Numerical simulation of road tunnel fires involving heavy goods vehicle with solid fuels

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Abstract. The road tunnel fire is an emerging topic in literature and many key areas are still undiscovered. Road tunnel fires can be catastrophic and can result in a significant loss of human life and property. In literature various experimental and numerical studies are available on road tunnel fires. Most of these studies involved heavy goods vehicle with a combination of wooden/plastic pallets to represent fuel arrangement. The fire scenario of heavy goods vehicle with solid wooden/plastic fuel is not well studied. The burning behavior of pallets and solid blocks are different and hence the tunnel conditions would be different under fire in both these cases. This will result in a significant difference in key parameters such as heat release rates and temperature profiles inside the tunnel. To study these effects, full-scale fire tests are ideal and recommended, however, due to extremely high cost, downtime, and legal obligations it’s not always practical to conduct a full-scale fire test especially for road tunnels involving a heavy goods vehicle. In lieu of full-scale tests, numerical analyses are often used to understand these phenomena. This study focuses on studying the road tunnel fires involving heavy goods vehicle with solid fuels using CFD modelling in FDS (fire dynamic simulator). A pyrolysis model will be used to generate the anticipated heat in the tunnel. The kinetic properties of materials will be used in order to correctly calculate the pyrolysis rates of fuel. The findings of the heat release rate and lining temperature from the simulation will be compared with available results of heavy goods vehicle fires which involved pallets as fuel.

Nomenclature

m – Mass loss rate
C – Carbon
H – Hydrogen
N – Nitrogen
O – Oxygen
T – Temperature

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
PE - Polyethylene
PS - Polystyrene
PUR – Polyurethane
RWS - Rijkswaterstaat
TGA- Thermo-Gravimetric Analysis
1. Introduction
The road tunnel industry is growing rapidly and witnessing various technological challenges. Apart from various construction and maintenance challenges in road tunnels, fire safety is also considered as a big challenge. The past fire event witnessed massive loss of human lives and property. The road tunnel fires are nowadays controlled by various engineering means. An uncontrolled tunnel fire is not acceptable and not permitted by authorities and international design community. A tunnel fire is very different from an open fire due to its characteristics and impact of heat feedback from walls and ceilings which are not available in the open fire. This makes it more challenging in terms of controlling the fire and approaching to the base of fire for extinguishment.

Past studies on road tunnel fires are carried out to study various characteristics and phenomenon by full scale fire tests, model scale test and numerical simulations. Most of these studies focused on HGV fires because a HGV is believed to release highest heat among the common vehicles expected in modern road tunnels (except hazardous material and patrol tankers). The most discussed characteristic of tunnel fires is heat release rate (HRR) as most of the tunnel fire safety is designed based on this parameter. Ingason H. and Lonnermark A. carried out full scale fire tests for HGV scenario in an abandoned road tunnel of Norway for different fuel combinations and reported a highest peak HRR of 202 MW for a fire involving approx. 11 tons of fuel (80% wood and 20% PE plastic) [1]. Other tests, in the Runehamar experiments had shown lesser HRR. Based on the findings of this test many international standards including National fire protection association (NFPA-502) updated the peak HRR values for road tunnel fires involving HGV to 20-202 MW [2]. It is to be noted that this peak HRR (202 MW) and various other similar studies involved fuel in pallet configurations. Usually a pallet configuration involves high surface area and less mass, and this help in burning of fuel at faster rate as HRR depends on surface area and mass of fuel.

It will be interesting to know the behavior of solid fuels in similar tunnel environment because with solid fuels the surface area is much reduced for the same mass. This study investigates the HRR for a case of fire involving a HGV in a road tunnel similar to Runehamar with solid fuel arrangement (80% wood and 20% PE plastic). All other influencing parameters are consistent with the Runehamar experiment. A numerical simulation using fire dynamic simulator, FDS [3] is used to study this scenario. FDS is a computational fluid dynamics (CFD) model of fire-driven fluid flow. Smokeview [3] is a visualization program that is used to display the results of an FDS simulation. FDS solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow with an emphasis on smoke and heat transport from fires. The LES approach is used for turbulence modelling in FDS.

Pyrolysis model of FDS is used in present study to calculate the actual HRR rather than using a burner fire and specifying the expected HRR for accurate measurement of HRR from the fuel combustion. FDS allows using pyrolysis model but it requires the kinetic and thermal properties of burning fuel. The following sections establish the finding of present study and compare the results with original Runehamar test.

2. The Runehamar model and current conditions
2.1 The Runehamar full scale fire test
A series of full scale fire tests were conducted in Runehamar tunnel of Norway in 2003 [4]. The main intention was to investigate the peak HRR and fire spread to other vehicles. HGV fire was simulated with different fuel arrangements. The tests were carried out by SP fire research of Sweden with cooperation of TNO, Netherland and SINTEF-NBL, Norway. The Runehamar is abandoned asphalted road tunnel with 1600 m length, 6 m height and 9 m width with 0.5 to 1% slope. These tests used different combinations of wooden pallets, plastic pallets of polyethylene (PE), polystyrene cups (PS), cardboard cartons and polyurethane mattresses (PUR) to represent a HGV cargo. Table-1 shows the fuel arrangement used in different tests of Runehamar tunnel.
Table 1. Fuel arrangement used in different Runehamar tests [4].

| Test No. | Description of fuel load                                                                 | Total weight Kg | Theoretical calorific energy (GJ) | Maximum HRR (MW) |
|---------|----------------------------------------------------------------------------------------|-----------------|-----------------------------------|------------------|
| T1      | 360 wood pallets measuring 1200x800x150mm$^3$, 20 wood pallets measuring 1200x1000x150mm$^3$ and 74 PE plastic pallets measuring 1200x800x150mm$^3$; 122m$^2$ polyester tarpaulin | 11010           | 244                               | 202              |
| T2      | 216 wood pallets and 240 polyurethane mattresses measuring 1200x800x150mm$^3$; 122m$^2$ polyester tarpaulin | 6853            | 135                               | 157              |
| T3      | Furniture and fixtures (combination of plastic, wood, armrests, sofas, toy etc.), 10 big rubber tyres (800kg); 122m$^2$ polyester tarpaulin | 8506            | 179                               | 119              |
| T4      | 600 paper cartons measuring (600mmx400mmx500mm) and 15% by mass of unexpanded polystyrene (PS) cups (18,000 cups) and 40 wood pallets (1200x1000x150mm$^3$); 10m$^2$ polyester tarpaulin | 2849            | 62                                | 66               |

The Runehamar tunnel was protected with insulation boards for any possible structural damage. A ventilation of 3 m/s was provided at the end of tunnel using mobile fan. The Figure-1 shows a cross section of tunnel where fuel is placed in test-1 (T1), while Figure-2 shows the fuel arrangement in all four tests carried out at Runehamar tunnel.

![Figure 1. Cross section and fuel arrangement in Runehamar tunnel for T1 [4].](image-url)
Figure 2. Arrangement of fuel in T1, T2, T3 and T4 of Runehamar [5].

In all the tests shown in Figure-2, the fuel was located above 1.1 m of floor level with a length of 10.45 m, width of 2.9 m and height of 2.9 m. In T1 the top of fuel surface was covered with 0.5 mm thick polyester tarpaulin. The location of fuel was 1037 m from east portal. The total fuel weight in T1 was 11040 kg with a total surface area of 1024 m². This study will discuss only T1 (test-1) of Runehamar tunnel test due to the occurrence of the highest peak HRR of 202 MW in this test.

2.2 Present Model
A rectangular tunnel of 150 m length 7 m wide and 5 m height is considered in present model. The tunnel walls and ceiling is assumed to be of concrete and a 3 m/s rate ventilation is provided at the west portal of model tunnel. The fuel location is 15 m downstream from west portal and measuring 10.15 m long, 2.7 m wide and 3.11 m high. The fuel sizes are very close to the full scale Runehamar fire test-1. Figure-3 and Figure-4 shows the general arrangement of tunnel and fuel in present study.

Figure 3. Current tunnel arrangement.

Figure 4. Fuel arrangement and tunnel geometry used in present study.
Comparisons of Figure-2 and Figure-4 shows that pallets type geometry were used to represent fuel in the Runehamar tests while solid box type geometry is used to represent fuel in the present study. A total 12 levels of solid fuel is modelled out of which 4th and 8th level of fuel is made of PE plastic while others are wooden fuel. Each level consists of total 60 solid fuel boxes and each such box measures a surface area of 1.45 m$^2$, hence total surface area of fuel is 1044 m$^2$. Considering densities of used PE and wood material the total weight of fuel is calculated 55,332 kg.

A quick comparison of current model and Runehamar test-1 shows that current model consists of approximately 5 times more weight due to solid geometry of fuel and almost similar surface area. It is important to note here that in current fuel modelling a gap of 50 mm was maintained between all fuel boxes however FDS accumulated these mini gapes at different positions hence the surface area of present study reduced drastically.

3. Modelling parameters

The numerical simulations are performed using Pyrosim [6] which is a preprocessor and graphical user interface for FDS and Smokeview. The Pyrosim version 2017.2.1115 which uses FDS version 6.6.0 and Smokeview version (SMV) 6.6.0 versions is used in present study. FDS code utilizes the equations of conservation of mass, species, energy, momentum and equation of state to solve the set of partial differential equations and computes the density, velocity components, mass fraction, pressure and temperature. Radiation transport solver is used in conjunction with LES turbulence model. Combustion is calculated from pyrolysis of fuel, where fuel is decomposed with the heat and mixed with the oxygen to support combustion.

The simple chemistry model is used to define fuel composition. Also fuel is assumed to contain only C, O, H and N. The fuel in present study is a combination of 80% wood and 20% PE plastic and hence $C_1H_2O_{0.8}$ compositions are used to represent fuel [7] while undergoing chemical reaction. A radiative fraction of 0.35 and 22 MJ/KG heat of combustion is used while $CO$ yield, soot yield and hydrogen fraction are 0.012, 0.012 and 0.1 respectively [7].

A complex pyrolysis model [8] of FDS is used to calculate the thermal decomposition of fuel in present study. For each reaction of each material component kinetic parameters of the reaction rate are specified. The reaction rate can be specified as [8]:

$$ r_{ij} = A_{ij} Y_{s,i}^{n_{s,ij}} \exp\left(-\frac{E_{ij}}{R T_s}\right) X_{O_2}^{n_{2,ij}} ; \quad Y_{s,i} = \frac{(\rho_{s,i})}{(\rho_{s}(0))} $$

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 are should be derived from a common set of experiments like TGA The fourth term of the reaction rate equation is used to simulate oxidation reactions.

The model was prepared in Pyrosim using a mesh size of 250 mm, such mesh sizes was used after studying grid sensitivity and as suggested by previous users for similar applications. Cheong, Spearpoint & Fleischmann [9] studied the Runehamar tunnel fire using numerical simulation with FDS and used similar mesh sizes. The various important modelling parameters used in present study to simulate HGV fire in road tunnel similar to Runehamar tunnel test are listed in table-2 [7, 9, 10, 11 & 12].
Table-2. Key thermal, pyrolysis properties and boundary conditions used in present study

| Item details                  | Values               |
|-------------------------------|----------------------|
| Concrete                      | Wood                 | PE                   |
| Density (Kg/m³)               | 2100                 | 566                  | 1376                 |
| Specific heat (J/Kg.K)         | 880                  | (1.2-6.5) changing   | 3.2                  |
| Conductivity (W/(m.K))         | 1.0                  | 0.21                 | 0.06                 |
| Emissivity                    | 0.7                  | 1.0                  | 0.9                  |
| Pre-exponential factor (Åij) (s⁻¹) | -                   | 5.8x10⁸              | 1.68x10¹²             |
| Activation energy (Eij) (kJ/kmol) | -                   | 1.23x10⁹              | 2.01x10⁵             |
| Reaction order (n)            | -                    | 2.2                  | 0.92                 |
| Heat of reaction (kJ/kg)       | -                    | 100                  | 930                  |
| Type of reaction              | -                    | Endothermic          | Endothermic          |
| Heat of combustion (MJ/kg)     | -                    | 12.1                 | 35.0                 |
| Thickness (mm)                | 500                  | 250                  | 250                  |
| Heat release rate             | To be determined by  | simulation           |                      |
| Ventilation (m/s)             | 3                    |                      |                      |
| Ventilation duration (minutes)| 0-30                 |                      |                      |
| Ignition source size (MW)     | 5                    |                      |                      |
| Ignition time (minute)        | 0-5                  |                      |                      |

4. Results and discussion:

4.1 Results from numerical simulation

The results pertaining to peak HRR and ceiling temperature is shown from the Runehamar test-1 and current simulation. It is important to note here that most of the key parameters which may affect the peak HRR and lining temperature a kept same as Runehamar test in current simulation. Figure-5 shows the peak HRR distribution from Runehamar test and Figure-6 for current simulation. Figure-7 shows the temperature distribution at 10 m downstream on fuel at ceiling location for Runehamar tests and Figure-8 shows the same for current simulation.

The Figure-9 shows the measured incident heat flux at ceiling of tunnel in Runehamar test-1, the graph shows measurement at 0, 10, 20 and 40 m downstream of fire. The Figure-10 shows the locations where the incident heat flux is measured in current simulation while Figure-10a, Figure-10b and 10c shows the variation of incident flux along the tunnel section for 0-10 m, 10-25 m and 25-40 m downstream of fire respectively.
Figure 5. HRR distribution for Runehamar tests [4].

Figure 6. HRR comparison for current simulation and Runehamar test-1.
Figure 7. Temperature distribution for Runehamar tests [4].

Figure 8. Temperature comparison for current simulation and Runehamar test-1.
Figure 9. Incident heat flux measured in Runehamar test-1 [4].

Figure 10. Incident heat flux measured in current simulation at different locations.
Figure 10a. Incident heat flux measured in current simulation at ceiling 0-10 m downstream

Figure 10b. Incident heat flux measured in current simulation at ceiling 10-25 m downstream
4.2 Discussion

The Figure-5 shows the HRR variation for Runehamar tests, the curve for T1 is our interest and shows a peak HRR value of 202 MW for HGV fire. The peak was achieved at approximately 17 minute after the ignition and after that it dropped drastically. In the current simulation as shown in Figure-6 the peak was achieved at 8 minutes after the ignition and reached a value of 21 MW, after that the HRR remain stable in the range of 12-21 MW with minor fluctuations and continued for the entire simulation time (30 mins). In the Runehamar test-1 the entire fuel was involved in fire after few minutes of start and fuel pallets burnt completely after certain time. In the current simulation fire spread was not observed to entire fuel, it was rather limited in the last portion of fuel. No significant (exponential) rise or decline in HRR was observed in current simulation during entire period of 30 minutes as fire didn’t spread well to the entire fuel and complete burning of fuel boxes didn’t happened.

The temperature distribution near ceiling of tunnel at 10 m downstream for Runehamar tests are shown in Figure-7 and Figure-8 compares temperature profile from test-1 of Runehamar with current simulation. This comparison shows that the temperature in current study is much lower than the Runehamar test-1 findings. During Runehamar test-1 the peak temperature reached 1350 °C at approx. 20 minute, however in current study the temperature reached approx. 645 °C after 1 minute which reflects the instability as fire was just started, after fire being stable the maximum temperature recorded was 577 °C at 16 minute after ignition. Later the peak and before the peak the temperature range was 300 °C -500 °C for most of the time. These low ceiling temperatures confirms that only partial fuel is involved in fire and fire is not fully grown. Tomar M. et al. [13] has studied such behaviors using FDS and found temperature near ceiling at 10 m downstream fire reaches more than 800 °C for such application after 4 minute of ignition.

The measured incident heat flux variations at the ceiling for different downstream distances are shown in Figure-9 for the Runehamar test-1. The other graph shown in Figure-10a, Figure-10b and Figure-10c represents the incident heat flux variation at ceiling for similar distances. The comparison of incident heat fluxes reflects that in Runehamar test-1 the heat flux at 0 m downstream was in the range of 100- 200 KW/m² during 10-30 minutes from fire. However the incident flux contour obtained
from current simulation for 0-10 m downstream shows that heat fluxes stays very less compare to Runehamar test and attains maximum value of 45 KW/m² at approx. 20 minute. Similarly at 10 m distance, Runehamar test shows heat flux in the range of 300-400 KW/m² during 10-30 minutes while current simulation attains maximum value of 40.5 KW/m² at approx. 25 minute. Incident flux data at 30 m and 40 m distances for Runehamar test are 200-300 KW/m², 100-200 KW/m² during 10-30 min while current simulation shows a maximum incident heat flux values of 8 KW/m² and 3 KW/m² attained at different times.

**Figure 11.** Spread of fire in current simulation at 30 minute after fire

The incident flux comparison between Runehamar and current simulation shows a big drop in incident heat flux values in current case. As noticed from the comparison of HRR and temperature distribution, incident flux values from current simulation also confirms that fire is not fully developed even in 30 minute time, also the fuel pallets are not complete burnt. Figure-11 shows the involvement of the fuel in fire after 30 min of ignition.

5. Conclusion and way forward:
The summary of discussion and Figure-11 reflects that in current simulation the fire is only limited to some portion of fuel and remaining fuel is not involved in fire. Compare to Runehamar test-1 where most of the fuel was involved in fire and burnt out, in current simulation the fire is not fully developed.

There could be many reason for this fire behavior, such as the pyrolysis process is very slow given the material is solid and has a dense molecular structure and hence all the molecules of wood and PE are not thermally decomposed and resulted underdeveloped fire. Another reason for undergrown fire is less surface area as compared to Runehamar test. Figure-12 and Figure-13 shows this behavior and reflects how surface area is drastically reduced in current simulation due to FDS limitation.

Current fuel geometry has an effective surface area of only 175 m² compare to 1044 m² of Runehamar test-1. Although while modelling the fuel, a surface area of 1024m² was configured by allowing a thin gap of 50 mm between horizontal fuel boxes and 10 mm between vertical fuel boxes, but due to FDS modelling limitation the FDS combined these thin gaps to form few distributed gaps. The next reason for underdeveloped fire is higher fuel weight. The Runehamar test-1 used 11,010 kg of total fuel while in current simulation the actual fuel weight was 55,332 kg. This increased fuel weight was required to meet the needed surface area in modelling, but on the same time the fuel weight was heavily increased. This increased weight resulted in heavy fuel load and dense structure and hence the pyrolysis of fuel and fire spread become very slow and resulted in underdeveloped fire. The HRR is related with mass of fuel and surface areas [14, 15] and hence this fire behavior is justified. Similarly the less grown incident fluxes and temperatures compare to Runehamar test-1 are
justified. Similar challenges were experienced in the past during fuel modelling by various researchers while attempting HVG fires in tunnel [7, 9].

![Figure 12. Fuel boxes modelled in current simulation to reflect 1024m² surface area](image12)

![Figure 13. FDS combined thin gaps to reflect 175m² surface area](image13)

This phenomena is interesting and indicates that there could be HGV fire scenarios which would result in much less HRR for a prolong time compare to Runehamar test-1, which is used as a benchmark in the tunnel design industry. As not all the HGV carries pallets as a fuel, however HGV containing pallets still continues to represent worst possible scenario. The finding of this work summarizes that a HGV carrying solid dense fuel will result in much lesser HRR compare to Runehamar test-1.

**The way forward**
The main challenge in current simulation was fuel modelling, as meeting the surface area and fuel weight of Runehamar test-1 is not possible with solid fuel modelling in FDS. A more sophisticated modelling approach to be used to truly represent the fuel pallets such as used in Runehamar test-1. There are various other simulations to be carried out for further investigation on this subject but due to
simulation time, it is not easy for example this simulation with a workstation of Intel Xenon 2.40 GHZ 12 core processor with 32 GB RAM took around 45 days.

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7. References

[1] Ingason H., Lönnermark A., “Heat release rates from heavy goods vehicle trailer fires in tunnels” Journal of Fire Safety, 646–668, 2005.
[2] National fire protection association USA, NFPA 502, 2017 ed. “Standard for Road Tunnels, Bridges, and Other Limited Access Highways”.
[3] NIST 2017, Fire dynamic simulator and Smokeview technical reference guide.
[4] Ingason H, Li Y Z and Lönnermark A. Technical report “Runehamar tunnel fire tests” 2011, fire technology.
[5] Tarada F. “Fire in tunnels-can the risk be designed out” volume 9, issue 4, 2011, Eurotransport.
[6] Pyrosim user manual, Thunderhead engineering, 2018.
[7] Wang X. PhD thesis “Fire Dynamics Simulator (FDS) Pyrolysis Model Analysis of Heavy Goods Vehicle Fires in Road Tunnels” 2017 University of Canterbury, New Zealand.
[8] McGrattan K. el al “Fire dynamic simulator user’s guide” sixth edition NIST, US department of commerce, http://dx.doi.org/10.6028/NIST.SP.1019.
[9] Cheong M K, Spearpoint M J and Fleischmann C M, “Calibrating an FDS simulation of goods vehicle fire growth in a tunnel using the Runehamar fire experiment” Journal of fire protection engineering. Vol. 19, No.3, pp 177-196, http://dx.doi.org/10.1177/1042391508101981, 2009.
[10] Achenbach M, Lahner T and Morgenthal G, “Identification of the thermal properties of concrete for the temperature calculation of concrete slabs and columns subjected to a standard fire-Methodology and proposal for simplified formulations” Fire safety journal 87 (2017) pp 80-86, 2017
[11] Belleghem M V, Steeman M, Janssens A and Paepe M D, “Drying behavior of calcium silicate”. Journal of Construction and Building Materials, 65, pp 507-17, 2014.
[12] Sjodin V, “Thermal analysis of tunnel fires with different surface boundaries” master thesis, Lulea University of technology, 2014.
[13] M. Tomar, S. Khurana and R. Singh “ Behavior of tunnel lining material in road tunnel fire” IOP Conf. Series, Materials Science and Engineering, 346 (2018) 012077 doi:10.1088/1757-899X/346/1/012077
[14] Ingason H., Li Y.Z., Lönnermark A. 2015 “Tunnel Fire Dynamics” Springer New York.
[15] Drysdale D. 2011 “An introduction to fire dynamics” John Wiley & Sons, Ltd U.K.