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ON THE ACCURACY OF FDS SMOKE PROPAGATION MODELS IN THE CONTEXT OF TUNNEL RISK ANALYSIS

[1]Oliver Heger, [2]Peter Sturm

[1]ILF Consulting engineers Austria GmbH, Austria
[2] Institute of Thermodynamics and Sustainable Propulsion Systems, Graz University of Technology, Austria

ABSTRACT

In the recent past the Fire Dynamics Simulator (FDS) has become one of the primary tools for fire- and smoke propagation simulation in the context of tunnel fire safety. FDS has been extensively validated for compartment fires but validation for tunnels is scarce. After a quantitative validation against a full scale fire test is presented, the paper demonstrates how specific numerical options, in particular the size of the CFD mesh, influence the accuracy of the smoke propagation results. By doing so the investigated FDS modelling concepts are related to achievable prediction accuracies as well as the expected computation times. This enables informed decisions about the choice of model characteristics based on the necessary accuracy and available computational resources for future tunnel fire consequence analysis, typically used in tunnel risk models.

Keywords: FDS, CFD validation, CFD accuracy, risk model, tunnel fire simulation.

1. INTRODUCTION & OUTLINE

For more than two decades, tunnel risk models have been an important tool to increase road tunnel safety. With the implementation of EC Directive 2004/EC [1] tunnel risk assessment became a mandatory part of the safety design process for road tunnels on the European network. While the general methodology of tunnel risk assessment is well defined on an international level, for instance in [2], specifications for the detailed implementation are given at a national level through standards and guidelines. Therefore, detailed implementations can vary considerably from country to country [3],[4]. However, fire risk is one of the main aspects in each tunnel risk assessment methodology. Therefore, the capability to predict the consequences of a tunnel fire is of high importance for every quantitative tunnel risk model, being part of a tunnel risk assessment methodology.

A core feature of every fire consequence model is the smoke propagation model. Such models in general are used to predict the movement of smoke and convective heat and allow to calculate toxic gas concentrations, temperature and visibility at any location for any time inside the tunnel. This further allows to estimate the effects of a tunnel fire on evacuating persons by combination with evacuation and/or survivability models. This procedure is generally called fire consequence modelling.

In tunnel fire studies, the 3D CFD software Fire Dynamics Simulator (FDS) [5] has become one of the primary tools to model tunnel fire dynamics numerically. FDS is based on a low Mach number approximation of the Navier-Stokes equations, applying a LES formulation and particular suited for buoyant flows [6]. This formulation, in combination with the use of so called wall functions to treat boundary-layer effects without the need to resolve the boundary layer with great detail, allow for significantly larger cell volumes of the numerical mesh. This results in much shorter computation times compared to other 3D-CFD codes and in particular allow to use full 3D-CFD fire simulations in probabilistic, system-based tunnel risk models [7].

However, even though much larger cell dimensions are possible compared to other 3D-CFD codes, the accuracy of course decreases with increasing volume of the numerical grid cells. In addition to mesh resolution, also other numerical modelling options - like the treatment of convective heat transfer, accounting for thermal radiation, the utilized pressure solver, etc. – influence the accuracy of the smoke propagation prediction. The remainder of this paper documents the methods used to investigate these dependencies and presents results in terms of a relation between modelling options, prediction accuracy and necessary computation time.

In section 2 the general FDS model used in this study is described and validated by comparison against the well-known Memorial Tunnel fire test 501 [8]. In section 3 the influence of different mesh resolutions on convective propagation and temperature stratification – the key parameters with respect to smoke propagation – are analyzed qualitatively and quantitatively by application of a vector analysis metric. The influence on convective transport and temperature stratification are important to understand, but it is even more important to understand the influence on the accuracy of the risk model estimates. Therefore, the smoke propagation results obtained in the CFD parameter studies were further processed with a tunnel evacuation model based on the FED/FIC dosage-endpoint approach [9]. The results of this process are presented in section 4. A conclusion in the form of a reference table, relating modelling option, prediction accuracy and necessary computational effort is then given in section 5.

2. FDS TUNNEL FIRE MODEL

The present study is based on the parameters of a 20 MW full-scale fire test under natural ventilation, documented during the Memorial Tunnel Fire Ventilation Test Program [8]. The basic geometric properties of the Memorial Tunnel for the selected fire test (Test number 501) are given in Table 1. The most important numerical parameters for the FDS model are stated in Table 2. A detailed explanation of the numerical parameters can be found in [5] and [6]. The variation of these parameters as a part of the study is presented in the later sections. The values stated in Table 2 represent the standard model options.

To model the tunnel fire, time-dependent surface boundary conditions for convective heat flux and mass flux for CO, CO2, HCN and soot have been applied to a 3m x 3m area 1.0 m above the tunnel floor. As an educated guess, 75% have been assumed for the share of convective heat on the overall heat release rate (HRR) of the gasoline fire. The radiative share of the HRR has been neglected. To resemble the natural ventilation during the fire test, velocity boundary conditions, based on the measured bulk airflow velocity at the measurement point closest to the southern portal has been used at the (initial) domain inlet (853 m). Open boundary conditions have been used at the (initial) domain outlet (0m). The heat release rate (HRR) time curve and the inlet bulk airflow used as velocity boundary condition are depicted in Figure 1. As can be seen in the figure, the longitudinal flow is reversed approximately 140s after the fire start, which is taken into account in the velocity boundary conditions.

Table 1: Tunnel parameters

Parameter	**Value**
Tunnel Length	853 m
Cross-Section Type	Horseshoe
Cross-Section Area	60.3 m²
Tunnel Height / Tunnel Width	7.5 m / 9.0 m
Cross-passages	None (in simulation)

Table 2: Numerical parameters of the standard model

Parameter	Value
Fire Model	Time-dependent surface boundary condition for convective heat flux and smoke mass flux (CO, CO2, HCN, soot) at fire location
Ventilation Model	Velocity boundary condition at domain inlet, open boundary condition at domain outlet
Cell Dimensions	0.5 m x 0.5 m x 0.5 m
Convective Heat Transfer	Default
Radiative Heat Transfer	Default
Subgrid Closure	DEARDORFF
Simulation Method	VLES
Pressure Solver	FFT

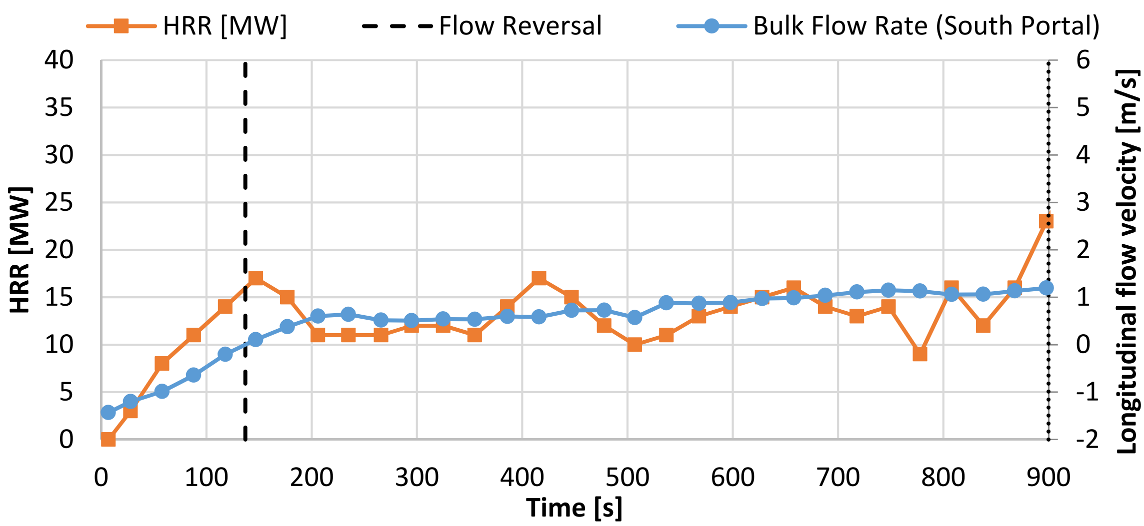

Figure 1: Velocity- & HRR time series used as boundary conditions in the CFD model

Figure 2 shows the temperature profile 170 seconds after fire start for the simulation and 120 seconds after fire start for the measurement data. The 50 seconds delay between experimental and numerical data has been added because of an observed irregularity on the measurement time-stamp. The temperatures at the majority of measurement locations start to rise unreasonably early after the nominal fire ignition. For instance, at a measurement position 31 m downstream of the fire, a strong increase of cross-sectional average temperature, indicating the arrival of the hot smoke layer, is documented three seconds after nominal fire start, which is, for a bulk airflow velocity of approximately 1.3 m/s physically not realistic. The temperature developments, however, at all measuring points, seem to be plausible in general. They in particular match well with the numerical results, despite the mentioned overall time gap. To estimate this time gap, the point in time, when the hot tunnel air from the fire source should theoretically arrive at the respective locations, was calculated based on the measured bulk flow velocity, assuming that propagation in the first phase is mainly driven by longitudinal airflow, not by buoyancy forces between hot and cold layer. By doing so, a time-stamp deviation between 40 seconds and 55 seconds was estimated for the experimental time stamp. This estimated time-delay was taken into account in the further validation process, by comparing results of the numerical computation with experimental results with a 50 s later time-stamp.

This on the one hand leads to a plausible downstream propagation speed of the hot smoke layer and to a good agreement between experimental measurement and numerical results.

Figure 2 shows the comparison of temperature contours for 37.8 °C (100°F) and 93.3 °C (200°F) in the longitudinal-vertical plane, 120s (170s time stamp for experimental data) after fire start. The contours show some deviation, in particular for the higher temperature contour. But with deviations between 0% (Δx_1) and 34 % (Δx_3), the results are interpreted to be in reasonable agreement, if the underlying uncertainties are taken into account. These uncertainties are on the one hand related to the measurements themselves, in particular with respect to the uncertainty of the heat release rate and the low time resolution of the measurements (30s measurement intervals), and on the other hand to missing model input data, e.g. rock temperature, portal pressure difference and wind pressure.

In addition to temperature contours also the time development of the cross-sectional average temperature has been compared along the tunnel. As an example, the comparisons at two longitudinal positions are shown in Figure 3. The general time-development is very well resembled by the simulations. The quasi steady temperature after the fire was fully developed deviate by approximately 10 - 20 °C (20% - 40%). The average temperatures suggest that back-layering is over pronounced in numerical simulations, as temperatures upstream the fire are above the measured values and temperatures downstream of the fire are below the measured temperatures. However, if the general uncertainties are again taken into account, the results can be understood as in good agreement.

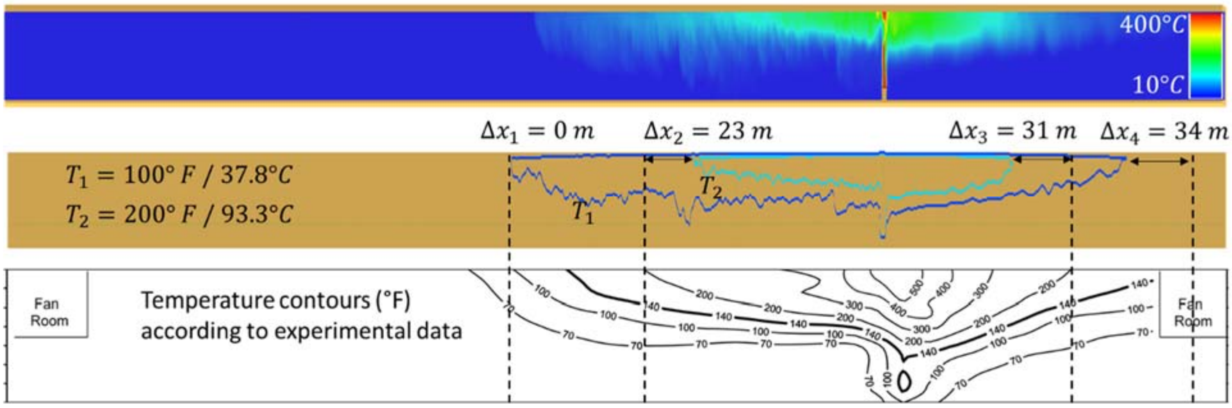

Figure 2: Comparison of temerature contourse – experimental measurement (bottom) vs. FDS simulation (middle) and full FDS temperature profile (top) ,170 s after fire start (120s according to experimental data).

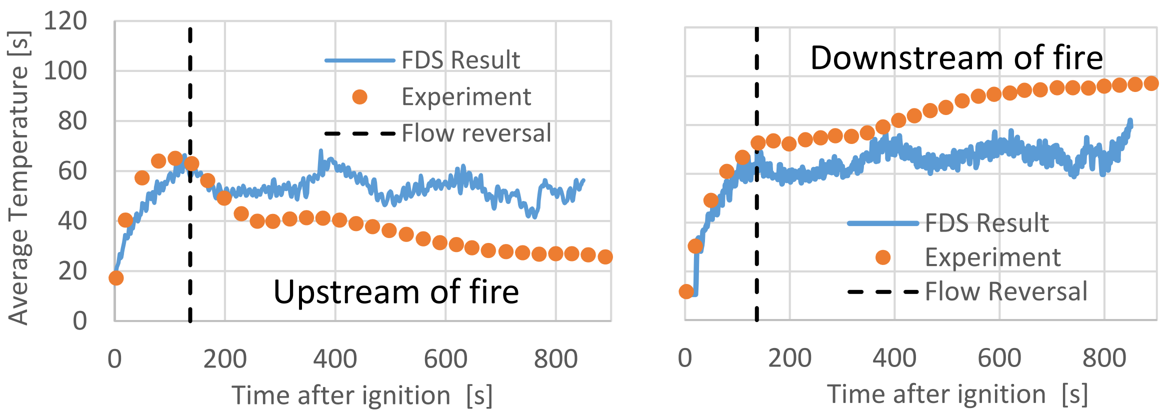

Figure 3: Comparison of cross-sectional average temperature development 62 m left (left) and 66 m right (right) of fire.

3. DEPENDENCE OF SMOKE PROPAGATION ON CFD MESH RESOLUTION

The propagation and distribution of hot smoke is closely related to temperature stratification and the distribution of hot gases. It is therefore convenient to analyse temperatures instead of smoke concentrations. In particular because smoke-/gas concentrations also depend on fire gas emissions, which are harder to measure than heat release rates. Therefore, the time-series of three parameters, describing convective propagation and layer formation are compared for different mesh resolutions in the following.

Figure 4 shows the time series of calculated cross-sectional average gas temperature, layer height and layer temperature difference, at one exemplary longitudinal position for different numerical mesh options, compared to the standard model according to Table 2. The curves clearly separate into two groups, differing in the chosen mesh resolution in z direction. Only small differences for meshes with 0.25 m resolution in z direction are observable. The variants with coarser resolution, including the standard model, deviate with respect to average temperature and layer height from the fine mesh results. Also a refined mesh around the fire site – 0.25 m x 0.25m x 0.25 m +/- 15 m around fire location, 0.5 m x 0. 5m x 0.5 m elsewhere – does not further increase the model accuracy in relation to the standard model, which is already in good agreement with the experimental result, see section 2.

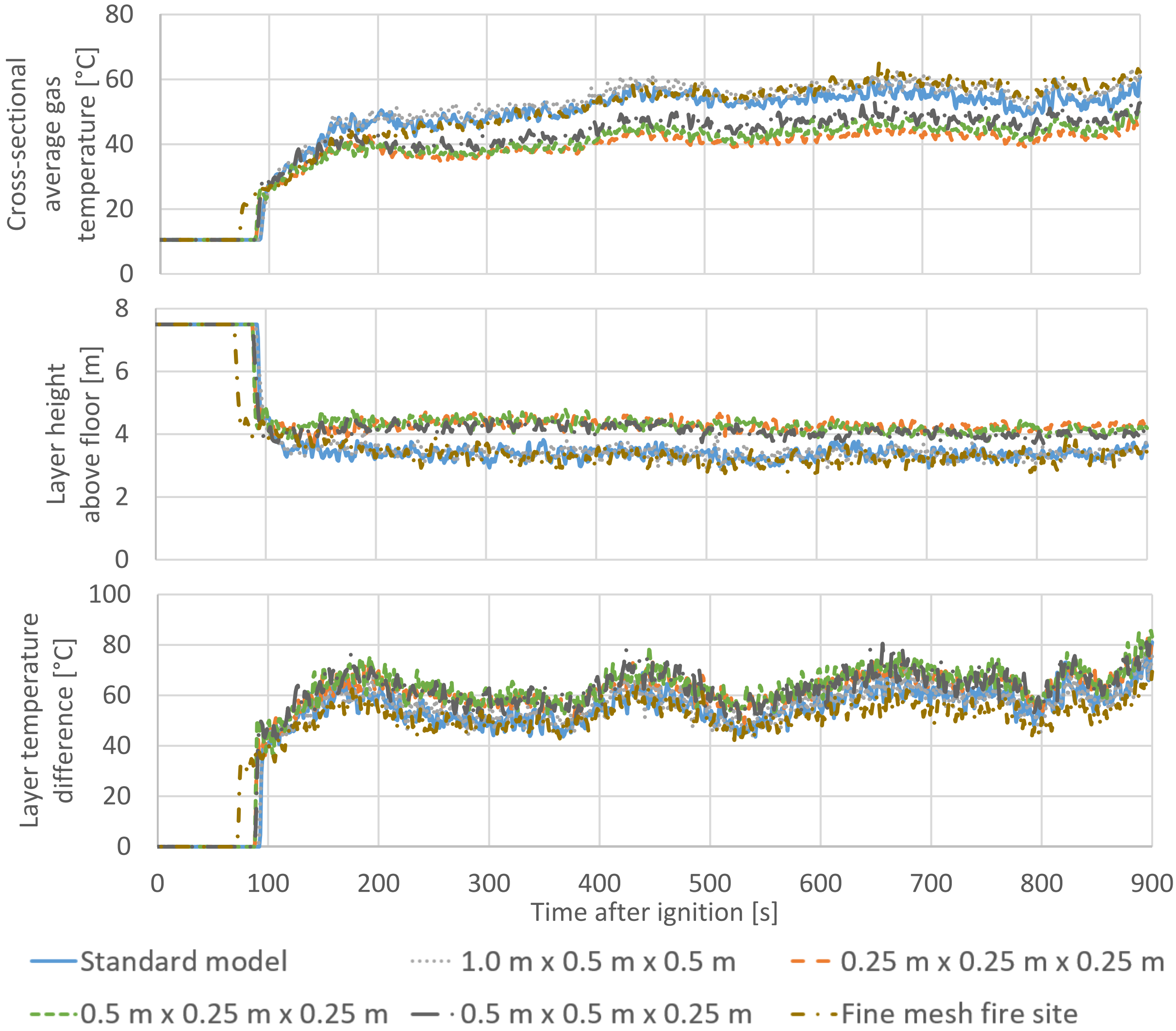

Figure 4: Comparison of average gas temperature, layer height and layer temperature difference 100 m before the fire

For the quantitative comparison, a vector algebra metric, suitable to measure the deviation of two time-series [10] is utilized. This metric assumes the two compared time series as two vectors in an Euclidean space. The relative difference used to quantify the deviation between the two time series – a and b – is then defined as the length of the difference vector – a-b – relative to the length of the base vector:

$$r_{pos} \equiv \frac{\|a-b\|}{\|a\|} = \sqrt{\frac{\sum_{i=1}^{n}(a_i - b_i)^2}{\sum_{i=1}^{n} a_i^2}}, \bar{r} = \frac{\sum_{pos} r_{pos}}{\sum_{pos}}$$

Equation 1: Relative difference between two measured time seires according to [Reference Peacock et al.] and averaged relative difference

A similar approach is also used in [11]. The standard model according to Table 2 has been shown to be in good agreement with the experimental measurement. Therefore, it is used as a reference in the quantitative comparison. Table 3 summarizes the averaged relative difference ($\bar{r}$) of average temperature, layer height and layer temperature difference, according to Equation 1, for the different meshing options, in relation to the standard model.. The difference is evaluated based on the time series at seven longitudinal positions along the tunnel – 214 m, 414 m, 514 m 594 m, 638 m, 718 m and 818 m. The values given in Table 3 represent the respective relative difference, averaged over all seven longitudinal positions.

Table 3: Relative difference for the investigated modelling options with respect to the standard model, averaged over seven longitudinal positions along the tunnel

Modelling Variant	**Average Temperature**	**Layer Height**	**Layer Temperature Difference**
Standard model	-	-	-
1.0 m x 0.5 m x 0.5 m	6 %	7 %	12 %
Fine mesh fire site	14 %	16 %	24 %
0.5 m x 0.5 m x 0.25 m	8 %	10 %	13 %
0.5 m x 0.25 m x 0.25 m	11 %	12 %	14 %
0.25 m x 0.25 m x 0.25 m	14 %	13 %	17 %

The quantitative comparison shows deviations of roughly 6 % to 24 %. Surprisingly, the mesh with increased resolution around the fire site shows the largest differences in relation to the standard model. Intuitively, one would expect it to be closer to the standard model than the 0.25 m x 0.25 m x 0.25 m, but instead it shows the largest difference. One reason could be that the solvers applied in FDS prefer homogenous meshes over meshes with changing resolutions. Despite the refined mesh around the fire location, the resulting deviations of the remaining (homogenous) meshes are between 6 % and 17 %. These deviations can in principle be significant, in particular because the mesh independence for the finest resolution has not been further investigated, which means that the deviations from the standard model could still increase in case of even finer meshes. However, the comparison with experimental measurements in section 2 showed a good agreement for the standard model. Therefore, deviations are expected to be overall limited, also for even finer mesh resolutions. Also, deviations in terms of temperature/smoke propagation and layer formation are important to know, but in order to understand how these deviations influence tunnel risk analysis results, consequences based on the respective fire simulation results need to be assessed. This is presented in the following section.

4. DEPENDENCE OF FIRE CONSEQUENCE MODELS ON MESH RESOLUTION

In general, a variety of different metrics to quantify the consequence of a tunnel fire exist, trying to model the impact of fire hazards on persons inside a tunnel.

One rather simple method is to use a visibility threshold. As long as the visibility is above a certain value (e.g. 5 m), evacuation is possible and persons continue to egress. When the visibility drops below the threshold value, evacuation is assumed to have failed. More sophisticated methods for consequence analysis aim to model the physiological impact of fire hazards on the human body, taking the effect of reduced visibility, toxin- and temperature dosage intake as well as respiratory and visual irritancy into account. An example for such a consequence model, based on the approach of [9], is utilized in the Austrian Tunnel Risk Model [12].

A common process to visualize the severity of a fire scenario with respect to such fatality thresholds is to evaluate the time until the respective threshold value is met at any position inside a tunnel. This is presented in Figure 5, where the time until the respective fatality criteria are met at any longitudinal location along the tunnel are compared for the different mesh options. For this purpose, gas concentrations, visibility and temperature at 1.6 m height have been extracted from the CFD results discussed in section 3.

Apparently, the time until incapacitation happens strongly depends on the chosen fatality criterion, much more than on the investigated mesh resolutions. While evacuation is possible for more than 600 seconds according to the FED/FIC criterion (except at locations very close to the fire source), safe egress times of only 200 to 400 seconds result from the visibility-threshold approach. However, the sensitivity to mesh resolution seems to be similar for both threshold values: Similar to the findings before, the results depend on the mesh resolution in z direction. Incapacitation times for a given fatality criterion are almost identical for all CFD meshes with a resolution of 0.25 m in z direction but strongly deviate from the results with coarser resolutions in z direction, in particular for longitudinal positions between 400 m and 600 m (0 m – 200 m left of the fire).

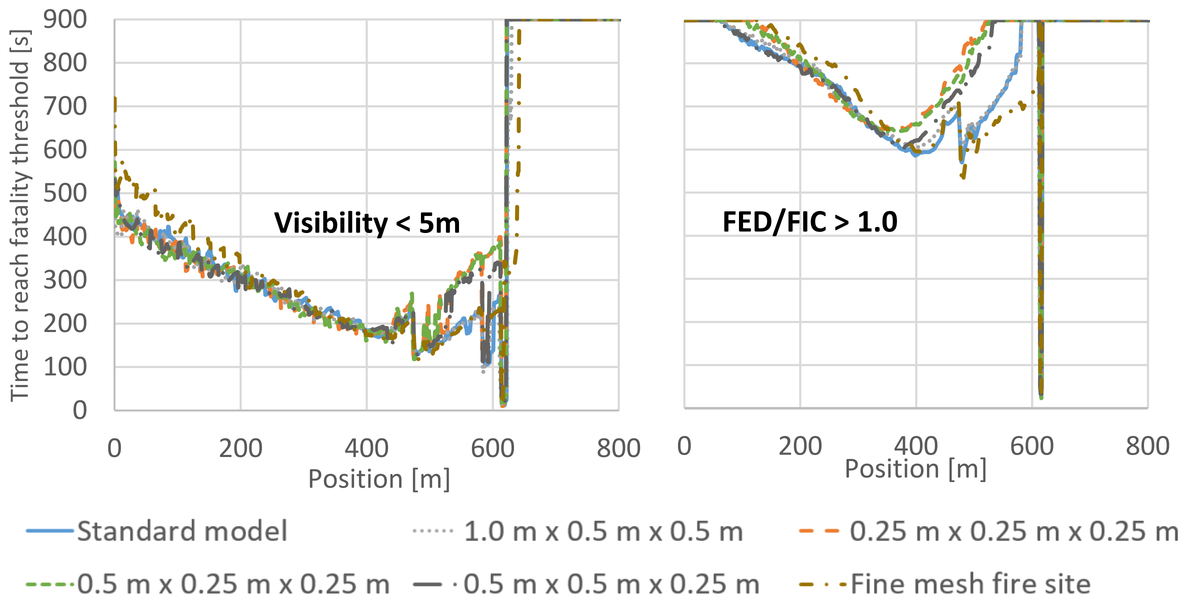

Figure 5: Time to reach fatality threashold values as a function of longitudinal position along the tunnel for visibility criterion (left) and FED/FIC criterion (right).

4.1. Resulting Consequence Numbers

In order to quantify the sensitivity of risk analysis results on the CFD model options, the number of expected fatalities in case of a tunnel fire (consequence number) has been calculated based on a simple agent-based egress model, relaying on the FED/FIC fatality threshold. The egress model is used to resemble the evacuation of tunnel users for a hypothetical congested traffic scenario. Therefore, agents start to egress at every tunnel meter 150 s after fire ignition. A walking speed of 1 m/s has been chosen for the agents which is modified based on local visibility and level of agent intoxication [12]. In addition it was assumed that a share of 3% of all tunnel users remain at their initial location for the whole simulation time of 15 minutes (representing people with reduced mobility, injured, wrong behaviour, etc.).

In addition to the mesh resolution also the influence of other CFD (FDS) parameter selections has been investigated:

Convective Heat Transfer Option: Typically, large gradients with respect to normal velocity and temperature (in case of hot flows) arise at the boundary layer of a viscous flow. This can be treated either by a fine resolution of the boundary layer or by so called wall models. A logarithmic wall model for near wall temperature has been used in addition to the standard near-wall model for normal velocity. This is supposed to increase the accuracy of the convective heat flux from hot tunnel air to colder tunnel surface without the need of small near-wall cell size .(HEAT_TRANSFER_MODEL = 'LOGLAW')
Also an additional time step constraint, limiting the size of the time step between two solver iterations, has been used which acknowledges the convective heat flux from tunnel air to the tunnel surface. (CHECK_HT=.TRUE.)

Radiative Heat Transfer: As described in section 2, only the convictive share of the fire HRR has been taken into account in the investigations. This is true for all investigated variants. However, also without a direct radiative heat source, the convective heating of the tunnel air leads to a temperature increase and therefore induces radiative heat flux from the tunnel air to the tunnel surface. In this variant, this radiative heat flux (or any radiative heat flux from a hot surface) is neglected (RADIATION = .FALSE.).

Subgrid Closure: In LES only a certain part of the turbulent dynamics is directly modelled on the numerical grid. The remaining share of the turbulent dynamic, in particular the final cascade to thermal energy, is treated by a so called subgrid model. As an alternative to the standard "Deardorff" subgrid model for the subgrid kinetic energy and the WALE near-wall subgrid model, the "Constant Smagorinsky" subgrid model and the "Van Driest" near-wall subgrid model have been used. (CONSTANT SMAGORINSKY + VAN DRIEST)

Pressure Solver: In the low Mach number approximation, applied in FDS, a fast non-iterative algorithm that utilizes Fast Fourier Transforms (FFT) is used to solve the pressure equation. In default mode the FFT is applied to each individual numerical mesh separately and the pressure solutions of the individual meshes are then matched together. As an alternative, the global Poisson equation can also be solved over the entire domain. (SOLVER='GLMAT')

Figure 6 shows the resulting consequence numbers for different numerical mesh options (left) and CFD parameter selections (right). The deviations in relation to the standard model are given as percentage values. The differences in terms of fire consequences are between – 8 % and + 6 %. These deviations are significantly smaller than the deviations in terms of temperature/smoke propagation and layer formation, discussed in section 3. However, whether such deviations are significant for a given risk model application, depends on the actual use case. Very often, only rough estimates are known for the necessary input parameters and the overall accuracy of the model results is generally limited. In such a situation the deviations shown in Figure 6 might be very small in comparison, and therefore be negligible overall. In other applications high accuracy CFD results can be of utmost importance, in particular when design options related to the flow profile (e.g. jet fan installation positions, etc.) are investigated. Generally speaking, a deviation in fire consequence numbers of roughly 5 % can be assessed as minor, in particular in combination with the computational effort associated with the higher accuracy variants.

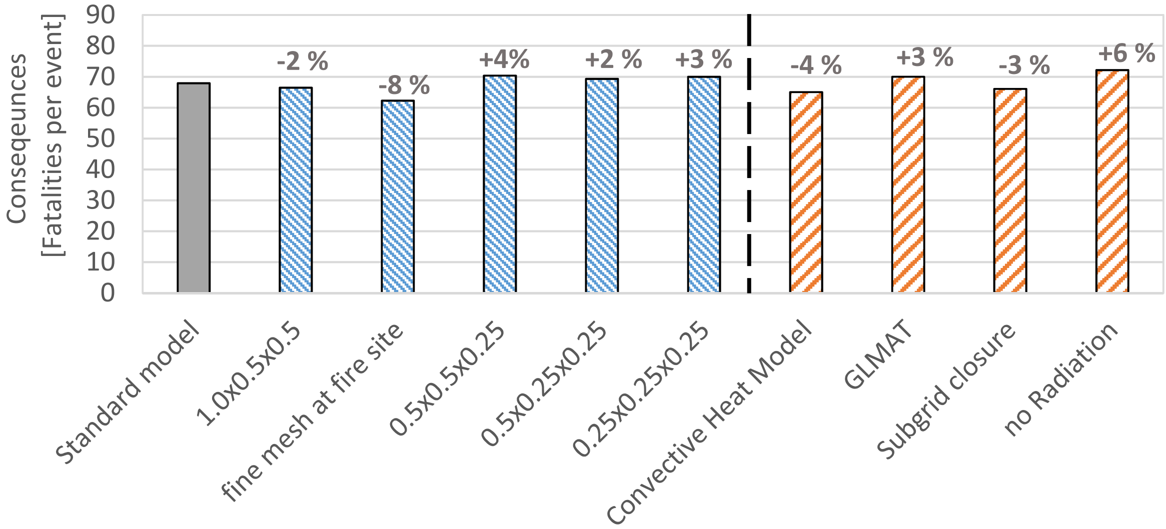

Figure 6: Comparison of fatality numbers resulting from the quantiative conseqeunce analysis of a congested traffic scenario based on the CFD results with respect to different numerical mesh options and CFD parameter selections

5. SUMMARY AND CONCLUSION

Comparison of FDS results and experimental measurement showed a good agreement for the FDS standard model with parameters according to Table 2. Based on this qualitative validation, a parameter study was carried out to investigate the effect of different CFD mesh resolutions and parameter selections on temperature/smoke propagation and layer formation, as well as fire consequence numbers (fatalities). The main result of the paper is presented in Table 4. The deviation of the investigated mesh resolutions from the standard model variant, in terms of temperature propagation and layer formation, is between 6% and 24%. This deviation significantly reduces to a deviation between -8% and 6% in terms of fire consequences to tunnel users (fatalities). The same observation can also be made for the other CFD model parameter variations where deviations between 4% and 35%, in terms of temperature and stratification, reduce to deviations of -3% to +6% in terms of fire consequences. The reasons for this reduced dependency of consequence numbers on mesh resolution and CFD model options are assumed to be manifold and the effect may also vary for different fire scenarios and tunnel setups. However, one important property of the FED/FIC fatality threshold approach is the accumulative nature. In contrast to the pure threshold-value (concentration, visibility) based approaches, which only depend on momentary values, localized variations over limited periods of time are naturally smoothed out by the FED/FIC approach. This should not be misunderstood as a model peculiarity but as the way the human body is believed to react on fire hazards based on fundamental research [9].

While the influence of the investigated mesh resolutions and CFD parameter settings on consequence numbers seem to be minor, the effect on the necessary computation time is tremendous. As an example, if we compare the finest mesh resolution – 0.25 m x 0.25 m x 0.25 m – with the standard model, an accuracy increase in fire consequence numbers of 3 % requires an increase of computational cost from 112 CPU hours to 1697 CPU hours. A reference system with 64 physical cores and a base frequency of 2.2 GHz has been used. The computation time represents the sum of the CPU times of all involved cores (60 - 30 nodes, depending on the variant).

It can therefore be concluded that the numerical costs for mesh resolutions finer than 0.5 m in any direction outweigh the benefit in terms of consequence number prediction accuracy. This is in particular important for probabilistic system-based risk assessment approaches, where a large number of fire scenarios has to be treated and an increase in numerical cost scales up with the number of scenarios. However, if numerical resources are available, an increase in mesh resolution in the vertical direction is recommended.

Table 4: Comparision of model accuracy and necessary computation times for investigated FDS model options

Variant	Temperature & Stratification	Consequences	Computation Time
Standard model	base value	67.9 fatalities	112 CPU hours
1.0 m x 0.5 m x 0.5 m	6 % - 12 %	4 %	- 85 %
Fine mesh fire site	14 % - 24 %	8 %	+ 179 %
0.5 m x 0.5 m x 0.25 m	8 % - 13 %	4 %	+ 87 %
0.5 m x 0.25 m x 0.25 m	11 % - 14 %	2 %	+ 655 %
0.25 m x 0.25 m x 0.25 m	14 % - 17 %	3 %	+ 631 %
Convective Heat Model	14 % - 28 %	4 %	+ 1596 %
GLMAT	4 % - 8 %	3 %	+ 203 %
Subgrid closure	8 % - 15 %	3 %	+ 16 %
No Radiation	10 % - 35 %	6 %	- 34 %

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