Behaviour of tunnel lining material in road tunnel fire

M Tomar¹, ⁴, S Khurana² and R Singh³

¹ PhD Scholar, Department of Mechanical Engineering, BITS Pilani – Dubai Campus, UAE
² Assistant professor, Department of Mechanical Engineering, BITS Pilani – Dubai Campus, UAE
³ Senior Mechanical Engineer, Systra – Delhi, India
⁴ Corresponding Author E-mail: mukeshsinghtomar@gmail.com

Abstract. The worldwide road tunnel linings are protected against possible fire scenarios to safeguard the structure and assist in occupant evacuation. There are various choices of active and passive protection available, passive protections includes calcium silicate boards, polypropylene fibers, vermiculite cement based sprays, and other intumescent materials. Tunnel fire is a complex phenomenon and researchers in the past has highlighted that there are various factors which affect the tunnel fires. The effect of passive protection techniques on tunnel fire is not well understood, especially for the insulation boards. It’s been understood from past research that for a heavy good vehicular (HGV) fire in the tunnel, the heat feedback effect is significant. Insulation boards may also affect the tunnel fires by altering the heat feedback effect in vehicular tunnels and hence this can affect the overall heat release rates and temperature profile inside a tunnel. This study focuses on studying the role of insulation boards in tunnel fires and evaluating its effect on overall heat release rate and tunnel temperatures.

1. Introduction
Fires are considered a major threat to infrastructure as well as for life safety of people in rail, road or metro tunnels. Fire in tunnels is very different from open fire or building fires in many aspects. When compared with open fires, the tunnel fire is influenced by heat feedback from surroundings and the effect of ventilations (Natural or mechanical). The major concern in tunnel fire is that the gas temperatures are very high (in order of 1300°C) and these fires last for long times which could be several hours or a couple of days. In large tunnel fires, HRR is the key factor to understand the behavior and outcomes of fire. The heat release rate (HRR) describes the development of fire in energy release rates usually expressed in megawatts (MW). In designing fire and life safety measures for tunnels including the ventilation system, structural protection, evacuation strategy, fixed firefighting system etc. HRR is a key parameter.

Heat release rate in the vehicular tunnels is always an interesting research topic for worldwide researchers. Many studies have been done in this field to establish an acceptable criterion for the heat release rates. The heavy good vehicle (HGV) is the most studied case where a wide range of heat release rate is observed in different experiments. The literature reveals that results from various experiments vary considerably despite they used similar experimental setups. The main reason for this variation is that HRR is influenced by various factors and all factors are not controlled in similar ways in different experiments. The HRR largely depends on various factors such as fuel size, fuel arrangement, fire locations, size of tunnels, ventilation system, fixed firefighting system, etc. [1]. This provides a wide range to the worldwide tunnel standards and designers.

This study considers the guidelines on HRR for various vehicle recommended by PIARC (Permanent International Association of Road Congresses) technical reports [2], NFPA (National Fire Protection Association) 502 [3] and various other renowned guidelines. The heat release rate for HGV varies from 20 MW to 200 MW. These high values of HRR were the outcome of Runehamar tunnel
fire tests [4], where a series of full scale experiments were carried out with different fuel arrangement and the maximum HRR was recorded to 202 MW. These high HRR figures raised concern among designers as using such high fire sizes, designing of ventilation system were almost impracticable in various cases. There are various factors which affect HRR for a given fuel arrangement in a road tunnel. A ventilation system is one of the systems which are believed to increase the HRR in tunnel fires, as reported by Carvel et al. [5] and other researchers. The fixed firefighting system (FFFS) is used in road tunnels to control the fire at an initial stage and restrict it from growing to the uncontrolled situation. The effect of FFFS on heat release rates is well studied and many results show that FFFS has capabilities to reduce HRR by 50-80% if activated timely as reported by [6]. Apart from above-discussed ventilation and FFFS, there are many other factors which are believed to affect the HRR. The passive fire protection systems which often mandated by various standards are usually not considered as affecting HRR. Very limited data are available on the effect of passive fire protection techniques on thermal conditions of the tunnel. There are various choices for passive fire protection in road tunnel fires, such as calcium silicate boards, polypropylene fibers (sometimes termed as fireproof concrete), vermiculite cement based sprays etc.

The purpose of this paper is to present an approach using numerical simulation (Fire dynamics simulator, FDS) to establish the effect of passive fire protection system on HRR inside a road tunnel. This study considers the similar tunnel dimensions, fire size, fuel arrangement, ventilation system and passive fire protection technique as of Runehamar experiments [4]. FDS 6.5.3 and Smokeview (SMV) 6.4.4 versions [7] are used to simulate the fire conditions of Runehamar full-scale test.

2. The Runehamar tunnel experiment and current models

2.1 The Runehamar test

Some large-scale tunnel tests took place in Runehamar tunnel in Norway in 2003 [4]. The tests were conducted to simulate HGV trailer cargo fire with different fuel sizes. The tests were conducted by SP fire research of Sweden with the cooperation of TNO in Netherlands and SINTEF-NBL of Norway. The Runehamar tunnel is a two way asphalted road out of service tunnel. It is 1600 m long, 6 m high and 9 m wide along with a slope ranging from 0.5-1%. It was a blasted rock tunnel with cross sections varying from 47 m² to 50 m². The type of fuel material used in all tests was combination of standardized wood pallets, plastic pallets made of polyethylene (PE), polystyrene cups (PS), cardboard cartons and polyurethane mattresses (PUR). The arrangement of fuel in different experiments in Runehamar tunnel is shown in table-1.

| Test No. | Description of fuel load | Total weight Kg | Theoretical calorific energy (GJ) | Maximum HRR (MW) |
|----------|--------------------------|----------------|----------------------------------|-----------------|
| T1       | 360 wood pallets measuring 1200x800x150mm³, 20 wood pallets measuring 1200x1000x150mm³ and 74 PE plastic pallets measuring 1200x 800x150mm³; 122m² polyester tarpaulin | 11010 | 244 | 202 |
| T2       | 216 wood pallets and 240 polyurethane mattresses measuring 1200x800x150mm³; 122m² polyester tarpaulin | 6853 | 135 | 157 |
| T3       | Furniture and fixtures (combination of plastic, wood, armrests, sofas, toy etc.). 10 big rubber tyres (800kg); 122m² 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 (1200x1000x150mm³); 10m² polyester tarpaulin | 2849 | 62 | 66 |
Structural protection was required in Runehamar tests to avoid damage to the structure. High-temperature resistant material (calcium silicate, PROMATEC®-T panels) was used for structural protection on all sides and ceiling of the tunnel near fire areas. The total length of thermal insulation with passive panels was 75 m. To enable multiple tests two thinner passive protection boards (20 and 25 mm) glued together with intermediate reinforcement was used as shown in ‘figure 1’. These boards were made of calcium silicate reinforced with selected fibers and fillers. Measurement of gas temperature, visibility, thermal radiation and gas species were recorded in these experiments. The tunnel was provided with ventilation through a mobile fan located at tunnel entrance at a velocity of 3 m/s. the ventilation system was driving smoke and fire gases to opposite end of the tunnel. Present study focuses to study the fire conditions of test-1, as this experiment resulted in highest peak HRR of 202 MW.

Figure 1. Cross section and arrangement of protection boards in Runehamar tunnel [8, 9].

The fuel was located on a rack storage system to simulate HGV trailer fire, the fuel sizes were 10,450 mm by 2900 mm with a height of 4500 mm covered with a 0.5 mm thick polyester tarpaulin. The platform was 1100 mm high from the road surface on which fuel was mounted. There was target fuel as well in tunnel downstream end but they are not discussed in this paper. The center of fuel was located 1037 m from the east portal in test 1 & 2. The center of the fire was 21.5 m from the east end (upstream) of the protection (passive protection panels) and 53.5 m from the west end (downstream) of the protection.

2.2 Current Model
A rectangular tunnel model of 150m x 7m x 5m (LxWxH) is considered for the present study. A number of gas temperature measuring stations are provided along the height of tunnel at various locations, as shown in ‘figure 2’. There are two models considered for this study, Model-1 is provided with concrete tunnel linings, and Model-2 is provided with calcium silicate boards along ceilings and walls for the entire tunnel. A longitudinal ventilation of 3 m/s similar to Runehamar test is also considered at the west portal of the tunnel. The location of the center of fuel is 20 m from west portal of the tunnel. The size of fuel is similar to Runehamar test, measuring 10m x 3m x 3.5m. The fuel is mounted on a rack 1 m above the tunnel floor similar to the arrangement used in Runehamar tests. The
heat release rate and fire growth rates are taken from test-1 of Runehamar to simulate HGV trailer fire scenario. This model is very similar to Runehamar tunnel in width and height as in Runehamar, the width of the tunnel was reduced from 9 m to approx. 7 m by application of passive boards and similarly height of tunnel was reduced from 6 m to 5 m as shown in ‘figure 2’.

Figure 2. Details of current models (Model 1/ Model 2).

3. Modelling/Simulation details
This study uses FDS 6.5.3 and Smokeview (SMV) 6.4.4 versions for proposed simulations, while Pyrosim v2017.1 was used for model preparation. Pyrosim is a pre-processor for FDS and it provides a graphical user interface and helps in quickly creating and managing the complex fire models. FDS is a CFD tool used in analyzing fire flows. Smokeview is used to visualize outcomes of FDS simulations. The FDS code uses conservation of various equations (energy, mass, momentum and state). Within FDS, set of partial differential equations are used to calculate the density, velocity, mass, temperature, and pressure components [7]. The turbulence model with large eddy simulation (LES) in the combination of combustion model (mixture fraction model) is used in the current study to simulate the required fire. FDS model numerically solves the Navier-stokes equation and discretizes the domain using explicit scheme. The main domain is made from a rectangular box which is further divided into rectangular grid cells. Important parameters considered for modelling as listed in table-2 [9, 10, 11, and 12]. Cheong, Spearpoint & Fleischmann [9] reproduced the Runehamar tunnel fire growth curves using numerical simulation and calibrating using FDS v4.0.7. The heat release curve was reproduced using a grid size of 300mm. Therefore, in current simulation, 300 mm grid size was used.

Table-2. Important modelling parameters.

| Item details                        | Values            |
|-------------------------------------|-------------------|
| Peak HRR                            | 202 MW            |
| Thermal conductivity, concrete      | 1.0 W/mK          |
| Thermal conductivity, calcium silicate boards | 0.48 W/mK |
| Density, concrete                   | 2100 kg/m³        |
| Density, calcium silicate boards    | 1440 kg/m³        |
| Specific heat, concrete             | 880 J/kgK         |
| Specific heat, calcium silicate boards | 840 J/kgK     |
| Emissivity, concrete                | 0.7               |
4. Results and discussion

All the above-discussed parameter in table-2 was applied to both models and simulated for HGV fire scenarios similar to Runehamar test-1 conditions. The experimental data of Runehamar test-1 and simulated results for current models using FDS are presented below. Other factors which may affect tunnel thermal conditions are not studied in this paper. Temperature distribution from Runehamar tests are shown in ‘figure 3’, while temperature distributions for current models are presented in ‘figure 4’, and ‘figure 5’. The radiative and net heat flux results for current simulations are shown in ‘figure 7’ and ‘figure 8’.

Temperature distribution near ceiling in Runehamar test [4].

Figure 4. Temperature distribution for Model-1 and Model-2 near ceiling (a) 10 m and (b) 20 m downstream of fire.
Figure 5. Temperature distribution for Model-1 and Model-2 below 2 m ceiling at (a) 10 m and (b) 20 m downstream of fire.

Figure 6. Description of heat flux models (sample showing net heat flux at 20 minute for Model-1)
4.1 Discussion

The peak temperature near ceiling during Runehamar test-1 \cite{4} was in order of 1200-1300°C, as shown in ‘figure 3’. The peak temperature shown by current Model-2 in ‘figure 4’ and ‘figure 5’ is similar to Runehamar Model, also the overall temperature distribution is similar to Runehamar test-1 result. This shows that the current results of temperature distribution are in good agreement with original full scale Runehamar test-1.

Results under ‘figure 4’ and ‘figure 5’ shows that Model-2 (with calcium silicate boards) resulted in a higher temperature at the ceiling and below 2m of the ceiling compare to Model-1. The difference of temperature near ceiling at approx. 20 minute is about 200°C between Model-1 and Model-2. The temperature difference reduces to roughly 100°C when measured 2 m below the ceiling for Model-1 and Model-2. The ‘figure 6’ describes the general arrangement such as direction of heat/smoke flow, axis and various surfaces for easy understanding of heat flux results. As shown in ‘figure 7’ and ‘figure 8’, the radiative and net heat flux downstream the fire at 20 minutes for Model-1 is in the order of 67.5 kW/m². While for Model-2 the radiation and net flux were enhanced and reached up to 76 kW/m² along the tunnel floor and side walls. The increase in heat flux for Model-2 is roughly 12-14%
All the heat flux and temperature were measured at the time (around 19 minutes) when peak HRR was supposed to appear in line with the results of Runehamar full-scale test-1.

The possible reason for an increase in tunnel temperature is due to the fact that calcium silicate board has a low thermal conductivity. When the hot gasses approach these boards, instead of absorbing or transferring the incoming heat, the boards reflect the incoming heat back to the tunnel environment and hence increasing the heat feedback effect. As the heat feedback phenomenon is usually higher at the tunnel ceiling and decreases towards the floor of the tunnel, the temperature difference between Model-1 & Model-2 is decreasing towards the tunnel floor. The possible reason of increased heat flux for Model-2 compared to Model-1 is due to the higher emissivity property of calcium silicate boards compare to the concrete. As radiation of heat depends on the emissivity of the material, a higher emissivity material will reflect more heat compared to a low emissivity material. The combined effect of lower thermal conductivity and higher emissivity of calcium silicate board and the complex heat feedback are the primary reason for increasing the temperature and heat flux in a tunnel.

5. Conclusion and way forward
As previously mentioned, in the design of tunnel fire safety systems peak HRR is one of the key parameter, and one should understand all factors which are affecting peak HRR in tunnel fires. Since the effect of passive protection on HRR is not well established in past, the current study tries to investigate this effect for a HGV fire scenario in the road tunnel. The finding of this study shows that using calcium silicate boards in heavy tunnel fires may increase the overall tunnel temperature and net heat flux downstream of fire. This finding can also relate to HRR since temperature behavior and heat flux indirectly shows the behaviors of HRR. It potentially indicates that using calcium silicate boards in tunnel fire may result in higher peak HRR. As other parameters are also important before concluding on such remarks, this study provides a hint that passive protection techniques may affect significantly peak HRR values and must be studied in detail, and alternative material/techniques must be investigated to avoid such conditions.

The way forward
Due to several limitations it was not feasible to predict the effective peak HRR for both models using FDS, but above results show a hint that calcium silicate boards increases tunnel temperature and peak HRR. One should perform the experiments to evaluate these effects and different passive fire protection techniques can be compared.

6. References
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