Review of Design Fire Heat Release Rate for Tunnels with Fire Suppression Systems

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ABSTRACT

Heat release rate (HRR) is one of the major components when developing design fire for fire engineering design. Though numerous efforts have been taken during the past decades, there is no consensus on nomination of a peak heat release rate when considering fire suppression effects for various type of fire loads, such as flammable liquid cargo (FLC) tankers, heavy goods vehicles (HGV), battery electric (BE) and hybrid drive cars, etc. The purpose of this paper is to initiate an open discussion to develop credible design fire HRR, which may help engineers in designing tunnel fire & life safety systems and structural fire engineering solutions.

KEYWORDS: Design fire, Fixed Fire Suppression, Fire Control, Shielded Fire, Heat release rate, Tunnels

INTRODUCTION

Control of combustion processes developed during emergency fire scenarios using water-based suppression agent including foam is a subject with many ongoing and active developments. Effectiveness of the system configurations for fire control and/or suppression is influenced by several parameters that need to be evaluated through testing and analysis. The designer of the tunnel system requires to know the maximum heat release rate (HRR) if the tunnel will be provided with suppression system. However, there is still no consensus on the design fire heat release rate for design purpose. Peak HRR can be significantly reduced when fire suppression systems perform to expectations for each type of tunnel fire loads, such as internal combustion engine (ICE) cars, battery electric (BE) and hybrid drive cars, buses with ICE or BE / hybrid drives, heavy goods vehicles (HGV) with ICE, BE or hydrogen powered fuel cells, Flammable Liquid Cargo (FLC) tankers, hazardous goods, etc.

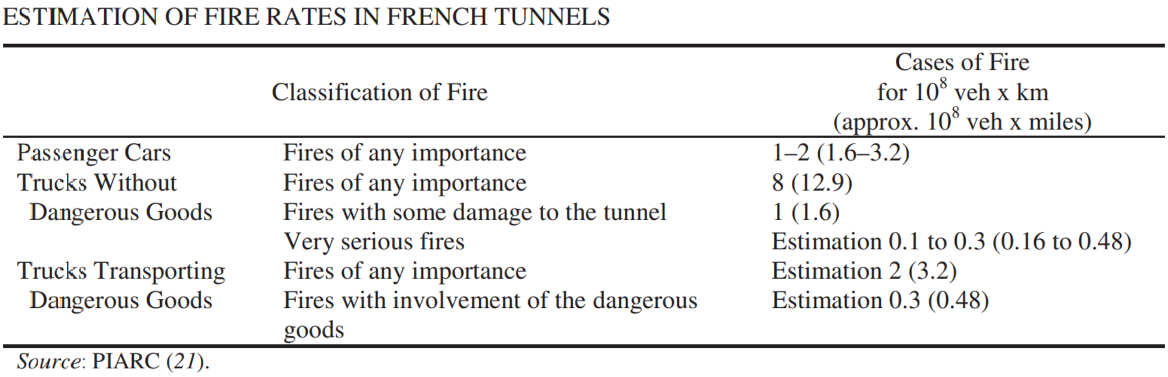
Previous work has ranged from component performance tests of spray nozzles to determine droplet size and spray characterization to full scale gallery tests of overhead multiple sprinkler spray head arrays on defined solid and liquid fuel packages. F. Tarada et al had recommended that heavy goods vehicles fire peak heat release rate can be reduced by around 35% with the deluge operation [ISAVFT 15]. Ingason and Maevski have contributed significant efforts on road tunnel vehicles fires, based on which NFPA 502 recommended some peak HRR values under fixed firefighting system (FFFS) for several type of vehicles in tunnel. There is also extensive practical experience with the application of deluge FFFS, particularly from Japan and Australia where such systems had been in operation for decades. However, there is no widely accepted conclusions on the maximum fire heat release rate which should be capped at for various type of vehicle fire scenarios when a suitable type of suppression system is in full operation.

The main objective of this paper is to summarize the fire growth rate, peak heat release and the peak temperature of different types of vehicles with a suitable type of fire suppression system corresponding to its type of fire load. This work may serve as a start point for developing design fire parameters for tunnel fire-life safety and structural fire durability design.

FREE BURN FIRE HRR WITHOUT FIRE SUPPRESSION

Free burn of fire without any suppression will develop a heat release rate controlled by ventilation and the fuel, and its HRR is usually higher than the case with suppression system. In this paper, the free burn fire will serve as the base cases to understand the suppression effects of various of fire suppression systems.

Igor Maevski [1,2] has completed a comprehensive review of highway tunnel fires and published a NCHRP Synthesis 415 in 2011. Based on tunnel fire incidents from 1949 to 2011, the review includes 45 tunnel fires where fire temperature of more than 1000 °C were achieved. PIARC Design Fire Characteristics For Road Tunnels[29] also summarized the heat release rates for various type of vehicles. Based on PIARC [21] as shown in the Table below that there are 8 truck fires happens for every 100 million driven kilometres, and at least one of them involves damages to the tunnel.



ESTIMATION OF FIRE RATES IN FRENCH TUNNELS

	Classification of Fire	Cases of Fire for 10^8 veh x km (approx. 10^8 veh x miles)
Passenger Cars	Fires of any importance	1–2 (1.6–3.2)
Trucks Without Dangerous Goods	Fires of any importance	8 (12.9)
	Fires with some damage to the tunnel	1 (1.6)
	Very serious fires	Estimation 0.1 to 0.3 (0.16 to 0.48)
Trucks Transporting Dangerous Goods	Fires of any importance	Estimation 2 (3.2)
	Fires with involvement of the dangerous goods	Estimation 0.3 (0.48)

Source: PIARC (*21*).

Table 2.3.3 of PIARC Fire and Smoke Control in Tunnels 05.05B, La Defense, France, 1999 [21].

Since fire characteristics of each type of vehicle fire are different, fire HRR of each type of vehicles are discussed separately.

Heavy Goods vehicles (HGV)

The most known fire tests which represent heavy goods vehicles is Ingason's tunnel vehicle fire tests[3], which recorded a peak fire heat release rate of 203 MW. HRR grew approximately at a t-squared ultra-fast rate. Tunnel gas temperature reached 1365 °C. Figure 1 shows the 2003 Runehamar tunnel fire HRR development curve of HGV tests [28].

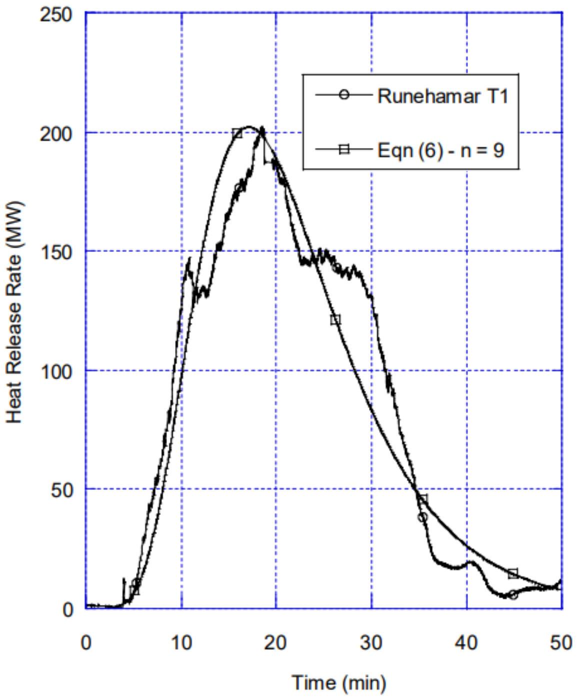


Figure 1: Tunnel fire HRR curves of HGV tests by Lemaire et al. [28]

Flammable Liquid Cargo (FLC)
Fire growth rate of Flammable Liquid Cargo (FLC) fire can be very fast, peak HRR of 300 MW can be reached within 90 seconds to 120 seconds after fire ignition [4, 30]. Its HRR growth rate can be as high as 165 MW/min linearly for a fully developed flammable liquid pool. Tunnel gas temperature can be as high as 1200 °C.

Battery Energy Vehicle (BEV) Car
The battery electric vehicle (BEV) uses an electric motor and relies on electric power for propulsion. The involvement of batteries in the fire may result in different toxic species, special consideration should be given to the design fire HRR and smoke species for analysing the fire ventilation for life safety in underground spaces. Based on a review of the recent publications on electrical vehicle (EV) fires, it is widely agreed that the fire heat release rate will not be higher than that for a conventional vehicle, which is around 7 MW [2, 5, 31]. In general, most of the EV fire accidents are caused by the thermal runaway of Li-ion battery (LIB), resulting for instance from mechanical damage after a collision. During the burning of LIBs, the generation of flammable/explosive gases and toxic smokes, such as hydrogen (H2), methane (CH4), carbon monoxide (CO), and hydrogen fluoride (HF), can pose a threat to those involved. According to the fire test on EV [6-10], HRR growth rate roughly follows the standard t-squared medium growth curve. Peak HRR of 6 to 7 MW can be reached at 500 -700 seconds after fire ignition[31].

Figure 1: a Renault-Samsung electric vehicle model ‘SM3.Z.E’ fire while driving 2016 Korea [10]

Multiple ICE Cars

Cecilia Lam et al [5] published test results for Internal Combustion Engine (ICE) Vehicles at the 5th Int conference on Fire in Vehicle in 2016. It recorded a time of 6-8 minutes to the peak heat release rate of approximately 7 MW to 10 MW, with a peak gas temperature of approximately 800 – 900°C. Peak hear release rate of two internal combustion cars can be as high as 10-20 MW [10, 21]. HRR growth rate roughly follows t-squared medium growth curve [7].

ICE Buses

According to statistics [11] in the United Kingdom, there are 3 to 7 bus fires per 1000 vehicles during the period of 1964 and 2013. As shown in Figure 3, bus fire peak HRR can be as high as 20-36 MW [12] and its HRR growth rate can be approximated with ultra-fast t-squared curve [25]. Gas temperature can reach 700°C according to PIARC [21].

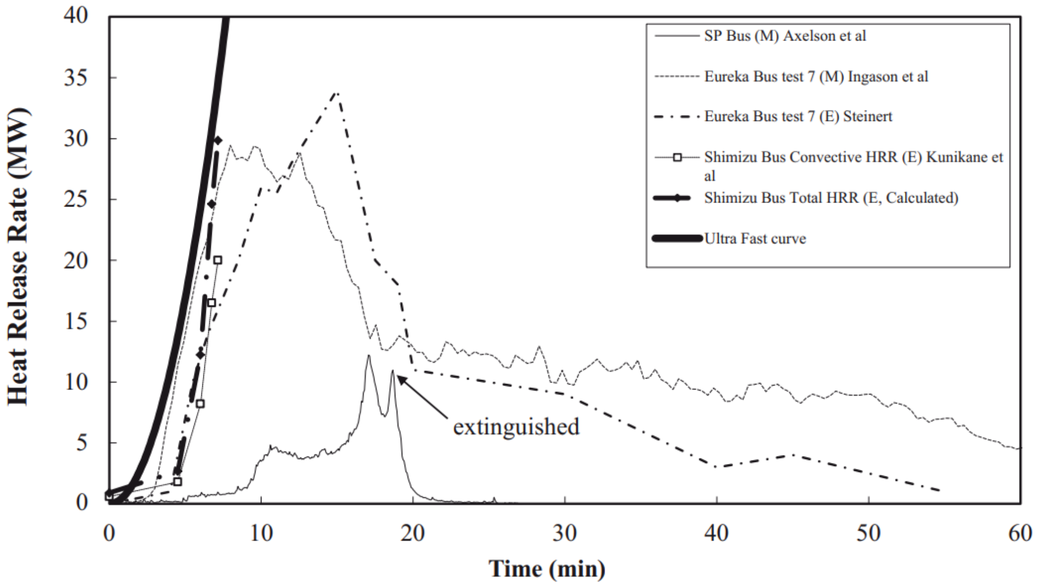


Figure 3: HRRs for buses in tunnel [25] (Source: Ingason & Li “Tunnel Fire Dynamics” Page 98)

Train Cars

Xavier Ponticq, Joel Guivarch et al [13] and Niclas Åhnberg, Axel Jönsson, et al [14] published their test and research data, which suggested that train fire peak HRR would mainly be in the range of 10 MW to 40MW. It was reported [14] that the design fires used in Swedish railway tunnels are 12 MW to 20 MW with a t-squared medium to fast growth rate. White [16] reported that Queensland train fire tests recorded a gas temperature of around 1100 °C.

Based on NFPA 72, If HRR is assumed to grow following a t-squared curve, the fire growth classification is given in Table-1 with coefficient α as shown in equation HRR = αt^2. Table-2 shows the peak HRR, fire growth rate as well the gas temperature that can be reached for structural fire durability design.

Table-1: Fire intensity coefficients (kW/s^2) for t-squared fire growth rate based on NFPA 72

α	0.00293	0.01172	0.0469	0.1876
HRR growth	Slow	Medium	Fast	Ultra-fast

Table-2: Peak HRR (MW) growth rate and gas temperature (°C) in tunnel without fire suppression

Type of Fire Load	HRR growth rate	Peak HRR without fire suppress	Linear HRR growth coeff. α1 (MW/min)	t squared HRR growth coeff. α2 (kW/sec^2)	Peak Temperature (°C)
HGV	Ultra-fast	200 [1, 3]	---	0.1876	1365°C [1, 3]
FLC	Linear	300 [1, 4]	165MW/min	---	1200°C [20]
BEV	Medium	7 [5-7]	---	0.01172	1000°C [27]
Multiple ICE Cars	Medium	10 – 20 [1]	---	0.01172	700°C [10,20]
ICE Bus	Ultra-fast	34 [11-12]	---	0.1876	700°C [20]
Train	Medium	10 – 35 [13-16]	---	0.01172	1100°C [16]

SUPPRESSION SYSTEM VS VEHICLE FIRE

Till now there is no widely accepted design fire heat release rate (HRR) curve for tunnel fires where fire suppression system is considered. Especially with the new energy vehicles, which add to the complexity for tunnel fire control. This paper only attempts to propose a set of design fires for tunnels assuming properly designed suppression system to accommodate various type of vehicles, and to recommend design fire curves under fire suppression conditions, which can serve as a start point for proposing reference HRR curves for tunnel system design.

Fires that involve different types of vehicles call for different type of suppression system to control the fire efficiently. For example, a deluge system is less effective for flammable liquid cargo pool fires than an aqueous film forming foam (AFFF) which can generate a banket on top of the fuel and isolate the oxygen from the fuel. A deluge system is less effective for buses or trains as these vehicles are shielded and the water is inaccessible to the fire seat inside the vehicle. An in-car water mist system would be more effective, though deluge system applied water can reduce the temperature of the released gases and can avoid the ignition of the neighbourhood vehicles. Table-3 summarizes fire suppression systems which is applicable for suppression of different types of vehicle fires.

Table-3: Applicable and effective fire suppression system vs vehicle types

Type of Fire load	HGV	FLC	BEV Car/Bus	Multiple ICE Cars or Buses	Train Car
Deluge	A	NR	A	A	A
Foam	A	A	Questionable	Questionable	Questionable
Water mist	A	A	A	A	Questionable
In-car mist	A	NA	A	A	A

A – Applicable, NR – Not Recommended, NA – Not Applicable, Questionable – effectiveness of fire suppression depends on the design of the fire suppression system and fire origin

Some tunnels may not have restrictions on vehicle usage, some may prohibit certain type of vehicles to use it. Fire safety design should consider the vehicle fire which demands the most sophisticated system for the subject tunnel. Fire suppression systems can be ranked from the simple to the sophisticated in the order of “no suppression”, “FFFS deluge”, “AFFF (foam)”, “water mist”, “in-car mist”, etc. Apart from the traditional cars, HGV and buses, flammable liquid cargo (FLC) fires and new energy fuel vehicles exhibit specific features and requires different fire suppression system for solid or cellulosic fuelled fires. Furthermore, the shielding effects is also an important factor to be considered, since most of HGVs are shielded and the response of fire suppression is different than these fires that are unshielded.

SHIELD VS UNSHIELDED FIRE

The impact of fire shielding should be factored in when considering the suppression effectiveness of water-based fixed fire suppression systems. Many existing studies observing effectiveness of FFFS utilize conditions where fire events are not shielded by freight cargo infrastructure. United States freight statistics indicate this approach may not best represent the current condition of freight operational characteristics for the nation’s truck population.

Of the five major modes of infrastructure freight transportation monitored in the US (*Roadway, Rail, Inland Waterways, Airways, and Pipelines);* Trucks on roadway account for roughly 73% of all domestic freight transportation based on freight by weight [19]. Of the 73% roadway truck freight in the US, majority is transported via ‘dry van’, or more typically known as trailers/containers. Other freight transport methods not used as often include:

- Open-top container (used for raw mining materials, pipes, tools, cable spools, construction supplies, bulk cargo, scrap metal)
- Flatbed (typically used for oversized or large pieces of equipment, construction equipment, building supplies)
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For purposes of this study, the following ‘dry van’ transport container are considered to have steel construction on top of the container:

- Tunnel Container
- Open or curtain sided storage container
- Insulated/Thermal, or refrigerated container
- Special purpose
- Intermodal
- Car Carriers
- Tankers (liquid storage)

The latest available data for physical and operational characteristics of various goods transport on freight trucks in the United States is based on a study in 2002 which shows that roadway freight cargo make up roughly 4.5% of freight traffic [20]. This is representative of open-top containers, and partially for freight covered by a tarpaulin. If flatbed cargo was also considered (which likely includes material not considered susceptible to immediate combustion or fast or medium growth fire curves), then this percentage increases to only 18%. The remaining roughly 82% of freight cargo transported on roadways at the time of these studies are container vehicles which may result in a shielded fire condition for any such emergency event. This representative percentage of shielded cargo loads on the US roadways is expected to increase when new data is issued in 2023.

This data would suggest that using open-top or flatbed containers as a basis to measure the performance of FFFS may not be the most plausible. Though these fire scenarios should be considered; a more useful and practical approach would be to use shielded fire conditions as a measure of FFFS effectiveness.

DESIGN FIRE HRR WITH FIRE SUPPRESSION

It is hard to accurately estimate the reduced HRR caused by the intervention of the fire suppression systems, and the design principle is to take a conservative approach. For different types of vehicle fires, fire control effectiveness varies with different type of suppression systems. Fire safety design should also consider a mitigation approach for the most severe scenarios, including failure of fire suppression system.

Apart from the type of fire suppression system, the peak fire HRR with the fire suppression operation will be influenced by various other parameters such as fire detection time, fire growth rate, location of fire origin, fire suppression system activation time, ventilation and the type of vehicles involved in the fire, etc. Major influencing factors of the peak HRR would be the type of fire suppression system and the time when fire suppression system is in full operation.

For fire suppression system activation time, it is determined by the fire detection time, positive alarm sequence, tunnel management control which determine the delay time to operate the fire suppression system. For example, the 2020 edition of NFPA 502 -2020 [6] Clause E4.2 stated that the maximum delay time to operate deluge system should not exceed three minutes.

For a given tunnel, fire can be detected if gas temperature rises quickly, or reach a threshold value, i.e., 68°C, if we assumed a delay time of three minutes for a dry FFFS operation, assuming HRR will be peaked within 20 seconds after FFFS operation for each type of fire with various type of fire load, based on the tested fire HRR growth, Table-4 summarizes peak fire HRR and fire detection time, fire suppression operation time, and the time when fire HRR is peaked.

To provide a overview of the maximum heat release rate that can be achieved in tunnels environment under low pressure deluge, high pressure water mist and foam systems, with the selected suppression systems that are applicable for different vehicle types as listed in Table-3, the peak fire HRR for HGV, FLC, BEV, ICE cars, ICE Bus, passenger train, etc. will be addressed separately.

Heavy Goods vehicles (HGV)

A heavy goods vehicle is a goods vehicle which exceeds 7.5 tonnes, permissible maximum weight according to definition. Ingason and Li et al [22-24] reported that HRR under deluge suppression can be as high as 20 - 40 MW, and all the fire suppression tests at Runehamar showed that fire HRR has been controlled at no more than 40MW, and stated that "after activation of the system the maximum temperatures at the ceiling were never higher than 400°C to 800°C" [23, 26]. Foam and water mist systems are both effective for HGV fires though these systems are more expansive to install or operative than the deluge system.

Flammable Liquid Cargo (FLC)

Fire HRR growth is very fast, according to the tests, its growth rate follows a bi-linear curve [4], based on a detection time of approximately 30 sec, the fire HRR peaked at 200 MW at 100 seconds under water mist suppression which started operation at approximately 60 second after detection. Gas temperature near the ceiling reach 1000°C. As shown in Figure 4, performance of AFFF behaves similar to that of the pure water mist according to Lakkonen [18]. Deluge system for FLC pool fire is not effective, and it is not recommended. M. Lakkonen et al [4, 17] compared the performance of high-pressure water mist and deluge system and suggested that high pressure water mist system is effective for FLC fires.

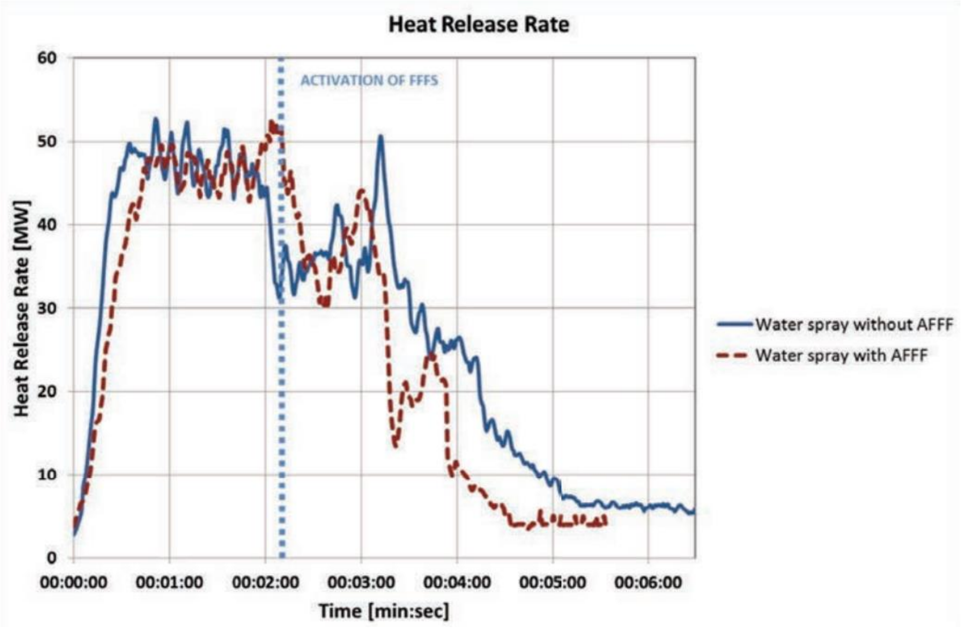

Figure 4: Measured HRR for all tests with fine droplet spray mist with and without AFFF [18]

Battery Electric Vehicle (BEV) Car
Battery energy vehicle (BEV) is powered by batteries, and fire maybe caused by short circuit, etc, and fire may restart even after the car has been dumped, which means fire may restart on the next day after the initial car fire appears to have been extinguished. The suitable fire suppression system would be deluge, water mist or foam. HRR under suppression [27] would be peaked at the time when fire suppression is in full operation. Gas temperature can be as high as 900°C.

Multiple ICE Cars
For traditional Internal Combustion Engine (ICE) cars, deluge water can cool the surrounding gases and avoid the ignition of neighbourhood vehicles. HRR under suppression operation could be capped at 10 - 15MW, its fire growth rate can be represented with t-squared medium curve. Gas temperature would not exceed 700°C.

ICE Buses
Because of it shield nature of buses, deluge is not an effective type of suppression system for ICE bus fires. Based on ultra-fast HRR growth rate [26], fire can be detected at 1.5 minutes, considering a maximum positive alarm sequences of 3 minutes which delays the application of suppression system, HRR will be controlled at 15-20 MW under FFFS suppression system, gas temperature can be controlled at 700°C though deluge water is inaccessible to the seat of the fire inside the bus. The most effective approach is to employ an in-car water mist system to extinguish the fire originated from the inside of the bus.

Train Cars
The best train fire suppression approach is in-car fire suppression, HRR under properly designed suppression system can be controlled at 2 – 12 MW based on medium fire growth rate and its detection time of 4.6 seconds. A worst scenario would see a maximum gas temperature of 600-800°C [4, 15]. Trains are similar to the buses or HGVs which are shielded, and deluge water may not directly access the seat of the fire and effectively suppress the fire inside the carriage, though it is effective for cooling the air external of the bus.

Fire can be controlled within 2 minutes after suppression system is in full operation [17]. Table-5 and

Table-6 compares the peak HRR and the maximum gas temperature that can be reached with and without fire suppression, respectively. With a properly design fire suppression system, peak heat release rate can be reduced by around 25 – 75%, and maximum gas temperature can be reduced by 10 – 45%. For cars or buses, the cooling effects of the fire suppression system can reduce the chance of ignition of neighbouring vehicles.

Table-4: Fire peak HRR with properly designed and operated fire suppression involving different type of vehicles

Type of Fire load	Growth Rate	Type of suppression	Peak HRR Q_{max} (MW)	Maximum tempera-ture (°C)	t_D (min)	t_S (min)	t_{max} (min)
HGV	Ultra-fast	Deluge	15- 50 [22,25]	400-800	1.5	4.5	4.8
FLC	Linear	mist/foam	200	800 [18]	0.5	3.5	3.9
BEV car	Medium	deluge/mist	3 - 7	800	4.6	7.6	7.9
ICE Cars	Medium	deluge/mist	10 - 15	700	4.6	7.6	7.9
ICE Bus	Ultra-fast	In-car mist	15 - 20	<700 [26]	1.5	4.5	4.8
Train	Medium	In-car mist	10 - 12	<600 [15]	4.6	7.6	7.9

Q_{max} – the maximum total heat release rate, t_{max} – time when maximum HRR is reached, t_D – fire detection time, t_S – suppression system discharge time

Table-5: Peak HRR (MW) with a properly designed suppression system* for different types of vehicles

Type of fire load	HGV	FLC	BEV Car	Multiple ICE Cars	ICE Bus	Train Car
Free burning	200	300	7	10 –20 [1, 20]	34 [11-12]	10 – 35[13-16]
Under fire suppression	15–50 [22,25]	200	3 - 7	10 – 15	15 - 20	2 –12
Suppression effect	75%	33%	50%	25%	70%	65%

* Properly designed suppression system refers to the system listed on Table-3 and Table-4

Table-6: Maximum gas temperature (°C) with properly designed suppression system* for fires involving different types of vehicles

Type of Fire load	HGV	FLC	BEV Car	Multiple ICE Cars	ICE Buses	Train Car
Free burning	1365°C [22-24]	1200°C	1000°C [27]	700°C	700°C	1100°C
With fire suppression	400-800 °C	800°C [18]	900°C	700°C	< 700°C [26]	< 600°C [15]
Suppression effect	41%	41%	10%	avoid fire propagation	avoid fire propagation	45%

*Properly designed suppression system refers to the system listed on Table-3 and Table 4

SUMMARY

Suppression of different type of vehicle fire requires selection of the most effective type of fire suppression system. Deluge system is effective for unshielded vehicle fires and can significantly reduce its design fire HRR. For shield type of vehicle fire, such as train or buses, in-car mist system is more effective than a deluge system. For FLC fire AFFF foam or water mist system are equivalently effective, but deluge system would not be effective for FLC fires.

If the suppression system operates as design expected, the maximum gas temperature for tunnel structural fire durability design would not exceed 800°C. The peak heat release rate would be reduced by approximately 25 - 75%, and the gas temperature maybe reduced by 10 – 45%. However, there is a probability of failure of the suppression operation which should be considered in the design.

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