Investigation of road tunnel fires: challenges and findings

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Abstract. Numerical simulations have widely been used in the past to perform various complex engineering problems and phenomena. Most of the time the main objective of numerical modelling was to validate the outcome of experimental findings. However, it’s not always possible to replicate the exact conditions of experiments while doing a numerical simulation. There are various obstacles in modelling complex engineering problems such as the capability of a program, computational resources, time, understanding the real physics, modelling of components etc. This study will focus on the road tunnel fires with a heavy goods vehicle. A full-scale experiment of road tunnel fires is not always feasible because of very high cost and legal procedures. This motivates alternative techniques such as numerical modelling to study such phenomena. A numerical analysis of road tunnel fire involving heavy goods vehicle is undertaken in this study using FDS (Fire dynamic simulator) program. The study will discuss the challenges associated with the numerical modelling of road tunnel fires. A comprehensive summary of real problems encountered in such modelling, their possible causes, alternative ways, their impact of overall results and few solutions will be presented in this study. This paper reviews the similar work done by other researchers worldwide and provides a benchmarking.

Nomenclature

\( g \) - Gravity
\( m \) - Mass Loss Rate
\( n \) - Reaction Order
\( r \) - Rate of Reaction
\( A \) - Pre-Exponential Factor
\( C \) – Carbon
\( C_p \) – Pressure Coefficient
\( D^* \) - Characteristic Fire Diameter
\( E \) - Activation Energy
\( H \) – Hydrogen
\( H_c \) – Heat of Combustion

N- Nitrogen
O – Oxygen
Q- Heat Release rate
T – Temperature
\( \rho \) - Density

Abbreviation

CFD - Computational Fluid Dynamics
FDS – Fire Dynamic Simulator
HGV - Heavy Goods Vehicle
HRR - Heat Release Rate
KW - Kilo Watt
LES- Large Eddy Simulation
MIN - Minute
MW - Mega Watt
NFPA- National Fire Protection Association, USA
PUR – Polyurethane
PE - Polyethylene
RWS - Rijkswaterstaat
PS- Polystyrene
TGA- Thermo-Gravimetric Analysis

1. Introduction

The tunnel construction industry is booming worldwide and every year the numbers of tunnels are increasing. There are tunnels constructed in the mountains and in deep inside the seabed as well. One of the important factors of such construction is fire and life safety. Tunnel fires have been studied by many researchers in the past using different methods. Full scale tests to replicate real life situations are the most reliable, while model scale and computational simulations are also reliable to some extent.

Recent advancement in tunnel construction industry witnessed complexity in tunnel geometries and their locations and hence in some cases full scale tests may not be able to represent exact tunnel conditions. The other major concerns of full scale tests are massive cost, limited number of testing facilities worldwide, time involved in preparation of testing, legal procedures and lack of flexibilities in existing tunnel testing facilities. In many situations it is not possible to build a full scale model due to size and geometry of actual tunnel. These problems can be overcome by performing numerical studies and simulating real scale fires. Modern Computational Fluid Dynamics (CFD) tools are capable of performing complex fire analysis in limited time. If simulations are performed effectively it can lead to a very cost effective solution and can also save significant time and resources. It is important to note that simulating tunnel fires is very challenging task as there are various parameters that affects the tunnel fires. A good understanding of tunnel fire dynamics, deep knowledge of CFD tool and finding different boundary conditions and material properties is usually the prerequisite of such complex studies.

In the present time CFD solutions are considered as performance based design approach for engineering application. Such tool divides a computational domain into number of small cells/domains and solves a set of differential equations using various algorithms. It is essential for users to understand the embedded mechanisms while solving a problem using such tools. The basic CFD modelling includes controlling equations, different turbulence models and numerical methods, while various sub models for tunnel fires includes pyrolysis model, gas phase combustion model, fire suppression model, wall functions, and heat transfer models [1].

There are various commercial CFD tools available and used in solving engineering problems such as ANSYS Fluent, ANSYS CFX, PHOENICS, STAR-CCM+. These are general CFD tools and contain various embedded models and has strong problem solving capabilities, but these tools are not constructed exclusively for fire modelling. There are also specific CFD packages for fire modelling such as JASMINE, SMARTFIRE, SOFIE, FDS (fire dynamics simulator) [2] and FireFoam [3], out of which FDS has become an emerging choice of users. In literature there are various studies available on tunnel fire using CFD modelling. Cheong et al. [4, 5] has done a study to simulate heavy good vehicle fire in road tunnel, Ingason H [6] et al studied numerical simulation of model scale tunnel fire to compare it with experimental data. Li et al. [7] studied the smoke characteristics of large tunnel fire, Wang X. [8] studied pyrolysis model of HGV in tunnel fire and compared it with full scale results. The findings of past researchers are different, only in few cases the finding of numerical simulation matches with experimental results. Many possible reasons are highlighted in the literature for scenarios where CFD results do not match with experimental data. This paper reviews tunnel fire modelling challenges using FDS version 6.6.0 (Pyrosim [9]) and associated findings.

2. Modelling challenges
2.1 Tunnel modelling
The geometry construction is the first stage in fire modelling. A user needs to specify the grid size for model construction. It is important to note that in Large Eddy Simulation (LES) the details at places smaller than the grid size are not studied. FDS does not accept geometry of sizes less than the grid size, meaning such obstructions are not accounted in fire flows even if modelled. Generally road tunnels are lengthy and hence a coarse grid size is mostly used. In the past, users [4, 5, and 10] have used a grid size of 150-250 mm for the entire tunnel including fuel geometry. Many users prefer to use non-uniform grid sizes by using fine grid sizes at fuel and coarser sizes at other places. The number of cells in a simulation is direct indication of computational time. A very fine grid size or DNS (Direct Numerical Simulation) may results in unpractical simulation time. For an instance a 50 mm grid size for 150 m long tunnel in pyrolysis model may require a computational time more than a year. Hence selecting a reasonable grid size is very important.

Cheong et al. [5] studied the effect of grid size on tunnel fire using grid size of 150 mm and 300 mm and found that the results of 300 mm grid size was closer to the experimental results. However such results are not conclusive and in all cases grid sensitivity must be carried out to achieve stable results.

The grid division for a given simulation to be optimal (Poisson friendly) and hence the calculation of mesh size is important. The cell size \((dx)\) in a simulation can be related to the characteristic fire diameter \(D^*\), the smaller the characteristic fire diameter the smaller the cell size to reasonably resolve the fluid flow and fire dynamics. The below relationship represents the characteristic fire diameter \(D^*\) [2]

\[
D^* = \left(\frac{\dot{Q}}{\rho \omega C_p T_{\infty} g}\right)^{\frac{2}{5}}
\]

Where \(Q\) is heat release rate and \(\rho, C_p, T, g\) are density, pressure coefficient, temperature and gravity respectively.

The quantity \(D^*/dx\) is considered as the number of computational cells spanning the characteristic diameter of the fire. The more cells spanning the fire the better resolution of the calculation is expected. In most of the fire modelling cases a 20-30 divisions \((dx)\) of characteristic fire diameter is considered as fine mesh [9] and can provides reasonable results.

2.2 Fuel modelling
As stated in section above a fine mesh is always preferred in tunnel geometry modelling including fuel. In tunnel fire simulations fuel modelling is one of the most complicated item. Most of real full scale tunnel fire experiments were carried out with wooden and plastic pallets and these pallets are constructed of many thin objects. Figure-1, 2 shows an example of type of pallets typically used in full scale fire tests, the same dimensions were used in simulating tunnel fires by Wang [8]. Similar size and shapes of pallets are been used by various other users to study tunnel fire modelling [4, 11].

![Figure 1. Fuel arrangement in T1 and T2 experiment of Runehamar [12].](image-url)
Figure 2. Dimensions of pallets: (a) wood pallets; (b) plastic pallets [8].

The pallets shown in Figure-2 consists various thin objects starting from 20 mm size. The dimension of heavy good vehicle (HGV) used in Runehamar full scale test-1 [12] was 10.4 m x 2.9 m x 3.3 m (L x W x H) in a 7.1 m wide tunnel (at fire location). Considering the pallet’s least dimension (20 mm) as cell size, a mesh covering nearby area of fuel will result in approximately 70 million cells (accounting 16 m length and tunnel height and width). These many cells are only for mesh covering fuel area; if all the meshes of entire tunnel are combined then the total number of cells would be extremely high. It will take massive computational time, may be in few months or even higher to run simulation for such high no of cells.

A solution to overcome high no of cells is to use bigger cell size such as 200-300 mm but the challenge is then FDS will not be able to capture small elements of pallets. Another option is to change the individual pallet sizes and rearrange the fuel in such a way it matches with the surface area and weight of experimental fuel conditions. It is important as heat release rate (HRR) in a fire depends on surface area and weight of the fuel. In selecting appropriate fuel pallet dimensions with a grid size higher than 200 mm and to fit within HGV sizes, its next to impossible to match with higher surface areas and weights such as 1024 m² and 11,010 kg found in Runehamar test-1 [12]. A pallet of dimensions more than 200 mm will have much less surface area then pallets used in experiments and the weight of such pallets will be much higher. This situation will lead to a scenario of 20-40% of surface area and 400-500% weight compare to experimental fuel arrangement. It is important to note that a gap is required between such pallets, else if solid pallets are stacked on each other most of the free surface area will be lost. Such issues make fuel modelling very difficult.

Past researchers tried various methods to overcome these problems. Cheong et al. [4] used a surface burning factor (SBF) which was established by dividing the surface area of gross bounding volume of a pallet fuel package by the fuel package area modelled in the simulations. The SBF was multiplied by the HRR per unit area from cone test data and then used in the simulations. This approach indirectly
accounted the total energy consumed in the fire. Tomar M. et al. [10] used simplified fuel geometry consisting layers of fuel and specified peak HRR values from Runehamar test-1 on the surface of fuel to study the temperature behavior inside the tunnel with different tunnel lining material.

Wang [8] used fine cell sizes of 150 mm x 100 mm x 50 mm to represent the geometrical details of wood and plastic pallets in simulation because the simulation time for actual 20 mm cell sizes was impractical. Apart from fuel area, in other locations a coarse cell size of 500 mm x 200 mm x 100 mm was used. Further, to achieve the equivalent surface area and mass of fuel the pallet was simplified in two elements based on different obstacle thicknesses of 50 mm and 100 mm. The simplified geometry of pallets provided nearly similar surface areas as of experiment. For mass calculations the available surface area and thermal thickness was used, small thermal thickness such as 25 mm and 18mm were used to keep resultant mass similar to experiment conditions. However it was not the actual conditions of fuel in the simulation but was used as an approximation. The HGV fire simulation with such cell sizes resulted in 3.1 million cells only for 2 meshes and took 2 months for a 30 minute fire simulation.

In summary modelling of fuel is more challenging and users are not able to represent fuel correctly in fire simulations which ultimately results in deviation of results from experiments.

3. Combustion reactions

In FDS there are two ways of designating a fire, first by specifying a heat release rate per unit area (HRRPUA) as part of surface another way is to specify heat of reaction and other material properties. In both cases FDS uses the mixture combustion model. In the mixture fraction model the reaction is assumed in the form:

$$C_xH_yO_zN_v + \nu_{O_2}O_2 \rightarrow \nu_{CO_2}CO_2 + \nu_{H_2}O H_2O + \nu_{CO}CO + \nu_S Soot + \nu_{N_2}N_2$$

Specifying HRR is the simplest way to specify fire but a reaction needs to be specified for the combustion. The FDS provides multiple fuel reaction from its library but they are limited to one fuel such as wood, PVC, polyurethane etc. but in real full scale tests usually more than one fuel is used. For an example in Runehamar test-1 a combination of wood and PE was used. Although recent versions of FDS allows users to specify multi fuel reaction but it increases computational time excessively. Another option is to specify a common reaction which can cover the burning reaction of all the fuel involved in combustion.

Wang [8] used a combined reaction using simple chemistry model [2] approach. The chemical formula of burning fuel was specified in terms of C, H, O, and N to represent 38% plastic (CH2)n and 62% wood (CH2O)n. The next step is to determine the yields of CO (\(\nu_{CO}\)) and soot (\(\nu_S\)) which shall also be derived from respective fuel arrangement (for example 38% plastic and 62% wood). To obtain the C, H, O and N values for a combination of fuel various literatures [13, 14] can be used, the challenging task is to obtain yields of CO and soot for respective percentage of fuel in a single reaction. Without CO and soot yield values it is not possible to trace the smoke and soot in results hence its must.

In a nutshell a combined reaction is always preferred to save on computational time compared to multiple reactions. Also providing multiple reactions is complicated when many fuels are presents.

4. Material properties

4.1 Heat of combustion

Heat of combustion is one of the important properties required in fire modelling apart from heat of reaction, thermal properties and kinetic properties of fuel materials. It is not always available and experimental analyses are often required to get these values. The heat release rate per unit area can be described as;
\[ \dot{Q} = \dot{m} \Delta H_c \]

The term \( \Delta H_c \) is the heat of combustion and \( \dot{m} \) is mass per unit area. The heat of combustion for common fuel materials can be obtained from literature [13, 14] but heat of combustion for entire combustion with multi fuel is difficult to find unless such values from similar arrangement experimental results are available for reference. The heat of combustion is a must when user specifies a customized reaction for the combustion. For simplification heat of combustion observed in Runehamar tests or other similar full scale tests can be used if studying similar HGV fuel fire in identical tunnel environment and not varying the other parameters.

It is important to note that forced ventilation rates affect heat of combustion greatly. The length of pallets/cribs can also influence the heat of combustion. The effective value of heat of combustion can vary the measured HRR. Hence during a simulation it is very important to analyze these values and choose most suitable heat of combustion. Usually cone calorimeter experiments are utilized to estimate the heat of combustion for different fuel material. Heat of combustion values for individual fuel materials are also required when pyrolysis model is used.

4.2 Thermal properties

The thermal properties of fuel are needed in FDS for effective calculation. Properties such as density, specific heat, conductivity and emissivity are must while conducting a fire modelling. Finding these properties is not a difficult task as they are mentioned in many literature sources [13, 14]. However, the challenging task is that some of these properties such as specific heat and conductivity are temperature dependent and as temperature increase their value changes. For simplification some user uses room temperature values and ignores the changes with temperature. It is advised to use temperature dependent values as FDS allows all these options. For obvious reasons a customized thermal property against temperature provides better results.

In conclusion finding material properties is easier using various literatures; however care should be taken as the literature values are achieved using a particular arrangement and conditions. In some cases simulation conditions can be different than these and hence most appropriated properties needs to be opted for more real results.

5. Pyrolysis Modelling

In most of the engineering application tunnel fires are simulated using gas burner producing a fixed heat release rate or by matching a HRR curve obtained from an experiment. This process can only simulate gas phase combustion. In many cases a more realistic fire is required to understand the solid fuel combustion. The pyrolysis model in FDS can predict the HRR based on fuel properties and environmental conditions. The present capability of CFD tools seldom succeeds in understanding of mechanism of condensed phase pyrolysis [1]. There can be a solid phase or liquid phase pyrolysis depending on the fuel inside the tunnel. In past most of the full scale tunnel experiment used solid fuel [12] to represent the fire. However, there are experiments which also used liquid fuels but such cases are very limited and hence this study will mainly focus on the solid pyrolysis.

The use of pyrolysis model in FDS is usually limited to simulate materials and bench scale experiments. Only few studies are available where pyrolysis model was used to analyze the HRR from large scale experiments. The finding of these studies reveals the limitations in using pyrolysis model to predict actual experimental results. McGrattan et al. [15] used Langrangian particles (a method of defining particles as an element of fluid with assigned properties) to study the fire of burning cables and burning trees. The kinetic properties of cables and tress were estimated using analytical method. The results obtained from simulation was partially represented the actual burning. The reason given for non-matching result was lack of comprehensive set of material properties.

Pau [16] used pyrolysis model to simulate fire spread on polyurethane foam mattress. Two foam slabs 1000 mm wide and 2000 mm in length with two thicknesses of 100 mm and 120 mm were used.
During simulation FDS failed to produce fire spread on foam slabs when material properties were used as input. The material properties were experimentally developed and refined by using material property estimation software Gypro. On the other hand FDS showed fire spread on foam slabs when activation energy \((E)\) was reduced by a 20-30% factor.

Li [17] utilized two methods in FDS to simulate a train carriage fire in a tunnel. One of the methods used was pyrolysis model. The material properties used in simulations were estimated using TGA experiments and was calibrated using cone calorimeter experiments. The simulation results predicted much lower peak HRR compared to the experimental results. The main reason provided for such under prediction of results were due to inappropriate kinetic properties and incorrect representation of combustible materials. In this study the method of derivation of kinetic properties was not provided.

5.1 Solid phase pyrolysis
The pyrolysis is the thermal decomposition process of a heated solid material to release gaseous fuel. The released combustible gasses will be burnt above the solid fuel in the presence of oxygen and charred residue may be oxidised. The FDS describes pyrolysis process through an Arrhenius like equation, which represents relationship between reaction rates and temperatures. The decomposition rate for a material undergoing one of more reactions can be described as below [1]:

\[
r_{ij} = A_{ij} Y_{s,i}^{n_{s,ij}} \exp \left(- \frac{E_{ij}}{RT_s} \right) \quad Y_{s,i} = \left( \frac{\rho_{s,i}}{\rho_s(0)} \right)
\]

The term \(r_{ij}\) represents the rate of reaction at temperature \(T_s\), of the \(i^{th}\) material undergoing its \(j^{th}\) reaction. The second term on right side of equation shows the contributions of other material producing the \(i^{th}\) material as a residue. \(\rho_{s,i}\) is the density of \(i^{th}\) material component of the layer, \(\rho_s(0)\) is the initial density of the later. The \(A_{ij}\) is the pre-exponential factor with units of s\(^{-1}\). The \(E_{ij}\) is activation energy in units kJ/kmol. Both of these parameters should be derived from a common set of experiments like TGA (thermo-gravimetric analysis).

FDS adopts one dimensional heat conduction equation to calculate the temperature gradient in solid phase which later determines the changes in decomposition rate with increase in temperatures. Based on these two equation gaseous fuel release rate and then heat release rate can be calculated.

5.2 Kinetic properties analysis
To apply pyrolysis model, the key properties \(A_{ij}, E_{ij}\) and \(n_{ij}\) as shown in equation above are needed. These properties are termed as kinetic properties of fuel. The TGA experiments are commonly used to determine the kinetic properties for different fuel materials. A very small amount of fuel sample (nearly 10 mg) is required to obtain these properties. TGA can provide mass loss curves and from that using various methods such as analytical methods [15, 18], genetic algorithm (GA) optimization methods [19], graphical analysis methods [20] and combining methods [21] kinetic properties can be derived. In addition to TGA experiments cone calorimeters at ambient air environment are also useful to validate the solid phase decomposition.

Matala and Hostikka [21] used analytical methods and GA optimization method to derive kinetic properties for PVC cable materials. In the analytical method of finding kinetic properties the reaction order is simplified to one and the \(A\) and \(E\) values are derived from simple analytical method based on the findings of TGA experiment. In the GA optimization method a random set of parameters testing against TGA experimental curves in order to find parameters which gives best fit with the experimental curves. The kinetic properties obtained from different methods will provide different results if used in simulation of cone calorimeter experiments. Hence an optimization to these kinetic properties is often used to achieve good fit against experimental data.

Li et al. [22] used Kissinger method with GA searching method to obtain kinetic properties of medium density fireboard (MDF). MDF is a wood based material with complicated decomposition
behavior. In complex decomposition behavior graphical methods cannot be applied and GA searching method requires very long computational time to find results. Hence the Kissinger method was used to narrow the searching range and GA method was used to find final results.

5.3 Importance of kinetic properties in combustion
Kinetic triplet \((A, E\ and\ n)\) are the key components in a pyrolysis model and they can significantly influence the decomposition rate. The \(n\) is termed as reaction order and the effect of \(n\) can be understood from Figure-3; which shows 4 plots of a DTG curves for different values of \(n\) while \(A\) and \(E\) are kept constant.

![Figure 3. Reaction rate profiles at different reaction orders [8].](image)

The Figure-3 shows that peak of reaction rate are reducing with increase in reaction order. The completion of reaction also shifts towards higher temperatures with high values of \(n\). This behavior suggests that with higher reaction order the reaction rates gets slower down and needed higher temperature to complete the reaction. However, the value of temperature at peak of reaction rate is remains nearly unchanged with changes in reaction order.

The activation energy \((E)\) also affects reaction rates; Figure-4 shows reaction rate curves for different values of \(E\) while keeping pre exponential factor \((A)\) and reaction order \((n)\) constant. The Figure-4 demonstrates that the peak reaction rate temperature is increasing with an increase of \(E\) values. The temperature range for pyrolysis is also getting increased with \(E\) values. It also represents that more energy (temperature) is required to activate a reaction with higher \(E\) values. However, the peak reaction values are only slightly changed with increasing \(E\) values.
The Pre-exponential factor also influences the reaction rates. The Figure-5 shows the influence of different $A$ values on reaction rates keeping $E$ and $n$ constant. It shows that peak reaction rate remains almost same with different $A$ values. However, the peak reaction temperature is decreasing with increasing $A$ values. The temperature to complete the reaction is also found decreasing with increase in $A$ values.

With above comparisons it can be concluded that a reaction order mainly represents the reaction rate and range of pyrolysis reaction. The activation energy and pre exponential factor is responsible for controlling the reaction temperatures, while influence of activation energy on peak temperature is significant compare to the pre exponential factor. In conclusion $A$ and $E$ determines the location for a reaction curve while $n$ represents its sharpness and shape.

It a nutshell the pyrolysis is the only mean in FDS to achieve HRR from a burning fuel but the associated properties which are needed for simulation are difficult to obtain. Especially the kinetic properties are expected to have lot of uncertainties if not properly optimized.

6. Simulation parameters
There are various simulation parameters which can also affect the simulation findings. Some of the important parameters are ambient conditions (Pressure and temperature), ambient oxygen mass fraction, ambient carbon dioxide mass fraction, relative humidity and wind velocity etc. In general
these values are taken by default while modelling in FDS but a careful selection of these properties to meet the actual conditions is must.

Most of the simulations especially in large scale fires are done using Large Eddy Simulation (LES) due to lesser computational time requirements. While FDS also allows using Direct Numerical Simulation (DNS) for studies where more detailed level analyses is required, but DNS is not recommended for large scale fires due to unpractical computational time involved. Another important thing while doing a large scale fire in confined space is to consider “Radiation Transport Solver” model in the FDS because radiation plays a greater role in overall heat transfer in such fire scenarios. FDS by default allows using 100 numbers of solid angles and 15 numbers of polar angles for better radiation calculations however a user can further customize it according to the simulation requirements.

FDS by default considered radiative source temperature of 900°C, but users must analyses the possible temperature in their simulation and hence need to adjust it accordingly. Also the default radiation fraction considered in FDS is 0.35 which represent the expected radiation in most of the fires but in large tunnel fires this value must be carefully chosen as in tunnel fire the radiation plays major role in overall heat transfer and may become significantly higher than these default values.

7. Conclusion
The full scale fire tests are the most preferred way to study fire behavior in tunnels but due to tremendous cost involved in full scale testing, numerical simulations are always looked as promising option. The CFD simulations for small fire and for gas phase combustion model are simpler and their result matches with experimental findings to a good extent. However, in large scale fires the fire simulations are challenging, this paper reviewed most of the aspects of numerical modelling of tunnel fire using FDS.

The main challenges are deciding mesh sizes as with small mesh sizes the computational time increases exponentially while with coarser mesh the fuel modelling becomes really challenging. In validating the full scale test results it becomes nearly impossible to meet the surface areas and mass of fuel with reasonable mesh sizes. Obtaining thermal properties are relatively easier but while using temperature dependent properties in FDS it is preferred to use variable values instead of just one value.

The main challenge of such modelling is to use pyrolysis model as obtaining kinetic properties of fuel material is challenging. There are various methods of obtaining and optimizing these properties but most of the time it varies a lot for two similar materials. Most of the past researchers who attempted validating large scale fires with simulations highlighted that inaccurate and insufficient information of kinetic properties was the main reason for non-matching results. Even after using most appropriate kinetic properties and other parameters a road tunnel fire simulation with a HGV on fire takes more than 2 months computation time on a high end PC, which is very high.

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