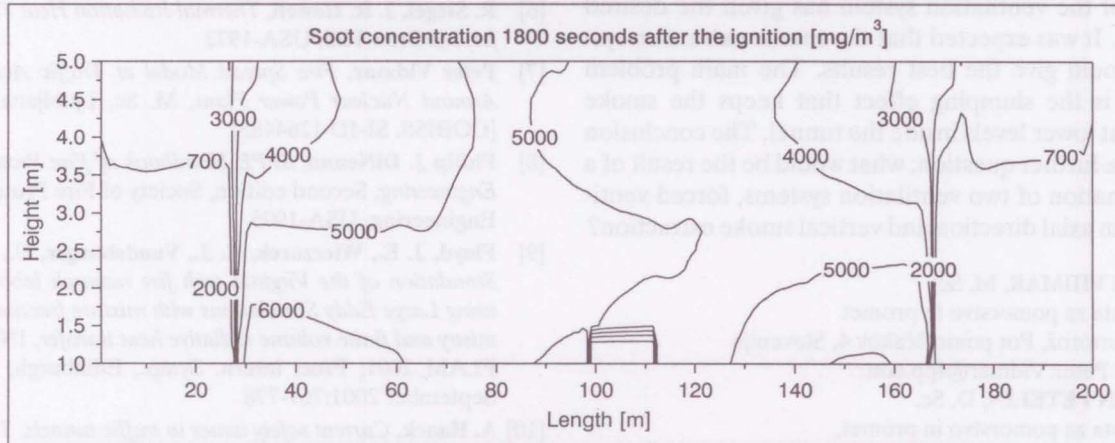


Figure 13 - Soot concentration 1800 seconds after the ignition for smoke extraction

travel at the lower layer of the tunnel. The smoke is kept down also because of the high density of soot. When smoke is kept at the lower layer, the fresh air ailments the fire from the upper part.

## 8. CONCLUSION

Figure 12 and Figure 13 show the temperature profile and smoke concentration levels respectively. The temperature level is slightly lower than in case of natural ventilation. However, the expected results were

more optimistic. The effect of heavy soot changes the dynamics of air-smoke movement. The simulation has shown that the smoke extraction was high enough to limit the smoke extension in the area between extraction openings. The main advantage found is that the velocity of smoke cloud movement is reduced because of extraction. The cloud slowdown is evidenced between 600 and 1200 seconds of simulation, when the maximum heat release rate is defined (Figure 6).

The reality of the fire danger in tunnels has become apparent after the catastrophic accidents that had occurred in the European tunnels. A lot of work



has been done to change the regulation regarding the tunnel construction, ventilating systems, alarm systems and other safety equipment. Small and also mid-scale fires may be considered to have been put under control in new tunnels. Older tunnels have introduced other safety systems, because structural changes could not be done. Standard tests, like Eureka 499, are carried out and the results used for safety system tunnel structure improvement.

The alternative proposed in the paper presents the possibility to use a computer program to simulate the behaviour of fire in the tunnel. Often, the experimental tests are used to improve computer models, and computer models are used to set up the experiment efficiently.

The paper has analyzed three characteristic ventilation systems. The geometry and the size of fire have been chosen the same in all three models. Many assumptions have been taken in account, where the most important is the length of the tunnel domain. It is assumed to be 200 meters cut out of the larger tunnel, much less than of tunnels like Mont Blanc, Tauern or Gotthard.

The discussion of results deals with the smoke behaviour extracted with different ventilation systems. Natural ventilation, forced ventilation in single direction and vertical smoke extraction have been considered and analyzed. Because of a very large fire defined none of the ventilation system has given the desired results. It was expected that the smoke extraction system would give the best results. The main problem found is the slumping effect that keeps the smoke cloud at lower levels inside the tunnel. The conclusion opens a further question: what would be the result of a combination of two ventilation systems, forced ventilation in axial direction and vertical smoke extraction?

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## POVZETEK

### MOŽNOST ANALIZE POŽARA V CESTNEM PREDORU

Osnovni cilj podane znanstvene razprave je analiza ključnih dejavnikov pri nadzoru in upravljanju požara v cestnem predoru. Simulacija 200 metrov dolgega izseka predora je izdelana z računalniškim programom FDS (Fire Dynamics Simulator), ki temelji na računski dinamiki fluidov. Model je uporabljen pri simulaciji treh različnih scenarijev ventilacije: naravna ventilacija, prisilna ventilacija v vzdolžni smeri ter ventilacija z izsesavanjem dima.

Po svoji vsebini, uporabljeni metodologiji ter dobljenih rezultatih in dognanjih, raziskava ponuja možnost nadgradnje in izboljšave varnosti in zanesljivosti pred požari v cestnih predorih in s tem zadovoljiti sodobne logistične zahteve po varnosti in zanesljivosti pri prevozu potnikov in blaga.

## KLJUČNE BESEDE

varnost v prometu, požarna varnost, cestni predori, simulacija požara, računska dinamika fluidov, CFD, numerične metode

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