 DOI: 10.3217/978-3-85125-883-7-20

THE APPLICATION OF ZONE MODELLING IN THE RISK ANALYSIS OF TUNNELS WITH ARTU SOFTWARE

[1]Michele Fronterre, [2]Rugiada Scozzari

[1]Cantene s.r.l., IT

ABSTRACT

Cantene has developed a software tool called ARTU, acronym for "Risk Analysis in Tunnels", that calculates the societal risk related to fire in tunnels. The tool combines probabilistic and deterministic approaches, including different sub-models: 1D fluid dynamics, queue formation, egress, interaction between fluid-dynamic conditions and people. Recently, a new version has been released, that includes zone modelling in the representation of fluid dynamics. Zone modelling makes it possible to represent phenomena like back-layering and smoke stratification that cannot be represented by 1D fluid-dynamic tools. These phenomena are particularly significant in the first phase of the fire, when mechanical ventilation has not reached the nominal airflow and the egress takes place. The stratification of smoke has particular importance in tunnels without mechanical ventilation due to the fact that the fire products move undisturbed. A zone modelling tool developed by Lund University was chosen and many adjustments were made along with the developers in order to make the software suitable to the tunnel fire application. The areas of applicability of the tool were also investigated. As a results, the zone modelling software has been integrated into ARTU, in order to automatically manage a multiscale analysis depending on the characteristics of the analysed tunnel.

Keywords: Risk analysis, 2004/54/EC, 1D fluid dynamics, probabilistic approach, validation, zone modelling, tunnel.

1. INTRODUCTION

Tunnels often represent crucial nodes of a road network, as they may represent points of connection between two otherwise disconnected areas or even allow for transnational connection between countries. For this reason, tunnel fires can have catastrophic consequences in terms of traffic disruption, property damage, and, more importantly loss of lives [1]. 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 [2]), risk assessment has become an integral part of tunnel design [3]. 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 [4].

Based on these premises, the Italian fire engineering and thermal science company Cantene srl developed a tunnel risk analysis tool called ARTU (acronym in Italian for Risk Analysis in Tunnels). This tool adopts a probabilistic approach to estimate the expected number of fatalities per year in existing and new tunnels. ARTU uses an approach based on pseudo-random sampling from distributions to define hundreds of different fire and egress scenarios. Random variables include pre-movement time and egress velocity, fire position, and the type of vehicle on fire (design fire). A deterministic approach is used to describe the interaction between fire products and people involved in each scenario [5].

ARTU estimation of risk is based on the analysis of a large number of different scenarios. Hence, in order to keep the computational cost acceptable, fluid dynamics representation is based on 1D model. Despite its low computational requirement, this modelling approach prevents the representation of phenomena like smoke stratification and back-layering that can occur in presence of low longitudinal velocity. These phenomena are common in naturally ventilated tunnels with small slope, when the fire is growing and not fully developed. Furthermore in mechanical ventilated tunnel, smoke stratification can be a desired effect during the egress of occupants, in order to ensure that a layer free of smoke in the lower part of tunnel section can be used as a mean of egress. ARTU's aim is to evaluate societal risk, namely expected number of fatalities per year, so its focus is on the first phase of the fire, i.e., during egress. A more detailed description of smoke stratification in the vicinity of the fire and during the first phase of the fire has the potential to better represent the interaction between occupants and fire, leading to a more accurate evaluation of societal risk [5].

2. TUNNEL FIRE MODELLING APPROACHES

The main modelling methods for the study of fire and smoke in tunnels are here presented considering increasing complexity and computational cost.

One-dimensional (1D) network models represent a system as a one-dimensional network of nodes, containing a single set of variables such as temperature, density, mass treated as homogeneous, and node connections that represent 1D transfer conduits between nodes [5]. The 1D model returns time-varying air temperature, air velocity, and volume airflow along the tunnel. The intrinsic limitations of 1D models are that the flow quantities are assumed to be homogeneous in each cross-section. As a consequence, 1D models are not suitable to simulate the fluid behaviour in regions characterised by high temperature or velocity gradients. These regions are the ones close to the flames or in the regions where well-defined smoke stratification is found [1].

Zone models represent a compartment as multiple uniform zones (typically two zones: a hot upper layer and a cooler lower layer). Zone models solve conservation equations between the uniform zones and typically include empirical relationships for phenomena such as fires and plume flow. Zone models are limited by the geometry they can represent (simple, cuboidal compartments) but are solved relatively quickly [5]. When applying control volume equations to tunnel fires, consideration should be given to the unique nature of some fire phenomena in tunnels. For example (i) an assumption that hot-layer properties are homogeneous along the length of the tunnel will only be tenable for very short tunnels; (ii) ambient and forced ventilation flows in tunnels may affect air entrainment in plumes; (iii) the relative velocities of hot and cold layers may mean that shear mixing effects at the interface may not be negligible [1]. Nevertheless, the use of tunnel fire zone models in probabilistic tunnel risk modelling is not a novel approach [6].

Field models, also called computational fluid dynamics (CFD) models, divide a domain into finite elements or volumes for which conservation equations are solved. Each finite element holds a set of conserved variables. Field models can be used to examine complex geometry but require large storage space, high computation requirements and have a high computational cost [7]. The physical behaviour of the fluid is represented by means of mathematical models, and it is possible to extend the description of the fluid to include effects such as turbulence, buoyancy, combustion and heat transfer by radiation and convection, all in a single simultaneous calculation. When solutions are obtained, they should be reviewed taking into account the influence of grid size and time step, what influence do boundary conditions have on the solution, adequate convergence of solution [1].

As systems in the built environment are getting larger and more complex, hybrid approaches (also called multiscale approaches) started arising. Computational limitations mean that the calculation domain must be curtailed, ignoring the two-way coupling between the total system and a fire. Coupled hybrid modelling (adoption of coupled fire dynamics sub-models with a range of computational costs) expands the domain and analyses of this two-way coupling within a reasonable timeframe [7].

3. DESCRIPTION OF THE SOFTWARE ARTU

ARTU estimates the expected number of fatalities per year in existing and new tunnels. A queue-formation model is used to determine the initial position of people along the tunnel, taking into account data about traffic conditions. The path of each person inside the tunnel towards the exit is calculated assuming that the people in a straight or curved tunnel can only move in one direction (along the tunnel wall), which can be approximated with a 1D modelling approach. ARTU takes into account the presence of other people in the surroundings and the reduction of visibility due to smoke. The estimation of damage is based on the effects of smoke on people, estimated by means of the FED (Fractional Effective Dose) parameter. For the majority of toxic products in a fire atmosphere, incapacitation or death occurs when the victim has inhaled a particular product dose of toxicant [8]. As with toxic gases, an exposed occupant can be considered to accumulate a dose of convected heat over a period of time [9]. ARTU calculates the FED for each person in the domain, based on oxygen, carbon monoxide, carbon dioxide concentration and gas temperature, obtained from the results of the fluid-dynamics routine.

For the fluid dynamics representation, the first release of ARTU used a third party software based on 1D fluid dynamics which includes geometrical data and characteristics of the ventilation system. The software returns time-varying air temperature, air velocity, and volume airflow along the tunnel. Since it is a 1D tool, it returns only one value for each variable at a set distance from the fire. This value represent an average over the cross-section of the tunnel.

To improve the resolution of the fire modelling representation available in ARTU, Cantene initiated a research project together with the Division of Fire Safety Engineering at Lund University. The aim of the project was to include zone modelling in ARTU with a multiscale approach.

4. THE MULTI-ZONE MODEL

The multi-zone model integrated within ARTU is based on an existing tool, the MZ Fire model [10], used to calculate the effects of a fire in an enclosure. The overall concept of a multi-zone model has been presented in previous publications [11].

The enclosure is divided into several regions (horizontal) and layers (vertical) this means that the entire enclosure is made up of several smaller computational volumes or zones that extends in the x-, y- and z-direction. The conservation of mass and energy are applied for each zone and the calculated properties (like temperature) are uniform in each zone. The fire is specified as a heat release rate and the heat and hot gases rises upwards from the fire in a plume that enters the highest located layer in the fire region, until it hits the ceiling. Plume mass flow is calculated with Heskestad's plume model [12]. The plume equation is developed from data of pool fires up to a diameter of 2.5 m [13] that is assumed to be axisymmetric and not influenced by wind. Air and hot gases are entrained in the plume from the layers that it passes through. Mass is transported horizontally to layers in adjacent regions due to hydrostatic pressure differences. The driving mechanism behind the transport of smoke in the MZ Fire model is temperature differences between the different zones. This makes the implementation difficult when momentum forces become important. To account for momentum resulting from when a fire plume hits the ceiling and a horizontal flow created, an empirical ceiling jet model is used. The vertical flow of mass between layers is calculated based on the conservation of mass.

Heat is transferred to solid obstructions through convection and radiation, and through 1-D conduction in obstructions. Heat is transferred between zones through the flow of hot gases and radiation [5].

5. APPLYING MULTI-ZONE MODEL TO TUNNELS

The MZ Fire model, which originally was developed for large enclosures, has been updated and adapted for tunnel environments. In fact, the use of zone models requires carefully consideration of: (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. The integration of MZ Fire model into ARTU involved a set of developments needed specifically for tunnel fire scenarios (e.g. tunnel gradient and tunnel section representations). In addition, an analysis has been done to determine the MZ model domain of application. Analysis was done by means of a benchmarking with full scale test data and field model simulations. Figure 1 compares the ceiling gas temperatures at different distance from fire obtained by empirical test, FDS field model simulation and MZ model simulation. The data refers to the Runehamar tunnel test T1, where an HRR with peak equal to 205 MW after 20 minutes from ignition was estimated.

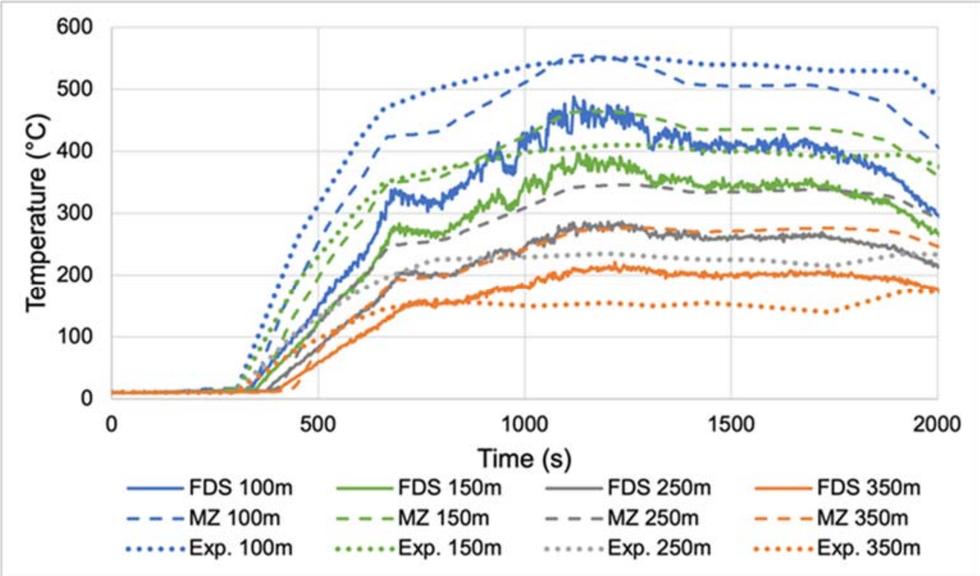

Figure 1: ceiling gas temperatures at different distances from the fire for the Runehamar tunnel test T1 [5]

Figure 1 shows that the ceiling jet temperatures closer to the fire source (100-150 m) are predicted well by the MZ Fire model, while the temperatures further away (250+ m) are over predicted. In general, MZ predicts a higher temperature closer to the ceiling, and lower temperature at the lower levels. The average temperature over the height is corrected. Nevertheless, since the focus is on predict the interaction between people and smoke, the under estimation of temperature in the lower height is not acceptable. For this reason, applicability of MZ model is set to HRR lower than 20MW, based on the extensive benchmark reported in [5]. In addition, benchmark results showed that MZ model can be suitably applied to short portion of tunnels (<200m from fire). These applicability limits make the zone model particularly appropriate to determine the tenability conditions in the vicinity of fire, during the first phase of emergency, when egress takes place.

6. CASE STUDY

The selected case study is a bidirectional tunnel with natural ventilation.

Table 1: the case study

Length	910m
Cross sectional area	60m^2
Slope	0.5%
Number of emergency exit	None
Traffic direction	Bidirectional
Average annual daily traffic	8.460 veh/day
% of heavy goods vehicle	9%
Ventilation system	Natural
Fixed-fire extinguishing system	None

An analysis was done for a fire 50m from left portal involving a light vehicle. The corresponding HRR is taken from [13]. Peak value is reached in 300s from the ignition and corresponds to 8MW.

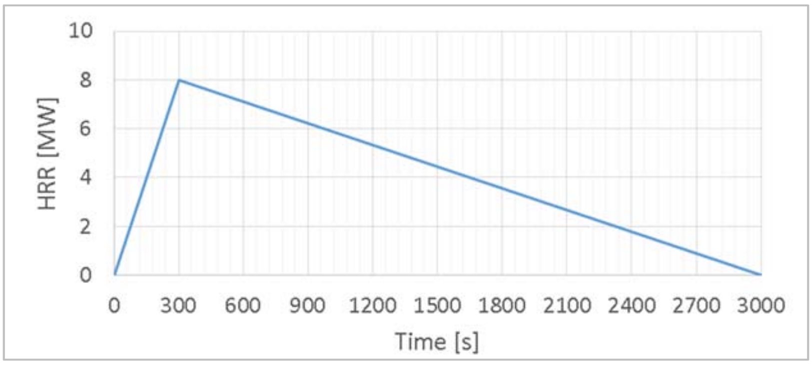

Figure 2: HRR curve

Figure 3 and Figure 4 show a comparison between the results obtained by the 1D and the zone modelling tool. In each figure, the upper graph shows the results from 1D model. The second graph shows the results from zone model that are related to a shorter domain (100m) in the vicinity of fire. The lower graph shows the combination of the two models, thus the multiscale approach result. Results from 1D model are averaged on the cross section of tunnel, while results from zone model are taken at 2 m from the floor, along the tunnel axis.

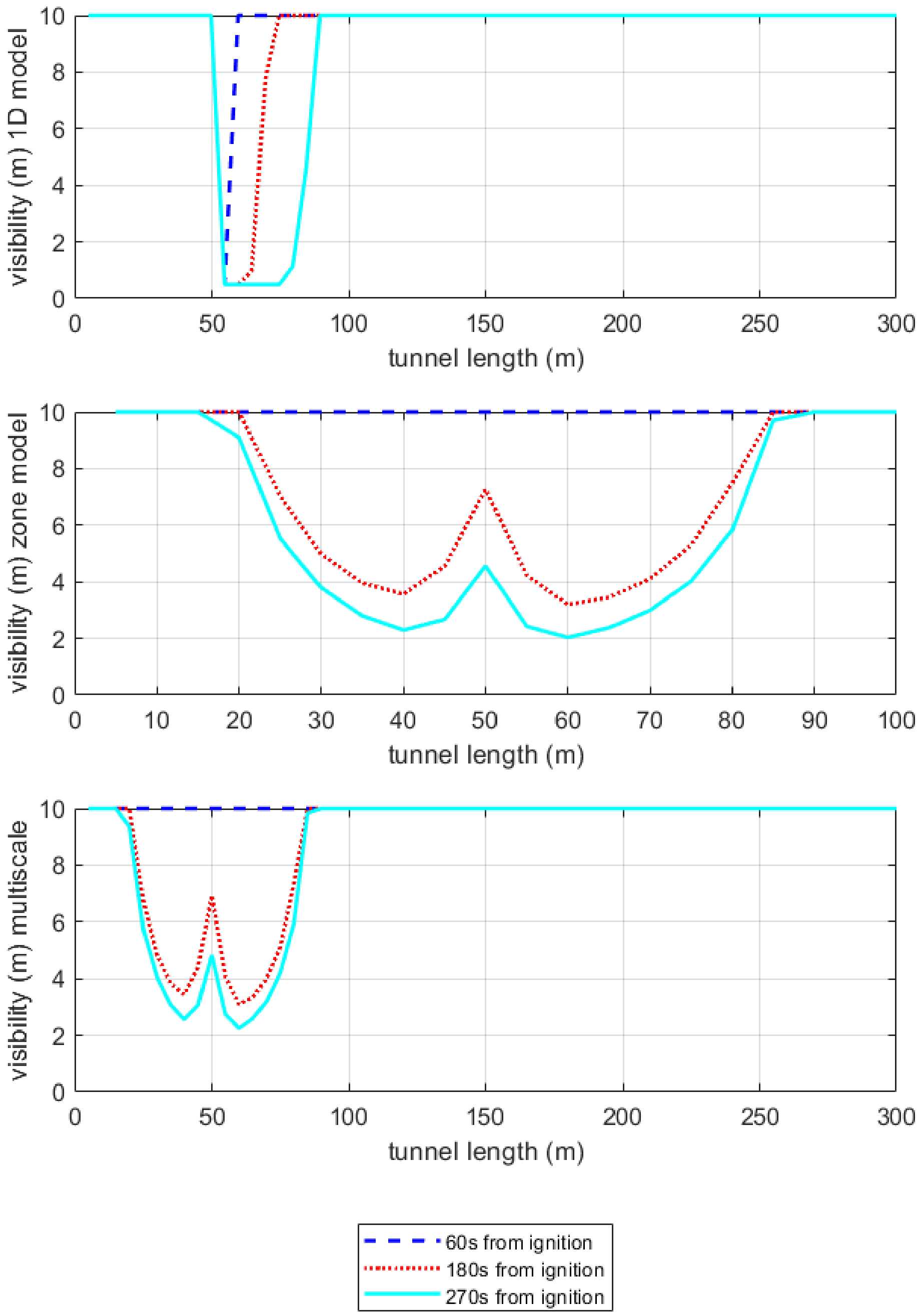

Figure 3: visibility along the tunnel at 3 different times

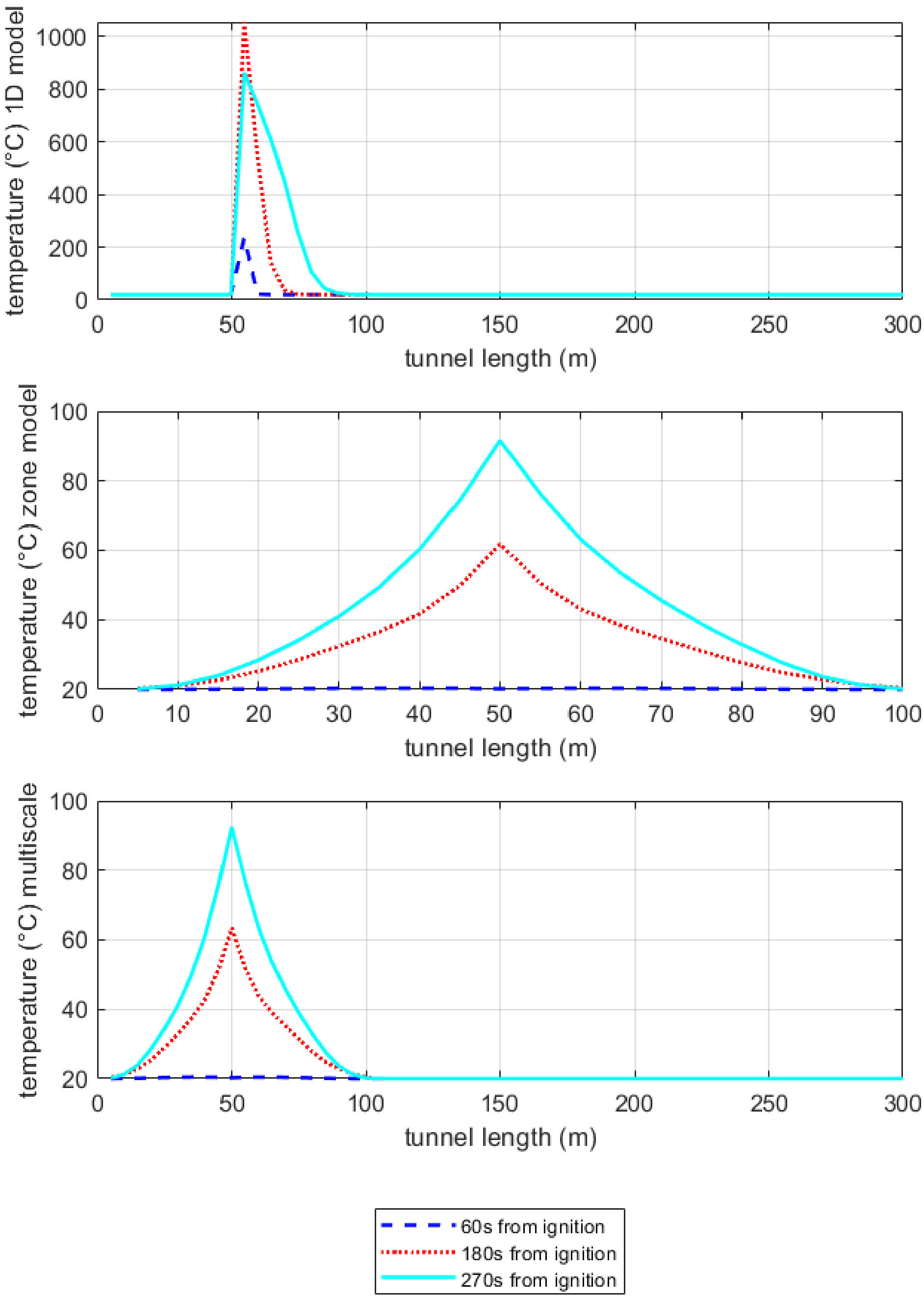

Figure 4: temperature along the tunnel at 3 different times

Applying zone modelling instead of 1D modelling makes the risk estimation more accurate, as explained in the following.

(i) 1D models gives a too conservative estimation for both temperature and visibility, in particular in the first 60 seconds from the ignition. In fact, when using 1D models, an implicit hypothesis is done that if there is smoke in a section of tunnel, people interact with it, because smoke is assumed as homogeneously spread in the tunnel cross section. Zone models instead, make it possible to estimate the smoke layer height, thus leading to a more precise estimation of users-smoke interaction (Figure 5).

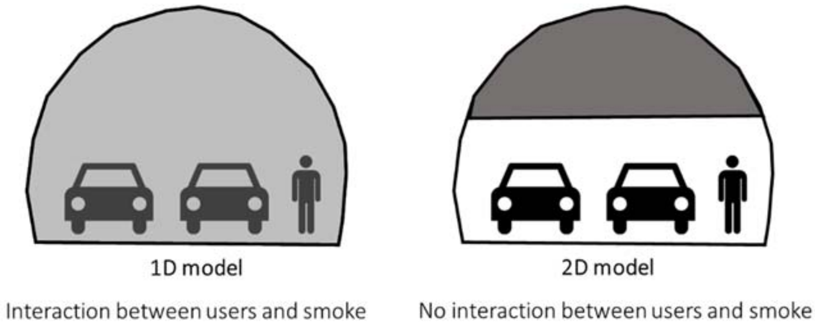

Figure 5: different estimation of users-smoke interaction

(ii) Zone modelling makes it possible to investigate the dynamic of smoke in the vicinity of fire. As described by [15], at a short distance from the point where the fire plume impinges on the tunnel ceiling, the smoke flow transits to a longitudinal flow on both sides in a tunnel with essentially no longitudinal ventilation and nearly no slope. Eventually such a layer will become thicker and descend towards the tunnel floor. This can be seen in the particular shape of the visibility output from zone model.

(iii) The zone model estimates the effect of slope in a more precise way than the 1D model. In 1D results, the smoke is pushed through the right portal by the effect of buoyancy. No back layering is represented because of the intrinsic limitation of this kind of model. 1D modelling cannot describe back-layering in case of a longitudinal velocity lower than critical value (Figure 6). The zone model instead shows the presence of back-layering through the left portal.

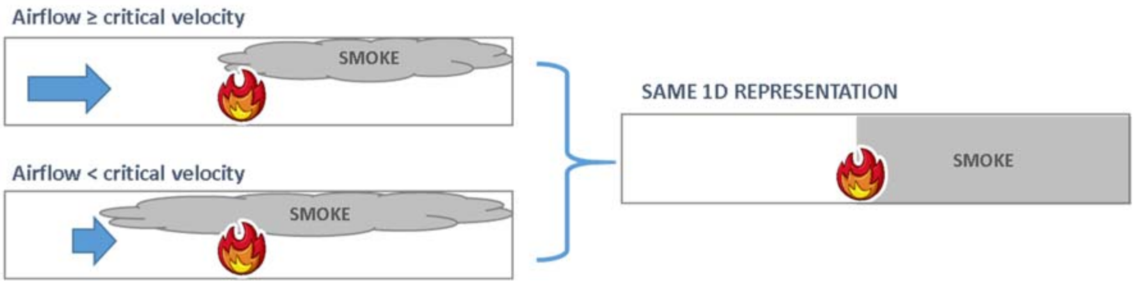

Figure 6: 1D representation of cases with different longitudinal ventilation

7. SUMMARY AND CONCLUSIONS

Zone modelling provides an alternative modelling concept to simple one-dimensional models and more advanced CFD models. The strength of the zone modelling compared to the 1D models is that it is possible to get the vertical and horizontal distribution of e.g., temperature and visibility in the simulated domain. Regarding more advanced models, the benefit of the MZ Fire model is that the simulation time is much smaller. Even if the results are promising caution should be taken when using the model, since it includes several simplifying assumptions. For this reason, it should be kept in mind that the zone modelling is a complement to other models and tools. For some situations a one-dimensional model might be more adequate. All in all, the possibility to switch between a more or less refined representations of tunnel fire dynamics (still having computational times that do not impede the use of this approach) offers more flexibility to the tunnel fire safety designer and expands the possible range of applicability of ARTU [5].

8. REFERENCES

[1] Beard, A., & Carvel, R. (2012). Handbook of Tunnel Fire Safety, 2nd edition. London, UK: ICE Publishing.

[2] The European Parliament. (2004). DIRECTIVE 2004/54/EC. Official Journal of the European Union.

[3] Kohl, B., Botschek, K., & Hörhan, R. (2007). Austrian Risk Analysis for Road Tunnels. Development of a new Method for the Risk Assessment of Road Tunnels. First International Tunnel Safety Forum for Road and Rail. Lisbon, Portugal.

[4] Beard, A. (2010). Tunnel safety, risk assessment and decision-making. Tunnelling and Underground Space Technology 25, 91-94.

[5] Johansson, N., Ronchi, E., Scozzari, R., & Fronterrè, M. (2021). The use of multi-zone modelling for tunnel fire risk analysis. Lund, Sweden: Lund University.

[6] Riess, I., Bettelini, M., Brandt, R., "Sprint - a Design Tool for Fire Ventilation," 10th International Symposium on Aerodynamics and Ventilation of Vehicle Tunnels, Boston, 2000.

[7] Ralph, B., & Carvel, R. (2018). Coupled hybrid modelling in fire safety engineering; a literature review. Fire Safety Journal, 157-170.

[8] Purser, D., & McAllister, J. (2016). Assessment of Hazards to Occupants from Smoke, Toxic Gases, and Heat. In M. Hurley, SFPE Handbook of Fire Protection Engineering, 5th edition (pp. 2308-2428). Springer Science+Business Media.

[9] NFPA. (2011). NFPA 502 Standard for Road Tunnels, Bridges, and Other Limited Access Highways. Quincy, USA: National Fire Protection Association.

[10] Johansson, N. (2021). Evaluation of a zone model for fire safety engineering in large spaces. Fire Safety Journal 120.

[11] Suzuki, K., Tanaka, T., Harada, K., Yoshida, H., 2004. An application of A Multi-layer Zone Model to A Tunnel fire. Fire Saf. Sci. 6, 7b–2.

[12] Heskestad, G., 1983. Virtual origins of fire plumes. Fire Saf. J. 5, 109–114.

[13] Kung, H.-C., Stavrianidis, P., 1982. Buoyant plumes of large-scale pool fires. Symp. Int. Combust. 19, 905–912. https://doi.org/10.1016/S0082-0784(82)80266-X

[14] CETU. (2003). Guide to Road Tunnel Safety Documentation booklet 4. France: CETU Centre d'études des tunnels.

[15] Ingason, H., Li, Y. Z., & Lönnermark, A. (2015). Tunnel Fire Dynamics. New York: Springer Science+Business Media.