Applicability of Zone Fire Models for Tunnel Fire Modelling: Effect of Spatial Segmentation and Comparison with CFD Models

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Abstract

This paper compares the use of zone fire models in simulating tunnel fires with CFD models. A concrete road tunnel fire is chosen as an illustrative example. Two different fire scenarios are considered: a fire involving a heavy goods vehicle (HGV) carrying a load of wood and a fire involving three passenger cars with gasoline tanks. Both fire scenarios are modelled using the CFAST zone model and, for comparison, the FDS CFD model. Given the limitations of the CFAST zone model, various spatial segmentations are considered, including 5, 7, 11, and 25 segments. The resulting graphs are then compared, particularly the heat release rate graph and the graphs of the maximum temperatures of the hot gases at the ceiling and the upper smoke layer. The outputs from the CFAST program are evaluated in terms of their relevance and applicability to the modelled space. Based on the results presented in this study, recommendations are made for future fire modelling in tunnels using the CFAST program.

Key words: Tunnel, Fire, Zone Model, CFD Model, CFAST, FDS, Segmentation

1 Introduction

Larger cities in the Czech Republic and worldwide aim to move transportation underground to improve its flow. Therefore, giving sufficient attention to tunnel fire safety is essential, as they represent a critical part of transportation infrastructure. Although the frequency of fires in tunnels is statistically lower than in enclosed buildings, they carry specific risks [1]. Even today, efforts are being made to enhance fire safety in tunnels, responding to the development of new technologies and materials for tunnel linings and the requirements for cost-effectiveness in design.

The most commonly used approaches in assessing the fire resistance of tunnel linings or structures are generally based on simple fire models represented, for example, by nominal temperature curves [2]. However, these models can be very conservative in some cases depending on the chosen fire scenario. In contrast, refined fire models (most commonly CFD models) can more accurately represent the actual course of a fire in a burning space, which can improve the tunnel's fire safety and the cost-effectiveness of the lining design. However, a disadvantage of CFD models is their particularly long simulation computation time.

Another type of refined fire models are the zone fire models (e.g., the CFAST zone model) which are much simpler than CFD models and are commonly used for fires in standard enclosed spaces. These are, however, generally unsuitable for tunnels and linear structures [3, 4]. Nevertheless, some zone fire models have been validated for these types of structures, see [46] and [47]. The key advantage of the zone models over the CFD models is their significantly faster computation time. When applied correctly, a zone model can offer substantial potential, for example, in providing a quick approximation of maximum temperatures in a tunnel during fire. However, there is a lack of studies on the reliability of tunnel fire modelling using the zone fire models (e.g., the CFAST model).

This study aims to assess the applicability of the CFAST zone fire model for modelling fires in tunnels, considering different spatial segmentations. Based on comparison of the result obtained using the zone models (i.e., the CFAST models) and an CFD model, the study seeks to propose recommendations for effective fire modelling in tunnels using the CFAST program.

2 State of the art

2.1 Tunnel Structures

Tunnels are linear underground structures characterised by a closed cross-sectional profile. They can be classified based on various parameters, such as the type of traffic, traffic intensity, tunnel length, construction method, and other factors. These parameters are key factors in determining tunnel safety requirements and the scope of mandatory and recommended technical and technological fire-safety equipment. From the perspective of traffic type, tunnels can be divided into road and railway tunnels. Based on construction methods, tunnels are classified as either bored or cut-and-cover or tunnels built using unique construction techniques [1, 5, 6].

Globally, there are more cut-and-cover tunnels than bored tunnels, primarily due to their more straightforward construction process and lower costs. However, technological advancements in tunnelling have led to increasing number of bored tunnels being constructed in the Czech Republic and worldwide, especially for large-scale projects. This trend is driven mainly by growing urbanisation, the need to minimise the impact on surface infrastructure, and the ability to operate in geologically challenging areas [7–9].

In the Czech Republic, the design of bored tunnel structures is governed by the ČSN 73 7501 standard. For cut-and-cover tunnel designs, loads are determined by the ČSN EN 1991-

1-1 to 1991-1-6 standards or the ČSN EN 1991-2 standard, depending on the type of future load above the tunnel. The stability of the excavation is primarily ensured by the primary and secondary (final) lining. The most common material for the primary tunnel lining is a layer of shotcrete reinforced with meshes and frames, or sometimes only fibre-reinforced concrete [10].

For railway tunnel design in the Czech Republic, the ČSN 73 7508 standard and the Technical Specifications for Interoperability (TSI) apply. Unlike European standards (EN), the TSI is mandatory. However, this standard is unsuitable for designing tunnels on high-speed rail lines [11]. Road tunnel design in the Czech Republic is governed by the ČSN 73 7507 standard and the TP 98 guidelines. Tunnels must meet not only fire safety requirements, safety and health standards for occupants, and conditions for smooth and safe travel but also requirements for cost-effectiveness and minimal maintenance effort during operation [12, 13, 14].

2.2 Characteristics of Tunnel Fires

Tunnel fires differ from open fires primarily due to the impact of natural ventilation on the combustion process and thermal feedback from the surrounding environment. Owing to the burning of fuels, extreme temperatures can be reached much faster in tunnel fires than in typical enclosed spaces within buildings [1, 15]. This reality is reflected in the nominal temperature curves designed for tunnels (Figure 1), which are significantly stricter than those for standard enclosed spaces.

Another significant risk in tunnel fires is the rapid accumulation of smoke in the enclosed space, which hinders evacuation and firefighting efforts [2, 3].

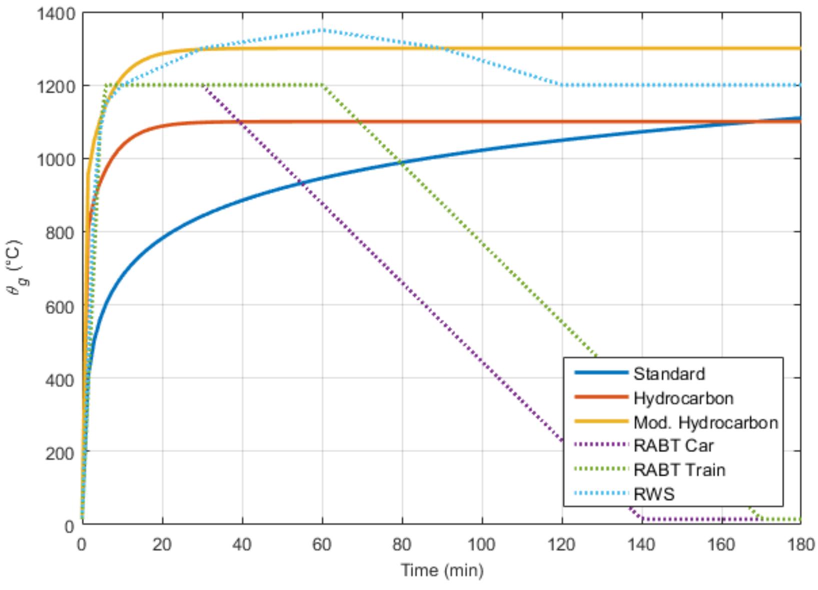

Figure 1: Nominal time-temperature curves for tunnels according to Eurocode and the FMC software tool [16]

Statistically, fires are most common in road tunnels. In contrast, the likelihood of a fire in railway tunnels or metro systems is significantly lower. However, the risk of severe accidents is much higher when such fires occur. Fires in railway tunnels are more challenging to detect, and extinguishing them poses an enormous challenge for emergency services [1, 15, 17].

Key parameters affecting fire development in tunnels include the heat release rate, air velocity, effective tunnel height, and fire source geometry. The heat release rate (HRR) is the primary parameter used to describe fire behaviour. It is influenced by factors such as the fire source and vehicle type, vehicle geometry and size, thermal feedback from tunnel structures, tunnel material and geometry, and ventilation conditions. Ventilation is critical to fire development and combustion processes. Generally, tunnel fires are fuel-controlled, as air supply is usually not limited. The gas temperature is crucial for determining the exposure of people and structures to thermal flux, estimating fire detection times, and assessing fire spread potential [1, 3, 15].

Critical airflow velocity and the back-layering of smoke are among the most extensively studied phenomena in tunnel fire research [18]. Back-layering occurs when there is insufficient oxygen supply in during a fire in a tunnel, which lead to incomplete combustion and the generation of significant quantities of combustion by-products. Near the fire source, turbulent airflows develop. The heat generated by combustion gradually warms the surrounding air, creating buoyancy forces that influence the movement and direction of airflow within the burning tunnel. If the longitudinal airflow velocity in the tunnel is insufficient, a reverse flow of hot gases forms near the ceiling. Smoke and combustion by-products can spread against stationary vehicles, reducing visibility to where safe evacuation becomes impossible. To prevent this phenomenon, the longitudinal airflow velocity inside the tunnel must exceed the critical velocity, typically estimated at approximately 3–3.5 m/s for most tunnels. For safe evacuation, the smoke layer height above the floor should be at least 2.5 metres or half the tunnel's height [19, 1, 3].

2.3 Numerical fire modelling

2.3.1 Fire models

From the perspective of numerical fire modelling, nominal time-temperature curves (e.g., the standard temperature curve ISO 834, see Figure 1) represent some of the simplest fire models. These curves, defined by the EN 1991-1-2 standard (see also [20–23]), are typically used in assessing the fire resistance of structures in fire engineering practice.

In many countries, the standard temperature curve can be used to assess the fire resistance of tunnels. However, in scenarios such as a fire involving a heavy goods vehicle, the temperatures in the tunnel can exceed the values represented by this curve. The standard time-temperature curve does not account for all materials, such as gasoline, chemicals, and others. For this reason, the hydrocarbon (HC) curve has been applied to tunnels in recent years. The HC curve was initially developed in the 1970s for use in the petrochemical and off-shore industries. Alternative (specific) temperature curves have been developed in some countries to simulate other hydrocarbon fires in tunnels, i.e. the Rijkswaterstaat Tunnel Curve (RWS curve) in the Netherlands [24] and the RABT/ZTV Curve in Germany. PIARC and the International Tunnelling Association (ITA) both recommend the use of the ISO 834 curve (60 min) for cars and vans and the RWS curve or the modified HC curve (HCM, 120 min) for trucks and tankers [25]. On the other hand, some nominal temperature curves designed for tunnels can be overly conservative in certain cases.

Other numerical fire models include natural fire models, divided into simplified fire models (e.g., parametric temperature curves) and refined (advanced) fire models. The latter primarily include Computational Fluid Dynamics (CFD) and zone fire models [2, 3].

CFD models (most notably the FDS model) represent the most sophisticated type of fire modelling and are widely used in fire engineering application, and there is extensive literature on their use for modelling fires in tunnels. In CFD models, the computational domain is divided into a large but finite number of three-dimensional control volumes (cells), most commonly cubic in shape, which collectively form a spatial grid. For more complex simulations, the number of these cells can range from hundreds of thousands to millions. Within each cell, governing equations are solved, including the equations of state, conservation of energy, mass, and chemical species, and the conservation of momentum [3, 4, 30]. The main drawbacks of CFD models is long computation time (on the order of several days) and significant hardware requirements [1, 4, 30].

Zone fire models represent an idealised fire behaviour simulation in an enclosed space. Their principle is dividing the computational domain into one or two homogeneous zones (layers) with uniform density, temperature, and gas concentration [3, 4, 26]. Zone models are classified into two types: one-zone and two-zone models. Two-zone models describe the burning process of enclosed fires in the early stages before spatial ignition (the so-called flashover effect). After the flashover effect, one-zone models describe the enclosure fires. The fire plume facilitates heat and mass transfer between the two layers. Numerical solutions are used to solve equations describing mass, momentum, and enthalpy, as well as plume models, vent flow equations, radiation, and combustion models [3]. The primary advantage of the zone models over CFD models lies in their simplicity (i.e. the simplicity of the modelling and user interface) and computational speed, where a single simulation lasts only a few seconds to minutes. This allows the zone models (e.g., the CFAST model) to be successfully employed for quick estimation of approximate temperatures in the modelled space.

In Figure 2, a schematic comparison of the spatial domain division into control volumes for various fire models is illustrated.

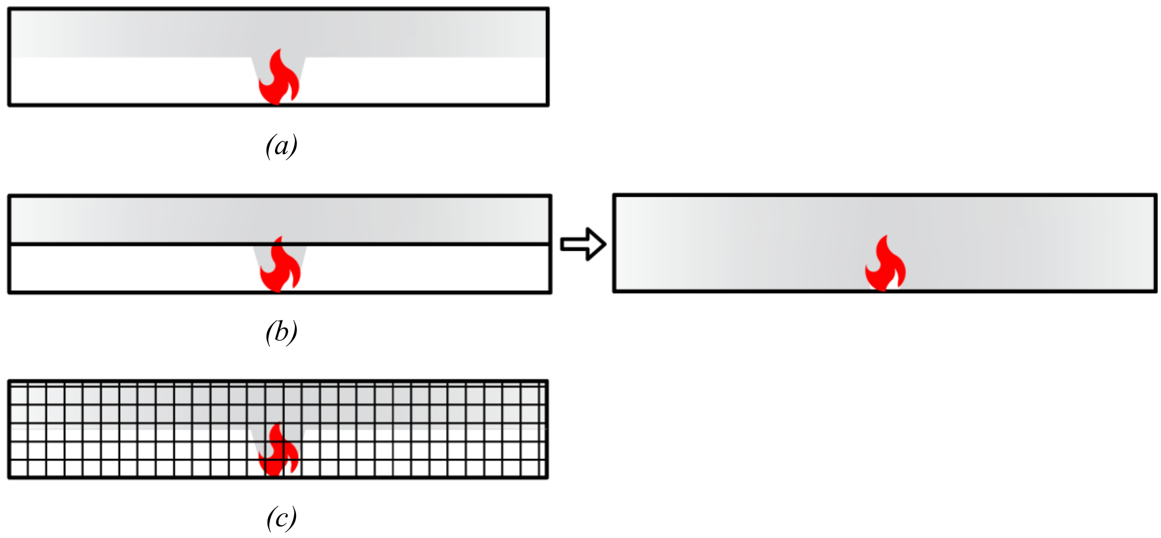

Figure 2: Comparison of the methods for dividing the space into control volumes: (a) Simplified fire models; (b) Advanced fire models – zone model; (c) Advanced fire models – CFD model

2.3.2 Numerical fire modelling in tunnels

In fire engineering practice, fire modelling has become more widespread in recent decades [3, 4, 30]. In addition to obtaining an accurate temperature profile of gases in a burning space and optimizing the design of fire safety equipment and evacuation scenarios, numerical models can also improve emergency procedures and assess tunnel structures under elevated temperatures, as discussed in [31, 32]. The concept of risk analysis also plays a crucial role in tunnel fire safety design. The results obtained from numerical models can serve as a basis for evaluating the risks to individuals' safety in tunnels during the developments of fire safety designs for tunnels [31, 33, 34].

CFD modelling has been widely used in performance-based fire safety design [1, 35]. Numerous research papers in the literature discuss CFD modelling of tunnel fires. Computed data from numerical models can be validated with good agreement with measured data from full-scale fire experiments, as demonstrated in [1, 36]. CFD modelling has been used, for example, to examine the effect of ventilation on fire development in road tunnels [37, 38], to verify the functionality of mechanical fire ventilation [39], air-tight tunnel dampers [40], or water-based fire suppression systems [41–43]. CFD fire modelling in railway tunnels has revealed that even small fires can threaten lives in the tunnel environment [44]. Regarding fire dynamics, it was found that as the train speed increases in railway tunnels, the flame height decreases, flame width and length initially increase and then decrease, and the flame tilt angle rises [45].

Unlike the CFD models, zone models are generally unsuitable for simulating fires in tunnels, as they are not designed for spaces dominated by a single prevailing dimension, see our previous work [27] and [1, 3, 4, 26]. While specific dimensional limits are not explicitly defined, it is typically ideal to maintain an approximately cubical shape for the modelled space [28, 29]. Nevertheless, several zone models have been developed and validated for linear structures, such as the CFAST zone model [28]. As the primary advantage over CFD models lies in their simplicity of application and computational speed, when applied correctly, the zone models (e.g., the CFAST model) can potentially be used in fire engineering practice even in tunnels, especially for quick preliminary assessments.

Since the zone models are generally intended for approximately cubical-shaped spaces, they are generally unsuitable for tunnels, in which the length to width ratio is more than 10 – see, e.g., [46][47]. For example, in the illustrative example presented in this paper, the ratio is 50:1. However, dividing the tunnel space into smaller separate segments (with smaller length to width ratio) and connecting the segments through virtual openings, as employed in this paper, represents a possible method of circumventing the limitations of the zone models. Thus, compared to tunnel modelling using CFD models, the most notable difference in the zone models is the need to segment the modelled space into smaller sections [46][47].

As the zone models are not intended for linear structures such as tunnels, fewer resources are available regarding their use in tunnel fire modelling than in the case the CFD models, and there is insufficient literature on how to optimally segment tunnels. Some papers, nonetheless, do employ the segmentation. In the paper by Bamonte P. et al. [46], a tunnel with the length of 220 m, a width of 10 m, and a height of 4.5 m, was modelled in the CFAST program [28] and segmented into 11 equal sections (i.e., the aspect ratio of 2:1), with the fire source in the middle of the tunnel. The authors found satisfactory agreement with the CFD model. In the paper by Tavelli S. et al. [47], a tunnel with length of 130 m, a width of 5.4 m, and a height of 2.4 m was modelled in the CFAST program and segmented into 19 sections (aspect ratio approximately 1.3:1), with the fire source again in the middle of the tunnel. The authors also found relatively satisfactory agreement with the CFD model.

In addition to the dimensional limits of the zone models, another issue when modelling tunnel fires using zone models is the influence of ventilation on the fire's progress. In the widely used CFAST zone model, ventilation conditions cannot be easily defined by simply specifying the airflow velocity (in m/s) as in the widely used CFD FDS model [35]. The CFAST zone model assumes natural ventilation by default. The flow through vertical openings, like doors and windows, is modelled using the Bernoulli equation for the pressure difference between two compartments [29]. The effect of different ventilation on the fire's progress was examined, for example, in the paper by Tavelli S. et al. [47]. In this paper, the tunnel was modelled using the CFAST program and the FDS program for comparison. A parametric study was conducted for airflow velocities ranging from 0.5 m/s to 2.0 m/s. It was found that different airflow values did not significantly impact the resulting temperature profiles from the CFAST program. In the case of the FDS program, different ventilation significantly affected the resulting temperature profiles, which also matched reality better.

Therefore, the CFAST zone model seems to not be suitable for modelling complex ventilation conditions inside tunnels [47]; see also our previous work [48].

3 Methods

A zone fire model and a CFD model were used for tunnel fire modelling in this paper. The fire scenario was simulated using the CFAST zone model [28] and, for comparison, with the FDS CFD model [35]. Although zone models are generally not designed for linear structures, the CFAST zone model allows tunnel fire modelling. Given the dimensional limitations of the zone model, it is necessary to segment the tunnel being modelled. However, insufficient literature is available on how to optimally segment the tunnel for modelling purposes. This paper aims to assess the applicability of the CFAST zone fire model in tunnel fire modelling using various spatial segmentations and comparing the results with those from the FDS CFD model. Fire modelling using CFD models is considered the standard in fire engineering practice, and the FDS program is widely used for modelling fires in tunnels.

3.1 Illustrative example

As an illustrative example, a fire in a bored reinforced concrete road tunnel was chosen. The tunnel is 500 metres long, with an idealised rectangular cross-section, 10 metres wide, and 5 metres high. It has a single bore with one-way traffic. The tunnel is ventilated solely by natural ventilation. The influence of the tunnel's slope was neglected.

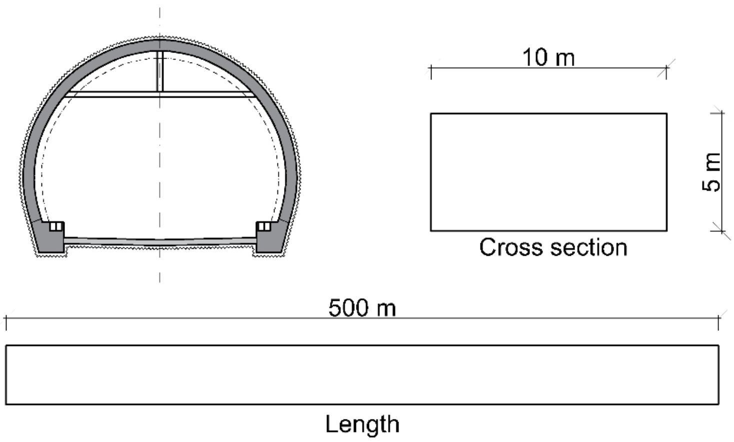

Figure 3: Tunnel geometry

The chosen fire scenario involves burning a heavy goods vehicle (HGV) carrying a load of wood and a fire involving three passenger cars with petrol tanks. Characteristics of the two different fire scenarios are stated below; see Table 1. According to statistics on actual fires in road tunnels, fires involving heavy goods vehicles cause the most severe consequential damage, while fires involving passenger cars are the most common [1]. The fire scenarios were modelled based on existing experiments' heat release rate (HRR) curves.

The fire source was always placed in the middle of the tunnel. Both HRR curves served as the primary input data for the zone and CFD models. The fire modelling procedure specific to each program is described below.

Tab. 1: Characteristics of different fire scenarios

Fire scenario	Dimensions [m]	Fuel material	Chemical formula	Heat of combustion [MJ·kg^{-1}]	Max. HRR [MW]
HGV	2.5 x 15.0 x 3.4	wood-based	$C_6H_{10}O_5$	18.1	128.1 *[49]*
3 passenger cars	4.0 x 7.0 x 1.6	petrol	C_6H_{14}	44.4	16.0 *[50]*

3.1.1 CFAST

The CFAST program defined necessary dimensions and openings, construction materials, and their characteristics. Given the dimensional limitations of zone models, the tunnel under consideration was divided into several equal segments. Several different spatial segmentation variants were considered, with 5, 7, 11, 15, and 25 segments, i.e., with aspect ratios ranging from 10:1 to 2:1 (see Figure 4). Note that the 5-segment variant is the lowest possible number of segments as the upper limit for the aspect ratio in the CFAST program is 10:1, and the upper limit for the maximum segment length is 100 m. The individual segments are interconnected by virtual openings matching the tunnel cross-section.

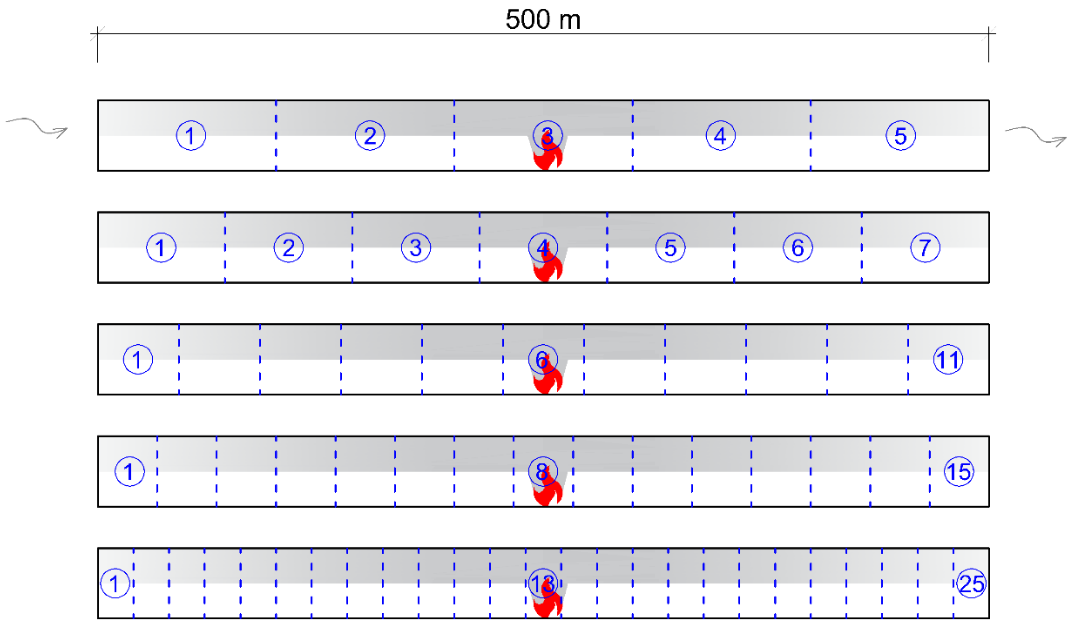

Figure 4: *Different variants of spatial tunnel segmentations in CFAST*

A thermocouple (labelled "Target") was placed under the ceiling structure at the axis of the fire source. A series of thermocouples were positioned under the ceiling along the tunnel axis at intervals of 10 metres. In the middle of the tunnel, additional thermocouples were distributed across the entire width of the tunnel's cross-section to determine the effect of the tilt of the combustion cone (see Figure 5). The duration of a single simulation in the CFAST program takes approximately several seconds to minutes.

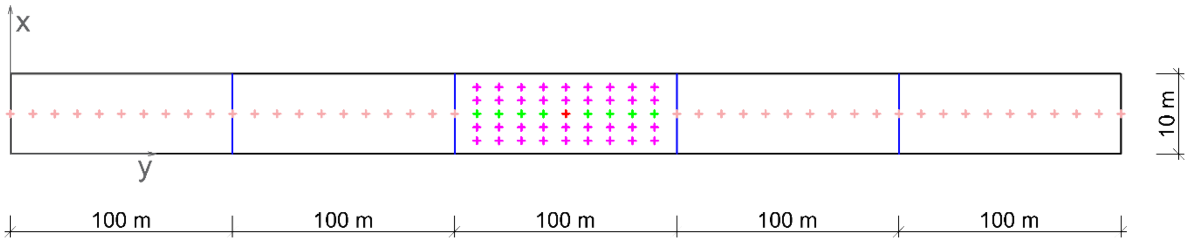

Figure 5: The arrangement of thermocouples in the CFAST model

3.1.2 FDS

The necessary dimensions and openings, construction materials, and their characteristics were defined in the FDS program. The airflow velocity was set to 3.0 m/s [1]. Unlike the CFAST program, CFD models are designed for such simulations, and the modelled space is not segmented. Due to the long computational time, a medium coarse computational grid with approximately 200,000 cells was used in the FDS program. The simulation duration in the FDS program takes approximately several days.

4 Results and discussion

The outputs from the CFAST zone and FDS CFD models were subsequently transferred to a spreadsheet and compared. The results obtained for both fire scenarios (HVG and three passenger cars) using CFAST and FDS CFD are shown and discussed below. The results are first discussed from the point of view of the heat release rate (HRR) curve (see Figure 6). Subsequently, the progression of the maximum hot gas temperatures under the ceiling and the upper smoke layer (see Figures 7 to 9) are discussed, and these temperatures are complemented by the standard ISO 834 temperature curve. In the case of the CFAST program, these temperature graphs represent the fire progression in the central segment of the tunnel, where the fire source is located. Finally, the temperature profiles are discussed (see Figures 10 and 11).

4.1 Heat Release Rate curves

For the fire scenario with three passenger cars (see Figure 6b), the HRR curve progression is identical to the input curve across all variants. The fuel's heat of combustion value significantly influences the heat release rate (HRR) curve progression. The CFAST program can account for the case where all fuel is consumed, and in that case, the HRR curve reaches its maximum prescribed values according to EN 1991-1-2 standard, which are also capped by the input HRR curve [29]. The calorific value of the fuel directly affects the amount of oxygen consumed during the fire and the concentration of CO_2 in the upper smoke layer. As the concentration of CO_2 in the upper smoke layer increases, the progression values in the graphs also rise. Therefore, the higher the calorific value, the higher the HRR and upper smoke layer temperature values in the graphs [29]; see also [27].

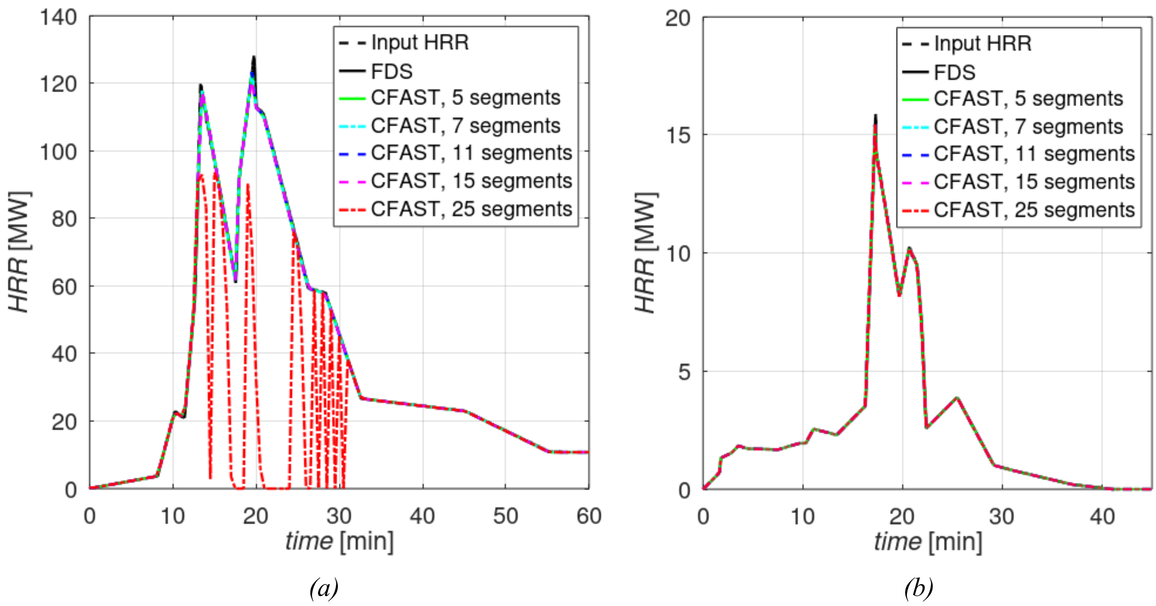

Figure 6: Heat release rate evolution: (a) HGV fire scenario; (b) three cars fire scenario

In the case of the fire scenario with an HGV, the HRR curve progression is identical to the input curve across all variants, except for the "CFAST – 25 segments" variant. In this variant, there is significant fluctuation in the HRR values after the initial spatial ignition phase.

The significant fluctuation in the HRR values in the "CFAST – 25 segments" variant indicates that, unlike in most other areas of numerical modelling (e.g. FEA), high granularity (i.e., dividing a tunnel into many segments) is not suitable for fire modelling in the CFAST program. The situation may appear paradoxical, as a finer mesh often yields more accurate results. However, in this case, finer mesh is not suitable as the issue is not related to the mesh refinement but to the distance between the fire source and virtual openings, see explanation below.

As previously mentioned, zone models are not primarily designed for the modelling of linear structures, which is reflected in their limitations. Though modelling a tunnel using spatial segmentation and virtual openings (as employed in this paper) represents a possible method of circumventing these limitations, this bypassing of the limitations is generally not recommended by the authors of the CFAST zone-model program. Many physical phenomena occur in these virtual openings, which the CFAST zone model does not take into account due to its inherent simplicity (compared to CFD models) [29]. The issue with virtual openings seems to be particularly pronounced when the fire source is located near these virtual openings, especially in fire scenarios with high heat release rates.

The comparison of the HRR curves can be summarized as follows. The fast CFAST model provides results comparable to the results obtained using the accurate FDS model. However, when high number of segments is used, the result obtained using the CFAST model can be unreliable, especially in large fires.

4.2 Evolutions of maximum temperatures

The evolutions of maximum temperatures (i.e., the maxima of temperatures from all thermocouples) obtained using the CFAST program and the FDS program can be observed in Figures 7 and 8.

4.2.1 CFAST temperatures

The temperatures obtained using the CFAST program (see Figures 7 and 8) clearly show the following well-known phenomenon. The temperatures of the hot gases around the thermocouples placed beneath the ceiling (“Target”) are significantly higher than those of the upper smoke layer (“ULT”). This occurs due to the fact that the calculation method for these temperatures in the CFAST program differs. The conditions and temperatures (“ULT”) inside the compartment are calculated using the standard two-zone model. In contrast, temperatures of hot gases around the thermocouples placed beneath the ceiling (“Target”) are calculated using modified empirical correlations specific to tunnels (or corridors) [29]. The thermocouples are treated as explicit differential equations, separate from the solver that calculates the layers' temperatures, the layer's volume, and the pressure difference between the layers. The thermocouples are affected by the temperatures of the layers but also account for radiant heat transfer [29]. As a result, they may be warmer or colder than the temperature of the upper smoke layer [29]. This calculation method provides a more accurate representation of the temperatures beneath the ceiling (which can be used, for example, in thermal analysis of tunnel linings to assess the fire resistance of structures; see also [51]). These empirical correlations also directly influence, for example, detectors or sprinklers placed beneath the ceiling [29].

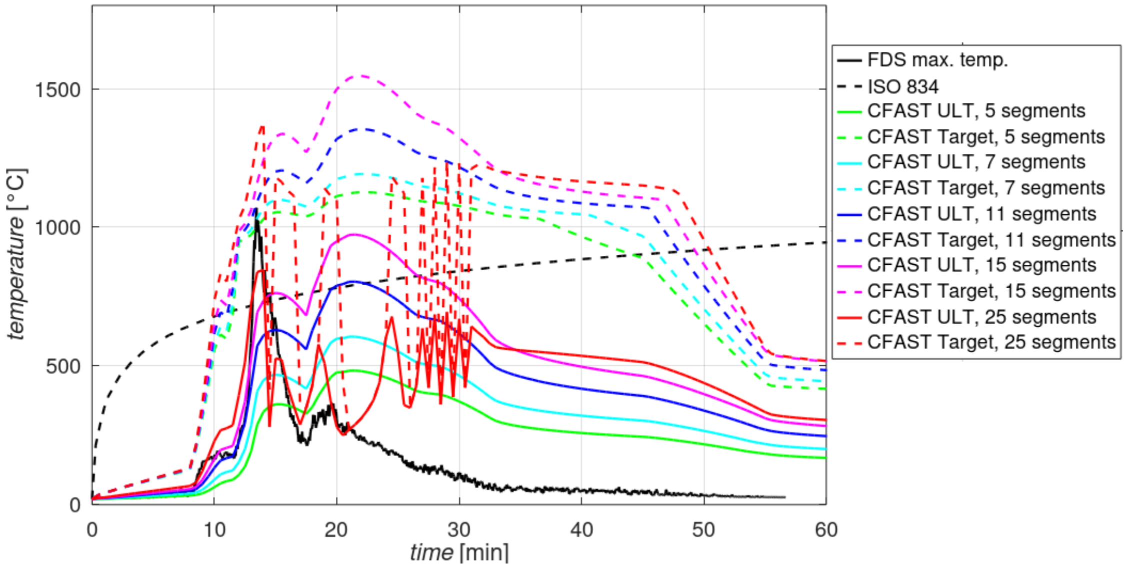

Figure 7: Maximum temperature evolution, HGV fire scenario

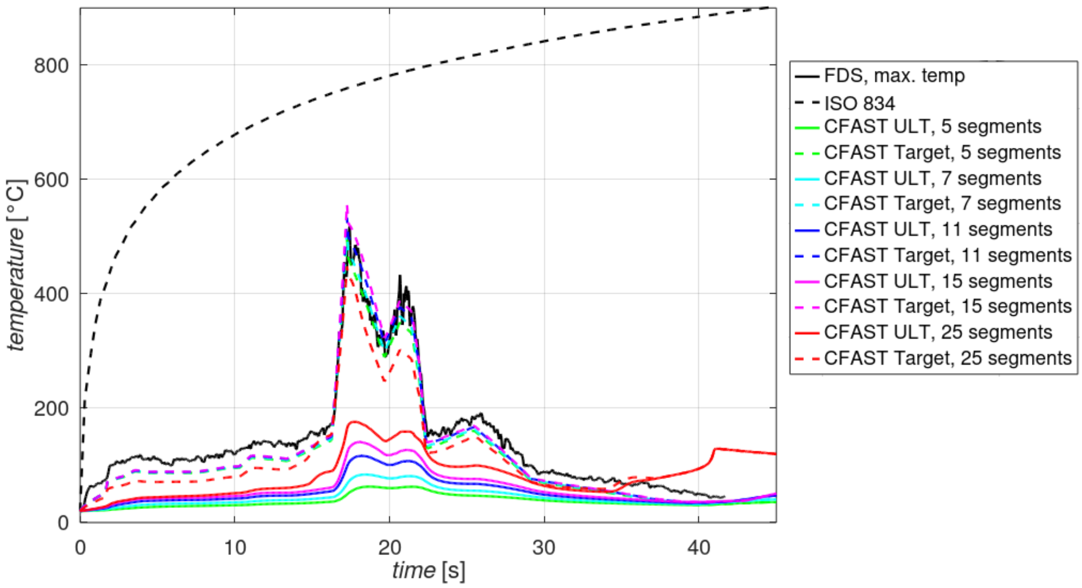

Figure 8: Maximum temperature evolution, three cars fire scenario

4.2.2 Comparison of temperatures obtained using FDS and CFAST

In the smaller fire scenario, i.e. the three passenger cars fire scenario, the "Target" temperatures (i.e., the temperatures of the thermocouples placed beneath the ceiling) obtained using the CFAST model are in an excellent agreement with the accurate temperatures obtained using the FDS model, see Figure 8. The "ULT" temperatures (i.e., the temperatures of the upper smoke layers) provided by the CFAST model are significantly smaller than accurate FDS temperatures.

In the larger fire scenario, i.e. the HGV fire scenario, the temperatures obtained using the CFAST model are generally not in good agreement with the accurate temperatures obtained using the FDS model, see Figure 7. The agreement of the temperatures can be summarized as follows.

- The “Target” temperatures obtained using the CFAST model are significantly higher than the accurate temperatures obtained using the FDS model, especially after the maximum temperature is reached.
- The “ULT” temperatures obtained using the CFAST model are in good agreement with the more accurate FDS temperatures in the beginning stages of fire; however, they reach significantly lower maximal temperatures. Moreover, the CFAST temperatures are significantly higher than the FDS temperatures after the maximum temperature is reached.
- With high number of segments (25 segments), the temperatures oscillate which points to a numerical instability. Thus, high number of segments seems to be inappropriate for the spatial segmentation of the tunnel.

4.3 Total maximum temperatures

The total maximum temperatures (i.e., the all-time maximum temperatures from all thermocouples) obtained using the FDS program and CFAST program can be observed in Figures 7 and 8. For easier comparison, the maximum temperatures are summarized in Table 2.

As can be readily seen in Table 2, in the HGV fire scenario, the closest match between the FDS results and CFAST results were obtained in the “CFAST – 5 segments” variant (a deviation of 5.3 %, specifically 56 °C) and the “CFAST – 7 segments” variant (a deviation of 11.4 %, specifically 122 °C). In contrast, significant temperature difference can be observed for in the “CFAST – 25 segments” variant (a deviation of 44.1 %, specifically 472 °C). This can be attributed to the previously described issue with virtual openings.

As can also be seen in Table 2, in the three passenger cars scenario, the closest match between the FDS results and CFAST results were obtained in the “CFAST – 7 segments” variant (a deviation of -1.9 %, specifically 10 °C) and the “CFAST – 11 segments” variant (a deviation of 2.9 %, specifically 15 °C). In contrast, significant temperature difference can be again observed for in the “CFAST – 25 segments” variant (a deviation of -13.5 %, specifically -70 °C).

Table 2: Maximum temperatures beneath the ceiling for individual fire scenarios

	Max. temperature [°C]					
Fire scenario	FDS	CFAST				
		5 segments	7 segments	11 segments	15 segments	25 segments
HGV	*1070 °C*	***1127 °C***	***1192 °C***	*1354 °C*	*1546 °C*	*1542 °C*
3 passenger cars	*518 °C*	*495 °C*	***508 °C***	***533 °C***	*557 °C*	*448 °C*

The difference between the results obtained using the FDS program and the CFAST program can be attributed, among other things, to the difference in the modelling of the ventilation conditions. As mentioned earlier, in the CFAST model, ventilation conditions cannot be defined by simply setting the airflow velocity (in m/s) as in the FDS program [35]. Ventilation conditions, among other things, affect the tilt of the fire plume. Thus, unlike in the FDS program, there is no tilt of the fire plume in the CFAST program. This, generally, leads to higher temperatures beneath the ceiling in the CFAST program as the thermocouples are aligned precisely with the fire source, as shown in Figure 9.

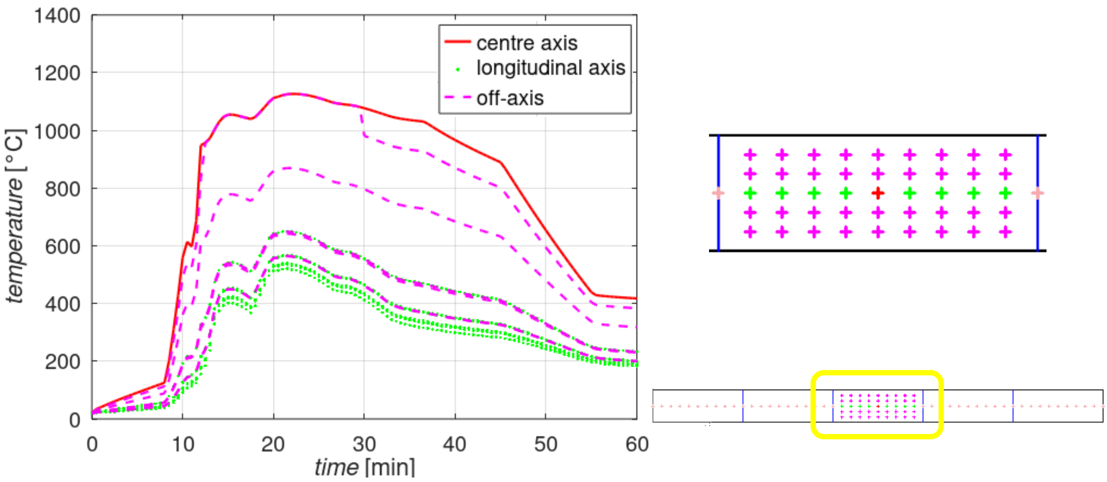

Figure 9: The temperature evolution beneath the ceiling at various distances from the fire source axis in the CFAST program, variant HGV-5 segments.

The comparison of the total maximum temperatures can be summarized as follows. The total maximum temperatures obtained using the CFAST model are in good agreement with the temperatures obtained using the FDS model, especially in the variant with small number of segments (the 5-segment, 7-segment, and 11-segment variants), when the "Target" temperatures are used. This holds true for both the smaller and larger fire scenario.

4.4 Temperature profiles

For both fire scenarios, the distributions of maximum temperatures in the longitudinal section of the tunnel at 10 minutes, 15 minutes, 30 minutes, and 40 minutes are shown in Figures 10 and 11.

In the HGV fire scenario (see Figure 10), the temperature distribution obtained using the CFAST program is symmetrical along the tunnel axis. In contrast, the results obtained using the FDS program show that the temperature distribution is slightly skewed in the direction of airflow.

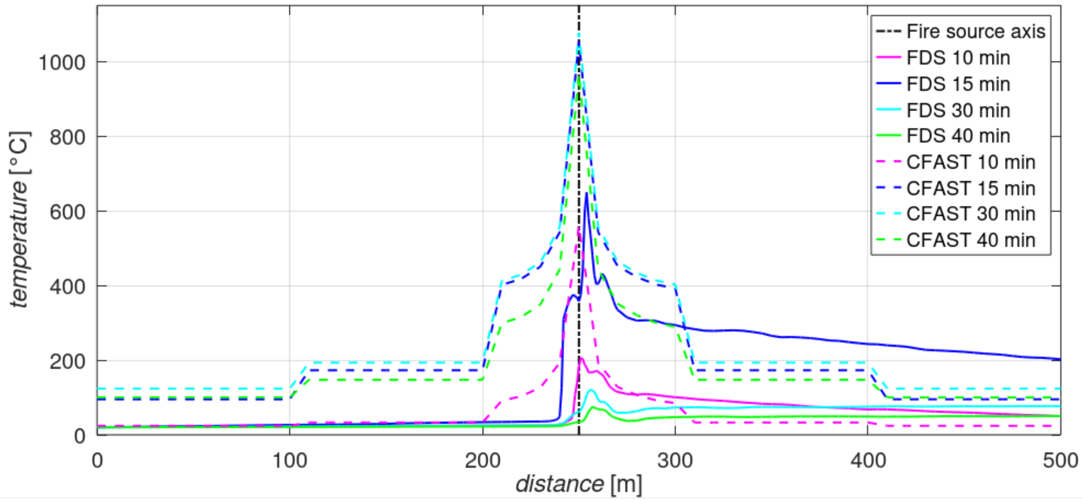

Figure 10: The temperature profile along the length of the tunnel at time "x"; HGV fire scenario.

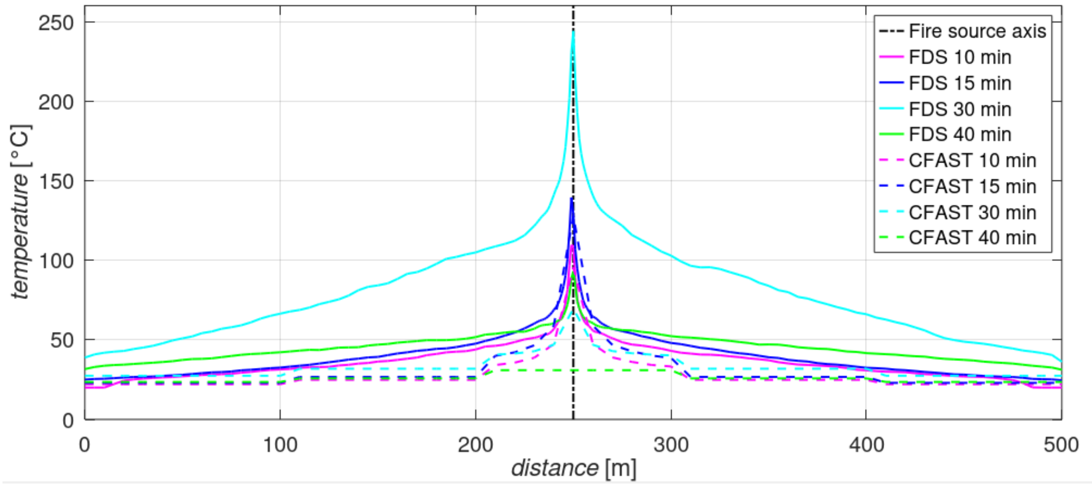

Figure 11: The temperature profile along the length of the tunnel at time "x"; 3 cars fire scenario

5 Summary of results

In the smaller fire scenario, i.e. the three passenger cars fire scenario, the results obtained using the CFAST model are in an excellent agreement with the accurate results obtained using the FDS model. The HRR curves are in perfect agreement, and the evolutions of maximum temperatures are also in very good agreement. The most precise results were obtained in the 7-segment, 11-segment, and 5-segment variants. The most imprecise results were obtained in the 25-segment variant.

In the larger fire scenario, i.e. the HGV fire scenario, the results obtained using the CFAST model are generally not in good agreement with the accurate results obtained using the FDS model. Though the HRR curves are in most cases in perfect agreement, the maximum temperatures provided by the CFAST model are significantly higher than the temperatures provided by the FDS model. However, as the CFAST model is most suitable for especially for quick preliminary assessments, it can be beneficial that it provides conservative (higher) temperatures. The most precise results were obtained in the 5-segment and 7-segment variants. In the variant with the highest number of segments (25 segments), the temperatures oscillated which points to a numerical instability. Thus, high number of segments seems to be inappropriate for spatial segmentation of the tunnel.

In summary, the CFAST model provided results which were either in good agreement or conservative, and the most accurate results were obtained when small number of segments were used.

The results presented in this paper demonstrate that fire modelling in tunnels using the CFAST zone model is feasible, even though the zone models are not primarily intended for this type of structures.

6 Conclusions

This paper focused on employing zone fire models with various spatial segmentations for modelling of fire in tunnels. As an illustrative example, a fire in a 500-meter-long, bored reinforced concrete road tunnel was chosen. Two different fire scenarios were considered: a heavy goods vehicle (HGV) fire with a load of timber and a fire involving three passenger cars with gasoline tanks. Both fire scenarios were modelled in the CFAST zone model and, for comparison, in the FDS CFD model. Due to the limitations of zone models, various spatial segmentation variants were considered in the CFAST model, with 5, 7, 11, 15, and 25 segments. The resulting graphs were compared, focusing primarily on the heat release rate (HRR) curve and the temperature profiles of the hot gases beneath the ceiling and the upper smoke layer.

The most notable results and conclusions can be summarized as follows.

- The CFAST zone model provided accurate results for smaller fire (i.e., a three passenger car fire).
- The CFAST zone model provided conservative results (higher temperatures) for larger fire (i.e., an HGV fire).
- Segmenting into a smaller number of sections (5 to 11 sections) seems to be more appropriate than segmentation into a larger number of sections (e.g., 25 sections) as it leads to more accurate results.
- Using large number of sections (e.g., 25 sections) seems to be inappropriate for spatial segmentation of the tunnel as in this case the fire source is located nearer to virtual openings, and thus, the issues related to the simplifications of physical phenomena occurring in these openings are more pronounced, especially in fire

scenarios with high heat release rates. This leads to less accurate results and numerical instability.

Based on the results of the study presented in this paper, the following recommendations for future modelling of fire in tunnels using the CFAST program are presented.

- Avoid placing the fire source near virtual openings and position it approximately in the middle of a segment.
- The tunnel should be segmented into a smaller number of sections rather than a larger number of sections. The presented study indicates that as few segments as possible is ideal as this reduces the number of virtual openings between the segments. However, the most appropriate number of segments for the specific modelled tunnel should always be derived by comparing the results with a more complex CFD model.
- Special care considering the placement of fire source and the number of sections should be taken when a larger fire is being modelled.
- When defining the individual compartments (segments), airflow characteristics specific to corridors or tunnels should be selected.
- Thermocouples placed beneath the ceiling should be used to determine the evolutions of maximum temperatures in the required locations. The temperature of the upper smoke layer should not be used as it is significantly lower when compared to accurate CFD models.
- When interpreting the results, keep in mind that CFAST seems to provide accurate results for smaller fires (e.g., three passenger cars) and conservative results for larger fires (e.g. HGV fires).
- The CFAST model should not be used for modelling of complex ventilation conditions or for the verification of forced ventilation performance inside the tunnel.
- In the context of modelling of fires in tunnels, the CFAST program should mainly be used for approximate quick preliminary assessments or approximate parametric studies. In more complex assessments, the results from the CFAST model ust be validated with CFD models, e.g., using the FDS program.

Though CFD models remain the most reliable method for accurately understanding fire behaviour in tunnels through numerical simulation, the results presented in this paper demonstrate that fire modelling in tunnels using zone models is feasible, even though these models are not primarily intended for this type of structures.

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