APPLICATION OF ARTU SOFTWARE AND MULTIZONE FIRE MODELLING FOR RISK ANALYSIS: A ROAD TUNNEL CASE STUDY

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ABSTRACT

In the previous editions of the Graz Tunnel Conference (2020 and 2022), the ARTU software was presented through a case study (a 6 km tunnel with longitudinal ventilation). ARTU calculates the societal risk related to fire in tunnels combining probabilistic and deterministic approaches and different sub-models: fluid dynamics, queue formation, egress, interaction between environment and people.

The current release of ARTU incorporates a multizone fire model - developed along with Lund University - that permits a better description of the smoke stratification and back-layering, compared to 1D fluid dynamic model.

In the present paper the current version of ARTU is presented through the results of the risk analysis of a 3 km road tunnel with jet-fans and smoke extraction shafts. Risk analysis results are expressed by means of FN curve and damage expected value. The results are compared with the ones obtained by the previous version of ARTU, which was based on 1D fluid-dynamic and did not include multizone fluid-dynamic model.

In order to analyze the effect of the back-layering phenomenon on the overall risk, a sensitivity analysis is done modifying longitudinal velocity and observing how this impacts the results obtained through the multizone fluid-dynamic model.

An in-depth study is performed about the smoke layer height, using CFD simulations to check the stratification prediction made by the multizone model.

Keywords: Tunnel risk analysis, 2004/54/EC, 1D fluid dynamics, zone modelling, Multi-Zone Fire model.

1. INTRODUCTION

Since the publication of the Directive 2004/54/EC of the European Parliament, related to tunnels within the Trans-European Road Network which are longer than 500 meters [1], risk assessment has become an integral part of tunnel design [2]. Furthermore, an appropriate risk assessment of existing and new facilities can be a useful tool to assess tunnel safety levels and inform decision makers and designers upon solutions to be adopted [3].

Based on these premises, Cantene developed a tunnel risk analysis tool called ARTU (acronym in Italian for Risk Analysis in Tunnels) [4][5]. ARTU performs the risk assessment of a tunnel simulating a large number of scenarios. Each scenario involves the fire in a different position and with a different HRR (Heat Release Rate) curve. Furthermore, scenarios vary for what concerns number and characteristics of people inside the tunnel. Each scenario returns a certain number of fatalities, the results are cumulated and plotted on a FN diagram.

ARTU combines probabilistic and deterministic approaches, including different sub-models: fluid dynamics, queue formation, egress, interaction between tenability conditions and people.

The fluid-dynamics is represented by means of 1D and zone models. One-dimensional (1D) models include geometrical data and characteristics of the ventilation system, representing the system under analysis as a network made by branches and nodes. 1D models returns time-varying air temperature, air velocity, and volume airflow by means of one value for each

variable at a set distance from the fire, representing an average over the cross-section of the branch. As a consequence, 1D models are not suitable to simulate the fluid behaviour in regions characterised by high temperature or velocity gradients, typically close to the flames or in the regions where well-defined smoke stratification is found [3].
Zone models are promising because they make it possible to represent phenomena like stratification and back-layering, keeping the computational cost relatively low. Nevertheless, when applying control volume equations to tunnel fires, consideration should be given to the unique nature of some fire phenomena in tunnels: (i) the ratio between length and height of the simulated domain; (ii) the representation of ventilation devices used in tunnels, such as jet-fans, that may require dedicated model input calibration efforts [3].
ARTU implements a zone modelling tool originally developed by Lund University, called the Multi-Zone Model [6]. The tool has been improved by the developers with the contribution of the authors of this paper, in order to make it suitable to the tunnel fire application. The model represents the entire enclosure through several smaller computational volumes (zones), for which the conservation of mass and energy are applied. Fire is specified as a heat release rate and empirical models are used to represent the plume and the ceiling jet [7]. A dedicated model validation for tunnel applications has been conducted through benchmarking against experimental data. Model results were also compared against results from the Fire Dynamics Simulator (FDS) [10]. The results of the benchmarking indicate that the Multi-Zone Fire model performs well 50–200 m away from the fire for heat release rates of 5–20 MW and moderate longitudinal ventilation flows [7]. Taking into account these results, currently the Multi-Zone Model is used in ARTU as an additional model to determine tenability conditions in the vicinity of fire during the initial phase of emergency.
The tool is still under development in order to improve its modelling capabilities and accuracy for tunnel fires. As an example, the Multi-Zone Fire model uses an empirical plume model that does not account for the effect of forced ventilation on the plume air entrainment. Another aspect that needs to be improved is the fact that the Multi-Zone Fire model does not include the turbulent mixing between zones and this could be an issue if the longitudinal ventilation flow is high [7]. Furthermore, the accuracy in the momentum conservation needs more efforts. More details about ARTU and the Multi-Zone Fire can be found in references [4][5][6][7][8].
This paper introduces a tunnel case study in which the use of ARTU is demonstrated while using its Multi-Zone component. The effect of the use of Multi-Zone model in the assessment of risk is presented. Then, a particular case is discussed, when the tunnel operates in maintenance configuration. As discussed in the following, in this case the risk predicted using 1D model is fictitiously equal to 0 and the Multi-Zone Model becomes crucial in risk assessment, due to its capability to represent stratification and back-layering. To further test the Multi-Zone approach, this is hence compared to a Computational Fluid Dynamics approach (e.g. using the Fire Dynamics Simulator, FDS) for the investigation of smoke stratification, and theoretical formula for the back-layering representation.

2. CASE STUDY

The case study is a bidirectional, urban, single-bore, 3190m long tunnel. The cross-section varies along the tunnel length from 55 to 165m^2. The tunnel is provided with 2 intermediate entrance ramps. The ventilation strategy is based on the smoke extraction by means of a vent near the fire (see a schematic drawing in Figure 1). Jet-fans are used to balance the pressure in order to assure a near-zero longitudinal velocity next to the fire. This in order to prevent smoke moving along the tunnel instead of being pulled out from extraction vent.

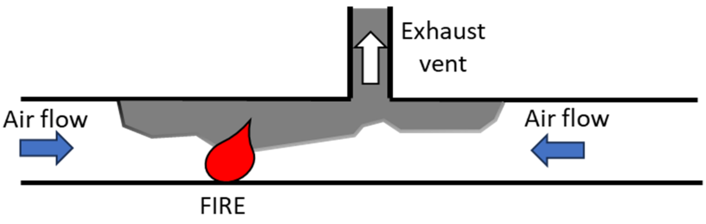


Figure 1: Single point extraction system

Figure 2 shows the longitudinal profile of the tunnel and the position of jet-fans, smoke extraction vents and entrance ramps.

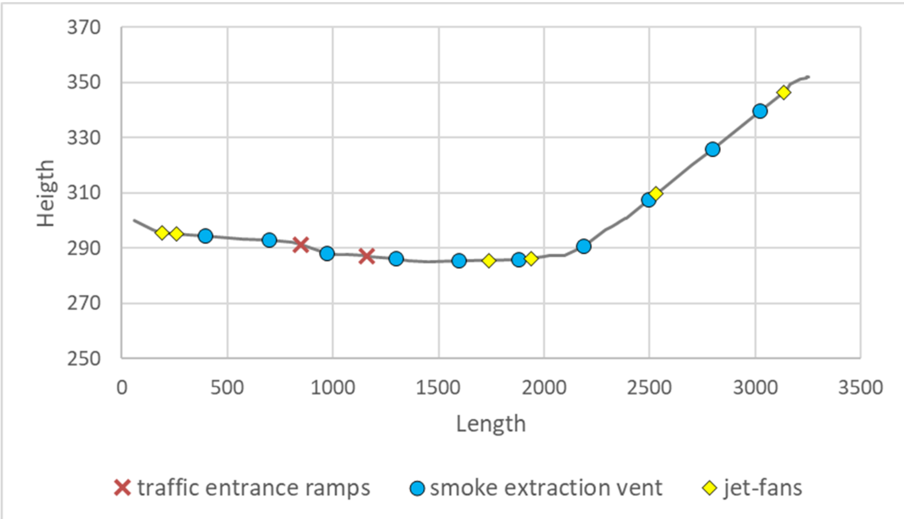


Figure 2: Longitudinal profile of the tunnel

2.1. Results of ARTU risk analysis

ARTU risk analysis has been performed both including and not including the Multi-Zone Model. Figure 3 shows the FN curves and the expected value of damage (EV), i.e., the integral of the FN curve.

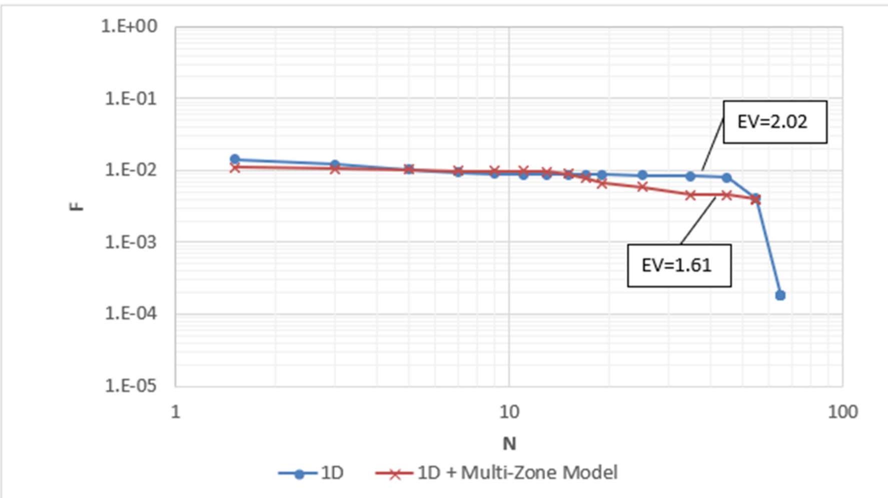


Figure 3: FN curves

Table 1 shows the results in terms of percentage of fatalities and chemical FED (Fractional Effective Dose) among all the analyzed scenarios used to create the FN curve. FED allows to quantify the interaction between people and smoke, taking into account the presence of toxicant, asphyxiant gases and hypoxia. FED equal to zero corresponds to no interaction. FED can be used in relation to different thresholds (e.g. incapacitation or lethal doses). FED incapacitation equal to one means that half of the population would be expected to be incapacitated [9].

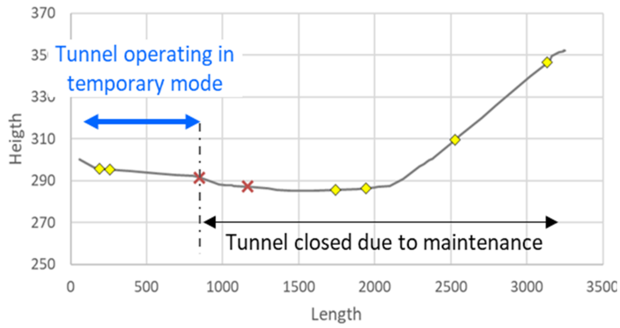
Table 1: Maximum and average scenarios results

	1D		1D + Multi-Zone Model	
	maximum	average	maximum	average
Fatalities	7%	0.09%	5%	0.05%
Chemical FED	0.63	0.04	0.45	0.02

Both the FN curves of Figure 3 and results of Table 1 show that the risk level estimated using the Multi-Zone Model is lower than the one based solely on 1D model. This is due to the fact that near the fire the 1D model does not take into account the stratification of smoke. 1D model considers the smoke as homogeneously distributed in the cross section of the tunnel. As a consequence - in the cases in which a stratification exists and hot smoke are confined in the upper part of the tunnel - a conservative estimation of the interaction between people and smoke is made above human height.
Since the capability to represent the smoke layer is a crucial point in the development and validation of the tool, an example of the smoke layer representation in the Multi-Zone Model is given in the chapter 3.

2.2. Temporary operation mode

When maintenance works are planned, the case study tunnel operates in temporary operation mode. Only the first section of the tunnel (from the lower portal to the first ramp at ~800m length) is opened to traffic (see Figure 4, left image). Traffic is monodirectional from the ramp to the portal. In case of emergency, a longitudinal ventilation mode is operated by jet-fans, pushing smoke through the portal.
Before the ventilation system activates, the smoke naturally tends to move toward the highest portal due to the tunnel slope. Nevertheless, the smoke velocity generated by the chimney effect in the first phase of fire is presumably lower than the critical. As a consequence, the traffic queue located downwards the fire (see Figure 4, image on the right) is exposed to the smoke back-layering. After the mechanical ventilation is activated, smoke are confined downstream the fire.



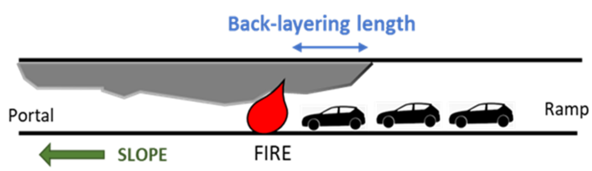


Figure 4: Tunnel (left) and smoke dynamic (right) in temporary operation mode

In this case, the expected value of risk calculated by means of the 1D model is equal to zero, because back-layering cannot be represented in 1D models (Figure 5).

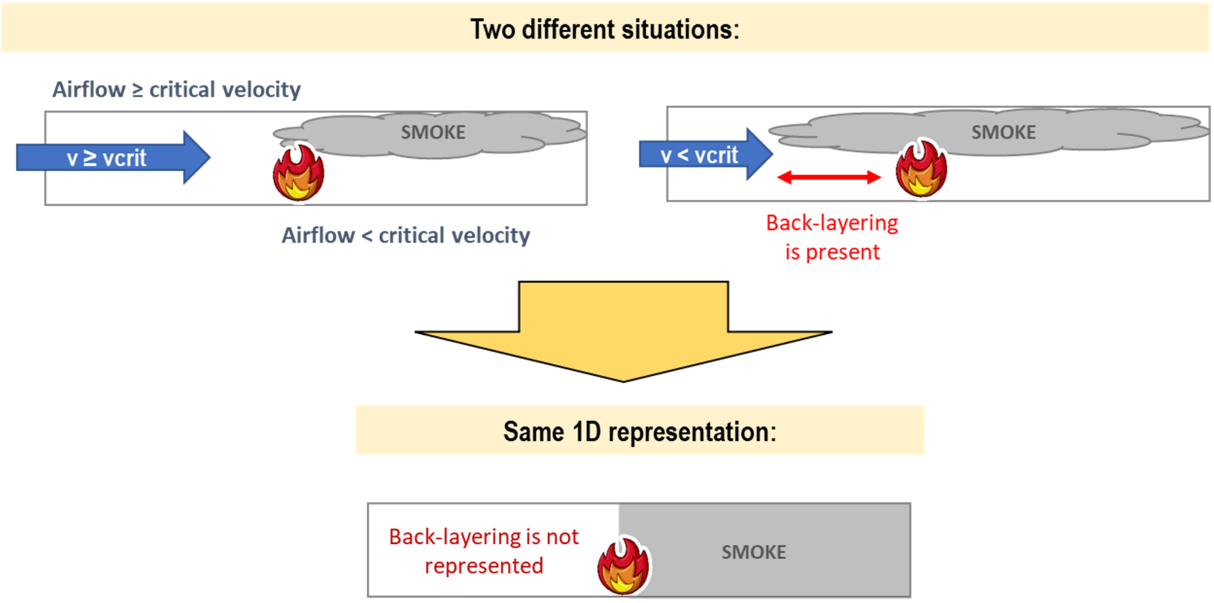


Figure 5: 1D representation of cases with different longitudinal ventilation

In this case, the use of Multi-Zone model is crucial for a proper assessment of the risk. An in-depth analysis of the back-layering representation in the Multi-Zone Model is given in chapter 4.

3. SMOKE STRATIFICATION REPRESENTATION IN THE MULTI-ZONE MODEL

To evaluate the capability of the Multi-Zone Model to address the representation of a smoke layer, a simple case test is analyzed with both the Multi-Zone Model and FDS. FDS (Fire Dynamic Simulator) [10] is a computational fluid dynamics model of fire-driven fluid flow that solves numerically the Navier-Stokes equations. Even though some issues arise when applying FDS to tunnels ([11][12][13]), this is a well-established and widely used model in fire engineering and tunnel ventilation design.

A simple test tunnel is used, in order to better appreciate the smoke stratification dynamic. This is different than the case study presented above. The tunnel is 200m long, with 80m^2 rectangular cross section shape (height 8 m, width 10m), no slope and no mechanical ventilation. The fire source has a constant heat release equal to 8MW and is located in the center of the tunnel.

Figure 6 and Figure 7 show the distribution of temperature on a vertical plane in correspondence to the tunnel longitudinal axis, at two different time steps.

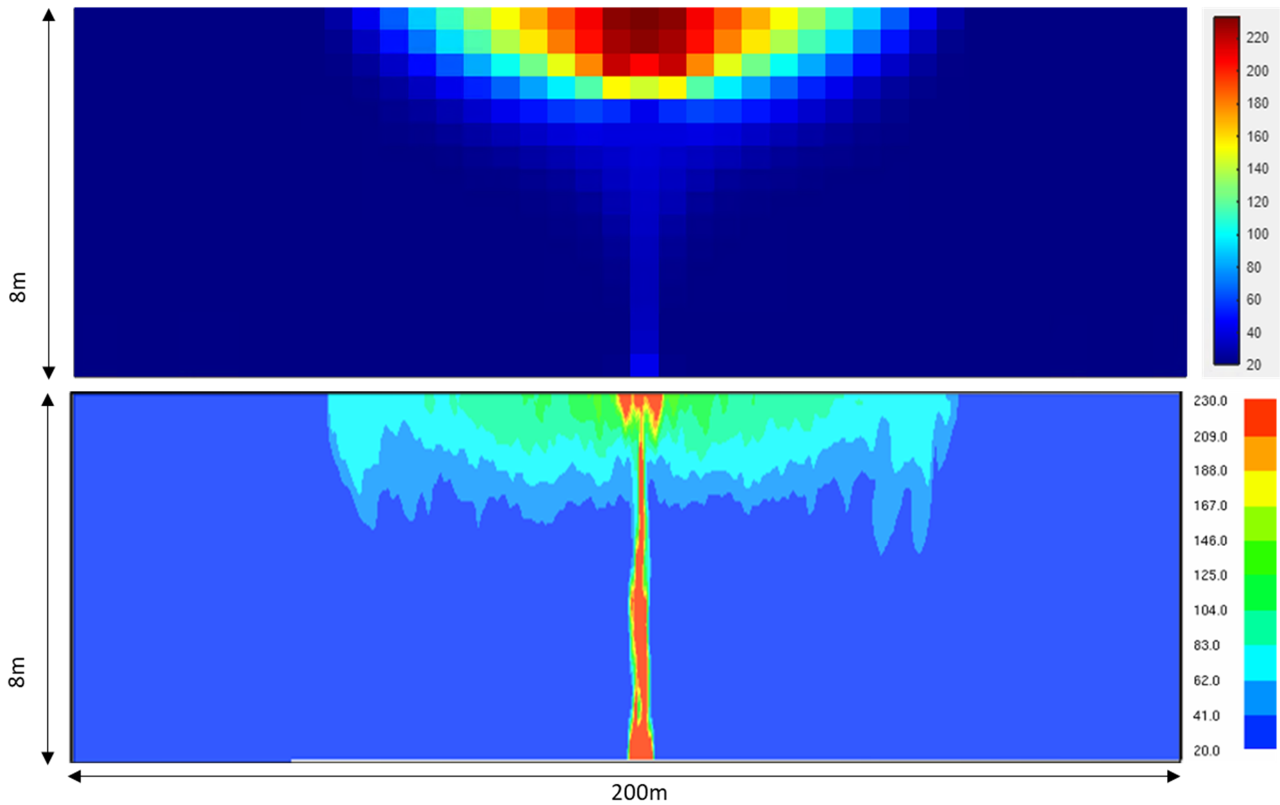


Figure 6: Stratification comparison between MZ (up) and FDS (down), 30s from ignition

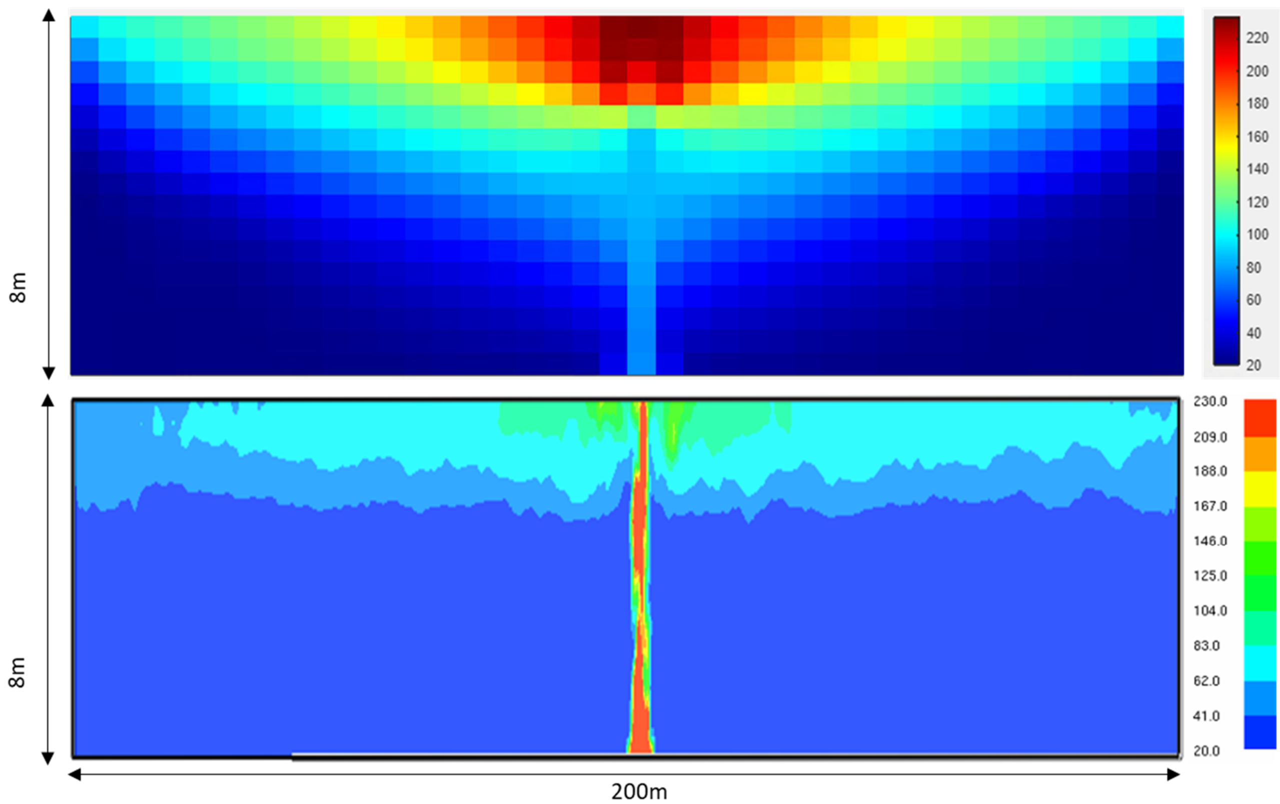


Figure 7: Stratification comparison between MZ (up) and FDS (down), 300s from ignition

At 30 seconds (Figure 6), when the smoke has not yet reached the portals, the extension of the area affected by smoke is the same in the Multi-Zone Model and FDS. Both the figures show that the Multi-Zone Model tends to overestimate temperature and the thickness of the smoke layer, in particular far from the portals. In general, a slower smoke propagation has been observed in the Multi-Zone Model respect to FDS simulations.
The main difference between the two models is the representation of the plume. in FDS the plume is fully represented by means of the solution of Navier-Stokes equations. In the Multi-Zone Model, an empirical model is used (Heskestad [14]). The fire plume rises until it hits the ceiling, entraining air and hot gases from the zones that it passes through. To account for momentum conservation when a fire plume hits the ceiling and a horizontal flow created, an empirical ceiling jet model is used. The ceiling jet velocity is introduced as a hydrodynamic pressure term in the model [7]. This aspect is crucial in the application of the Multi-Zone Model to tunnels respect to the application in large enclosures, and needs to be further investigated in order to assure that the momentum is conserved throughout the length of the domain.

4. BACK-LAYERING LENGTH ESTIMATION

In general, ventilation systems are designed to avoid back-layering. Longitudinal ventilation systems push the smoke downstream the fire. Transverse and semi-transverse ventilation systems push the smoke in a specific area of the tunnel, next to the extraction point (smoke confinement). Nevertheless, there are some situations in which the confinement of smoke is not achieved. This happens for example 1) in the first phase of fire since the ventilation system has not been activated yet, 2) in tunnels that are not provided with mechanical ventilation, 3) in case of ventilation system failure. In these cases, when back-layering arises, the use of 1D models could lead to an under-estimation of the interaction between people and fire products. The Multi-Zone Model indeed has a crucial role in the estimation of risk level.

The back-layering length is defined as the length of the smoke back-layering upstream of the fire when the ventilation velocity is lower than the critical, and can be expressed by the correlation proposed by Li et al. [16]. Li et al. carried out two series of tests in model-scale tunnels based on a dimensional analysis, and found that the back-layering length increases with the HRR for low HRRs and is nearly independent of HRR and dependent only on the ventilation velocity at higher HRRs. It is shown that the relationship between the ratio of longitudinal ventilation velocity to critical velocity and the dimensionless back-layering length approximately follows an exponential relation. [15]. Li et al. correlation is reported below.

$$L_b^* = \frac{L_b}{H} = \begin{cases} 18.5 ln\left(0.81\dfrac{Q^{*\frac{1}{3}}}{u^*}\right) & Q^* \leq 0.15 \\ 18.5\ln\left(\dfrac{0.43}{u^*}\right) & Q^* > 0.15 \end{cases}$$

$$Q^* = \frac{\dot{Q}}{\rho_0 c_p T_0 g^{\frac{1}{2}} H^{\frac{5}{2}}} \qquad u^* = \frac{u}{\sqrt{gH}}$$

Where g is the gravitational acceleration (m/s^2), H is the tunnel height (m), ρ_0 is the ambient density (kg/m^3), u is the velocity (m/s). $\dot{Q}$ is the total heat release rate (HRR) (kW), c_p is the heat of capacity (kJ/(kg K)), T_0 is the ambient temperature.

In order to evaluate the capability of the Multi-Zone Model in representing the back-layering phenomenon, a comparison is made between the values obtained from the model and the formula reported above. Table 2 shows the back-layering length estimated for the simple 200m long tunnel presented in previous chapter, in which a 8MW fire is located. The critical velocity is estimated by the following formula [14] and is equal to 2.5m/s.

$$u_c^* = \begin{cases} 0.81 Q^{*1/3} & Q^* \leq 0.15 \\ 0.43 & Q^* > 0.15 \end{cases}$$

Estimation of back-layering length by the Multi-Zone Model is made taking into account the temperature vs tunnel length in the upper zone. Zones are 5m long (along the longitudinal axis of the tunnel), 2.5m width and 0.5 high.
Figure 8 shows the temperature vs tunnel length in correspondence of the zone next to the ceiling, at steady-state conditions, estimated by the Multi-Zone Model. It can be seen that the higher the velocity, the lower the temperatures both downstream and upstream the fire.

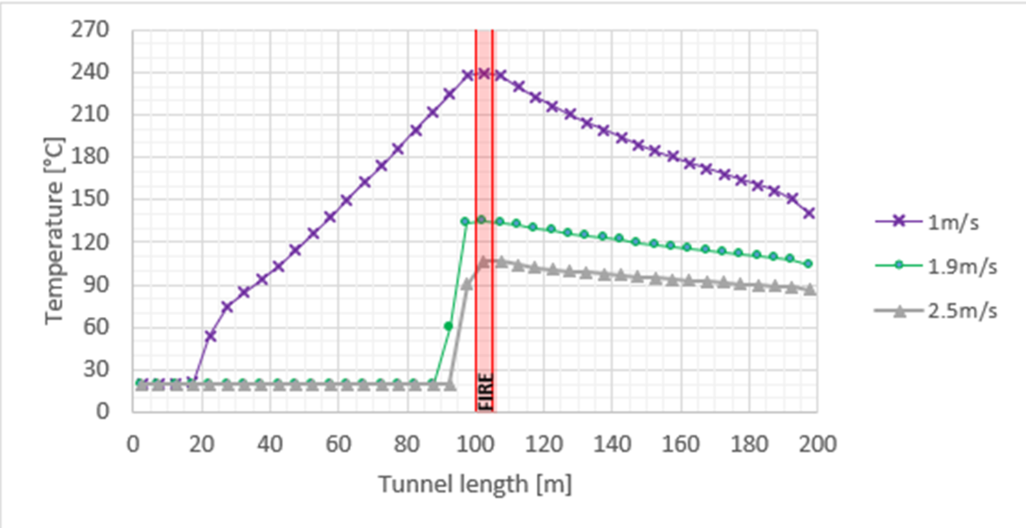


Figure 8: Back-layering representation in the Multi-Zone Model

Table 2 summarizes back-layering length obtained by formula presented above and Multi-Zone Model.

Table 2: back-layering length (formula vs Multi-Zone Model)

Longitudinal velocity	Formula	Multi-Zone Model
1.0m/s	103m	80m
1.9m/s	43m	10m
2.5m/s	0m	5m

The back-layering length estimated by means of the formula is higher than the one estimated by the Multi-Zone Model, when the longitudinal velocity is lower than the critical value. In the case in which the longitudinal velocity is equal to the critical value, the Multi-Zone Model shows a back-layering equal to 5m. It must be noted that the model resolution in the longitudinal axis is equal to 5m.
In general, the back-layering length is under-estimated by the Multi-Zone Model, and the accuracy increases when the ratio between critical velocity and actual longitudinal velocity is higher.

In the risk analysis, the Multi-Zone tool is used in the first phase of fire, when the longitudinal velocity is low. This is the phase in which the Multi-Zone tool prediction of back-layering is most accurate.

5. SUMMARY AND CONCLUSION

The Multi-Zone Model - which development is on-going thanks to the collaboration with Lund University - shows promising results in the accuracy of smoke dynamic representation. Typical three-dimensional phenomena that cannot be represented by means of 1D models, can be depicted using the Multi-Zone Model. This expands the possible range of applicability of the software ARTU, including tunnels which safety strategy is based on the stratification of smoke (transverse and semi-transverse ventilation systems, naturally ventilated tunnel with low slope). In these cases, the 1D model cannot represent the stratification, and over-estimation of fatalities occurs. On the other hand, the possibility to predict the back-layering length solves the 1D blindness to the diffusion of smoke at low velocity, typical during first phase of fire when ventilation system has not reached the target velocity, or in case of ventilation system failure. This makes the Multi-Zone tool suitable for increasing accuracy in the risk assessment of tunnel with longitudinal ventilation.
The accuracy gain in the estimation of risk depends on the type of tunnel and ventilation strategy. It is higher for naturally ventilated tunnels with low slope and tunnels with exhaust vents. The current version of the Multi-Zone Model shows in general a conservative estimation of smoke layer thickness and temperature, compared with the Fire Dynamics Simulator, and an under-estimation of the back-layering length especially for velocity near to the critical value, compared with analytical formula. Further development of the Multi-Zone Model will be aimed at addressing these issues.

6. ACKNOWLEDGEMENT

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