Heat Release Rates of Heavy Goods Vehicle Fires in Tunnels

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A fire in a tunnel can be a devastating and highly undesirable event if it is not addressed at the early stages of its development. This is particularly true for fires involving a heavy goods vehicle carrying combustibles with high calorific content. Heat, soot and toxic combustibles can be produced very rapidly and therefore significantly increase the difficulty for escape, rescue and fire-fighting activities.

A series of large-scale fire tests for road tunnel application was conducted at the TST tunnel facility in Spain in March 2012. The aims of this fire tests programme were to investigate the magnitude of the heat release rate generated with and without a low-pressure deluge fire suppression system; the effects of other measures in the presence of a fire suppression system such as reducing the longitudinal flow velocity; and to acquire information on the appropriate design parameters (e.g. nozzle type, discharge density and activation time) to adopt, based on the most probable fuel load used in the Singapore road tunnels. In order to ensure repeatability, simulated heavy goods vehicles consisting of 228 pallets with 48 plastic pallets (20% by volume) and 180 wooden pallets (80% by volume) were used in all fire tests. A longitudinal air velocity of 3 m/s was applied in the tunnel fire tests.

The test results confirm that a substantial reduction of fire heat release rate can be obtained using a low-pressure deluge fire suppression system, as long as timely activation of the water is provided. The provision of such experimental data thus addresses the current dearth of knowledge on the actual effects of low-pressure deluge systems on the heat release rates from HGVs in tunnel fires.

1 INTRODUCTION

Over the past few years, there have been a number of large fire test programmes with high calorific energy content conducted in Europe. These tunnel fire test programmes have provided better insights into fire development in tunnels, allowing tunnel designers to enhance the fire safety provision in new road tunnel projects. In the Runehamar fire test series [1], the peak heat release rate recorded on goods vehicles carrying high calorific energy contents varied from 201.9 MW to 66.4 MW and similar high peak heat release rates of 128 MW were observed in the EUREKA 499 fire tests [2] involving a HGV trailer carrying two tonnes of furniture. The Runehamar and EUREKA 499 fire test were conducted with no fire suppression system intervention and a tunnel air velocity of 3 m/s and 3-6m/s respectively.

These fire tests suggest that fires in tunnels are likely to develop more rapidly and have higher peak HRR. The outcome of these findings has indirectly increased the recommended design fire for heavy goods vehicle in standards such as NFPA 502 [3] and PIARC [4] (e.g. 200 MW for a heavy goods vehicle). However, these standards do not yet account for trade-off effects on the application of a fire suppression system to enhance road tunnel safety. There is limited public data [5] which shows the effeteness of a fixed water-based fire-fighting system (FWBFS) system (in term of heat release rate) during a tunnel fire as compare to a tunnel without FWBFS.

In 2011, the Land Transport Authority (LTA) of Singapore commissioned Efectis Nederland BV to conduct a series of fire tests for road tunnels with and without a fire suppression system. The aims of this fire tests programme were to investigate the magnitude of the heat release rate generated with and without a low-pressure deluge fire suppression system; the effects of other measures in the presence of a fire suppression system such as reducing the longitudinal flow velocity; and to acquire information on the appropriate design parameters (e.g. nozzle type, discharge density and activation time) to adopt based on the most probable fuel load used in the Singapore road tunnels. A total of 10 laboratory fire tests and 7 large scale fire tests (refer to Table 1) was conducted in this fire test programme.

Table 1: Large Scale Fire Test Schedule

Test	Test description (variation)	Discharge density (mm/min)	Nozzle type	Activation time (min)	Fire in suppression zone
1	Directional nozzle	12	Dir 180°	4	Centre of zone
2	Directional nozzle	8	Dir 180°	4	Centre of zone
3	Standard spray nozzle	12	Standard	4	Centre of zone
4	Standard spray nozzle*	12	Standard	4	Centre of zone
5	Standard spray nozzle	12	Standard	4	End of zone
6	Standard spray nozzle	12	Standard	8	Centre of zone
7	Unsuppressed	n.a.	n.a.	n.a.	Centre of zone

*Note: * Test 4 is a repeated test of Test 3*
Longitudinal ventilation rate in the tunnel was in the range of 2.8 to 3 m/s

2.0 LARGE-SCALE TUNNEL FIRE TEST

Large-scale fire tests were conducted in a test tunnel facility at Tunnel Safety Testing (TST) in Spain on March 2012. It is a two lane road tunnel built in concrete, with a lower gallery for emergency and services, and three emergency exits. The length of the test tunnel is 600m (Figure 1) and the rectangular shape configuration was used for this fire tests. The minimum dimension of the rectangular test section is (at the location of the fire source) 7.3m wide and 5.2m high with a longitudinal gradient of 1 %.

At the location of the fire source, walls are constructed inside the real test tunnel to protect the concrete against damage. The resulting cross-section is shown in the figure 2 below. Jet fans at the southern end of the portal are used to generate an air velocity of approximately 3 m/s in the tunnel for the entire duration of the fire test.

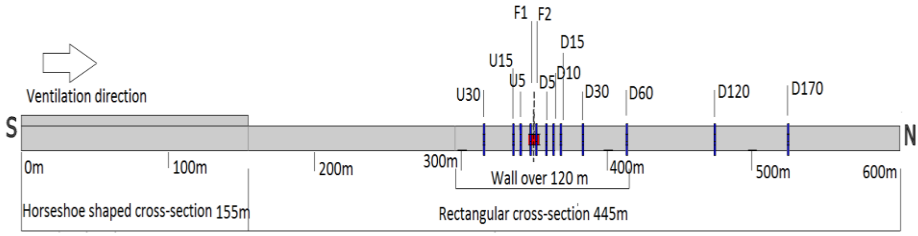


Figure 1: Cross-section of the test tunnel

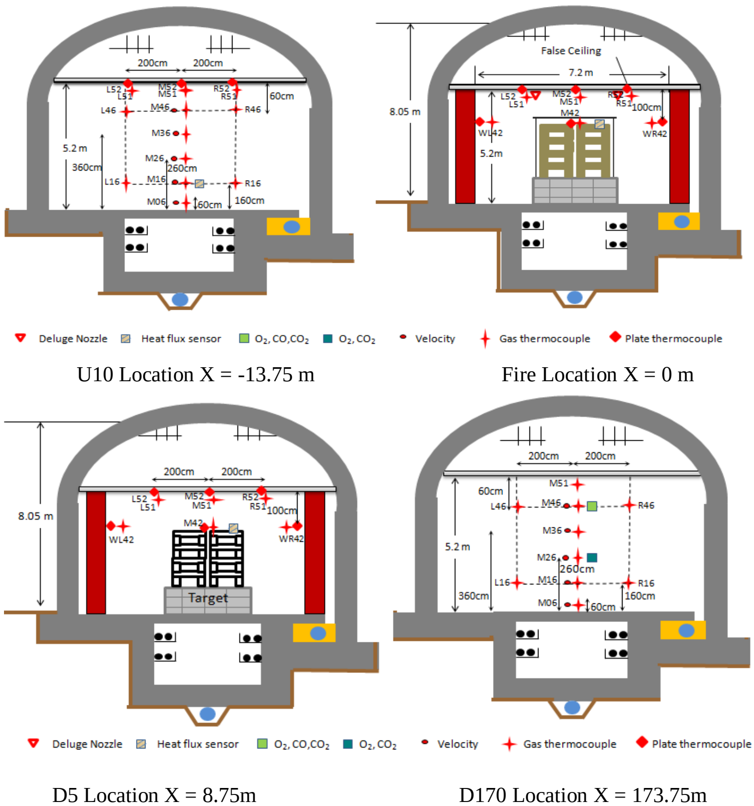


Figure 2: Cross-section of the test tunnel and instrumentation setup

In Singapore, vehicles carrying hazardous materials (‘hazmat’) are prohibited from entering road tunnels. The Singapore Civil Defence Force (SCDF) has implemented a Hazmat Transport Vehicle Tracking System (HTVTS) to enforce this [6] (Figure 3). The HTVTS has the ability to track the location of the hazmat vehicles and immobilise these vehicles remotely in the event of a violation. It controls the throttle of the vehicle, restricting the fuel injection to the engine and forcing the driver to slow down and stop. SCDF and police personnel are then dispatched to the incident.

Figure 3: Using GPS to monitors HazMat vehicles

The rules and regulatory requirement for vehicle using tunnels vary considerably among countries. In Singapore, the Road Traffic Act (Chapter 276, Sections 114 and 140) and the Fire Safety Regulation define the type of vehicles that are not allowed to access tunnels. Some of these restrictions include vehicles carrying flammable liquids, trailers, and vehicles whose overall length, width and length exceed 4.5m, 2.5m and 13m respectively [7]. Considering the regulation and prevention measure in place, a typical rigid heavy goods vehicle (HGV) fully loaded with pallets is a credible scenario to consider for the large scale fire test (Figure 4). The fire source consists of 228 pallets, with 48 plastic pallets (20%) and 180 wooden pallets (80%). The pallets were stacked in 12 stacks of 19 pallets high on a 1m elevation, with a steel frame around that bears the steel top cover and a thin plastic tarpaulin on both sides. Steel plate is also mounted on the front and rear end of the fuel load with a 1mm steel cover on top of the fuel load. The fire source is ignited by 2 trays (35cm x 70cm) with each tray containing about 1 litre of gasoline. The trays were positioned inside the two most upstream pallet stacks on the second pallet. To assess the risk of fire spread to a position downstream, a target consisting of two full pallet stacks was placed 5m downstream the rear end of the fire source. Figure 4 shows the fuel load setup used in the fire test.

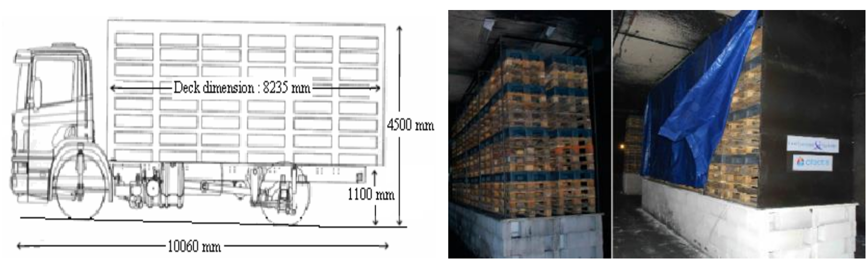
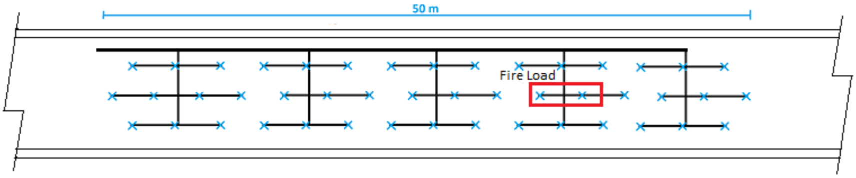


Figure 4: Photographs (left -HGV) and (right – Fuel load arrangement)

The scope in this fire test programme is to focus on deluge suppression systems with low operating pressure (up to 5 bars) and coverage area of at least 9 m^2 per nozzle. Two types of deluge nozzles were used in the fire test series: the pendant standard spray and directional 180° nozzles. These nozzle types were selected based on the findings from the phase 1 laboratory fire tests and their proposed application for the Singapore road tunnel projects. The deluge system is designed to activate two zones simultaneously with a suppression zone of 25 m each. A total of 46 nozzles were used over an area of 50 m (length) by 7.2 m (width). Figure 5 shows part of the deluge suppression system pipes at the ceiling for the large scale fire test programme.



Note: 2 zone of deluge piping operating at 25m per zone

Figure 5: Nozzle positioning, zone distance and fire location

3.0 Heat Release Rate Estimate

There are a few methods of heat release rate measurement. One of these methods uses the mass loss rate to establish the fire heat release rate. The other method is the oxygen depletion calorimetry method, where the heat release rate is based on the amount of consumed oxygen.

In fire tests with a suppression system, the mass loss rate method is not possible because the water flow during the activation of the suppression system will disturb the measurement of the mass loss of the burning fuel load and this will affect the accuracy of the heat release rate (HRR) measurement. The method based on oxygen depletion uses the amount of consumed oxygen to directly determine the generated heat by using the known amount of energy produced per consumed amount of oxygen (for a specific group of combustibles). Three different methods exist: besides oxygen only (method 1), the carbon dioxide (method 2) and both carbon dioxide and carbon monoxide (method 3) can be measured and used in the equations. The accuracy of these three methods increases with the number of the method [8]. In this work, the heat release rate estimate is based on method 3, i.e. where besides the oxygen concentration the carbon monoxide and carbon dioxide concentrations are also measured to increase the accuracy of the HRR estimate.

The heat release rate was calculated according to the "basic equations" 1 and 2 given in the paper by Dlugogorski et al [8]. The "basic equations" take into account the influence of the water vapour content and correspond mathematically to the equations derived by Janssen and Parker [9]. In contrast to the equations of Janssen and Parker however, the "basic equations" do not require calculation of the molecular flow rate nor the humidity of the incoming air and are therefore easier to use.

For convenience the "basic equations" are given below [8]:

$$\dot{q} = n^{e}_{total}(1 - X^{e}_{H2O})\left[0.5(E - E^{co})X^{e,d}_{co} + E\left(X^{i,d}_{o2}\frac{1 - X^{e,d}_{o2} - X^{e,d}_{co2} - X^{e,d}_{co}}{1 - X^{i,d}_{o2} - X^{i,d}_{co2}} - X^{e,d}_{o2}\right)\right] \quad \text{Eq. (1)}$$

From Dlugogorski et al [8], the total molar flows for an ideal gas:

$$n^{e}_{total} = m^{e,d}_{air} / (M^{e}_{total} \times M^{i,d}_{air})^{0.5} \qquad \text{Eq. (2)}$$

As the total molecular weight M^{e}_{total} differs from $M^{i,d}_{air}$ the relation in Eq. (2) is used to compute n^{e}_{total}.

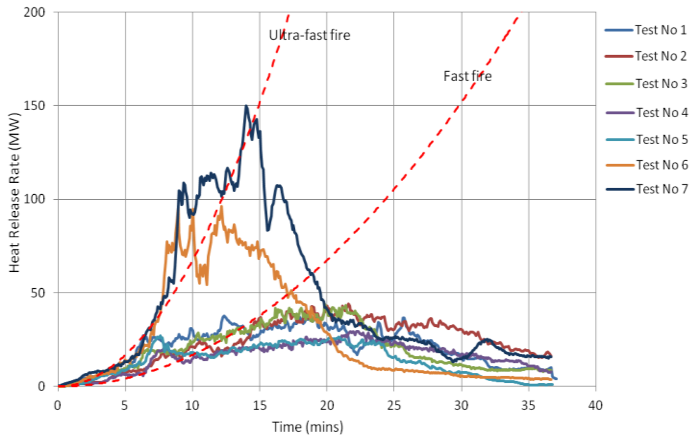
$$M^{e}_{total} = X^{e}_{H2O} M_{H2O} + (1 - X^{e}_{H2O})(X^{e,d}_{N2} M_{N2} + X^{e,d}_{O2} M_{O2} + X^{e,d}_{CO2} M_{CO2} + X^{e,d}_{CO} M_{CO}) \qquad \text{Eq. (3)}$$

The ‘exhaust’ molar flow rates are determined from the measured velocities, temperatures and mole fractions 170 m downstream from the fire location. The measured velocities, temperatures and concentrations at positions M16, M26 and M36 (see figure 2) are used to establish the contribution of the heat release rate at the lower 2/3 part of the tunnel cross section. The remaining portion of the heat release rate estimate at the higher 1/3 part of the tunnel cross section is measured at positions M46 and M51 (see figure 2) in the tunnel. The measured molar fractions of O_2, CO, CO_2 and water vapour at position M46, M26 are used for the heat release rate estimate in the upper and lower part of the tunnel. The molar fractions of O_2 and CO_2 of the incoming air are set at 0.2095 and 0.00041 respectively.

The molar fraction of N_2 at exhaust is determined with the following equation:

$$X_e,dN_2 = 1 - X_e,dO_2 - X_e,dCO_2 - X_e,dCO \qquad \text{Eq.(4)}$$

Given the uncertainty in the measurements and the observed velocity, temperature and concentration profiles at the downstream location D170M, a relative error of approximately ±10% in the calculated value of the heat release rate is expected. The heat release rate curve estimated and the photographs in these experiments are shown in Figure 6 and 7 respectively.



Note: Test 1 to 5 - deluge system operate at 4 minutes (for detail see table 1)
Test 6- deluge system operate at 8 minutes
Test 7- free burning

Figure 6: HRR for HGV fire with and without fire suppression

Figure 7: Photographs of the fire tests

4.0 DISCUSSION OF RESULTS

The following observations have been made:

i) Results from Figure 6 show that there is a significant reduction in heat release rate between the fire tests with deluge operating at 4 minutes (Test 1-5) as compared to the fire tests with delay operation at 8 minutes (Test 6) or free burning condition (Test 7). Upon activation of the deluge system, the peak heat release rates of this group of tests (Test 1 to 5) is reduced by 70% - 81% as compared with the fire test (Test 7) without deluge operation.

ii) Peak heat release rate values between 27 MW to 44 MW were observed for scenarios with deluge operating at 4 minutes (Test 1 to 5). In the scenario with delayed deluge operation (Test 6), the peak heat release rate is only reduced by

35%. The reduction in deluge system performance in Test 6 is probably not only caused by the delayed activation but also due to the damage which occurred to the nozzles above the fire. Operating the deluge system at the early stage of the fire development helps to reduce the severity of the fire during growth phase (Figure 6).

iii) All the tests with deluge operation within 4 minutes are controlled below the peak heat release rate of 50 MW. It appears that a fast to ultra-fast growth rate was observed during the first 7 minutes of the fire development for all the tests. The fire growth rate for Test 6 and 7 increased even more rapidly after 7 minutes when intervention of the deluge system is not applied (Figure 8).

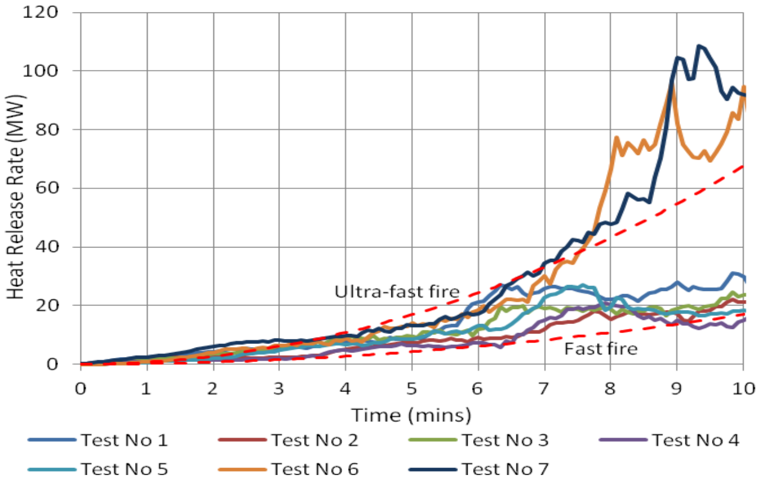


Figure 8: Large-scale fire tests fire growth rate

iv) From the results in Figure 9 (Test 1 and 2), a reduction in the discharge density was found to result in an increase in the peak heat release rate and released calorific energy (Table 2), due to less water being applied to the burning fuel load.

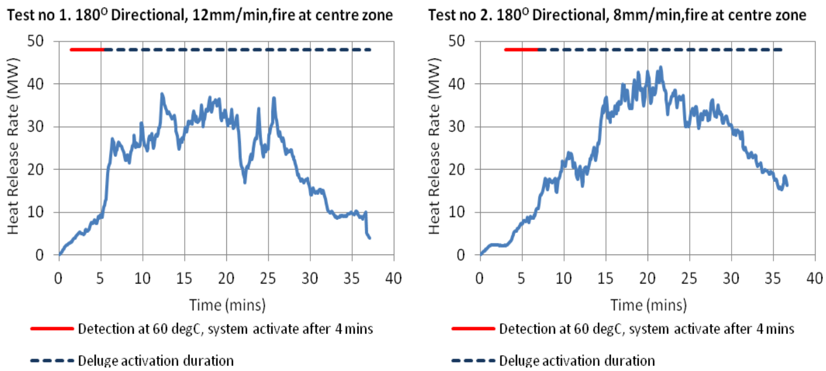


Figure 9: (Left) Test 1: 12 mm/min, (Right) Test 2: 8 mm/min

Table 2: Peak HRR and Calorific Energy

Test	Time to peak (min)	Peak HRR (MW)	Integrated calorific energy (GJ)
1	12.3	37.7	46.6
2	21.6	44.1	52.7
3	19.8	44.2	44.5
4	21.8	29.5	35.9
5	7.6	27.1	30.2
6	8.9	96.5	61.6
7	14	150	99.2

5.0 CONCLUSION

The heat release rate (HRR) of heavy goods-vehicle fires in a tunnel with and without deluge operation was presented in this paper. Peak HRRs of 27 to 44 MW were measured for deluge operation at 4 minutes, 97 MW for delayed deluge operation at 8 minutes and 150 MW with no deluge intervention were obtained in these fire tests. This fire test series shows that the activation of deluge system at the early phase of the fire development is important as its helps to reduce the severity of the fire development during the growth phase.

6.0 ACKNOWLEDGEMENTS

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