DESIGN FIRES IN TUNNELS

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ABSTRACT

This paper contains an overview of peak HRRs and temperatures in vehicle fires and a presentation of different mathematical tools to represent design fires. It also presents the main results from the UPTUN project on design fires in tunnels including a proposal for design fires.

1. INTRODUCTION

Design fires in tunnels are usually given as the peak Heat Release Rate (HRR), i.e. the fire power in MW, although it has become more and more common for engineers to combine the peak HRR with the fire growth rate. Full-scale tests in the Runehamar tunnel, of Heavy Goods Vehicle (HGV) loads, which were carried out in collaboration with the UPTUN project [1-6] show, for example that the HRR can reach over 100 MW in less than ten minutes. This means that the fire growth rate will be crucial in determining whether those caught in the fire can escape. Studies undertaken by Ingason *et al.* [7, 8] showed that the fire growth rate is more important than the peak HRR when investigating the safety of people trapped in fire smoke.

A summary of available information on measured HRR and gas temperature development from all major large scale fire test series with vehicles is presented, together with fire test data with vehicles in other types of applications. These values support the proposed design fires given within UPTUN project. The peak HRR varies between 1.5 MWs up to 202 MWs for road vehicles and from 7 MWs up to 43 MWs for rail vehicles. The gas temperatures in the ceiling vary from 110 ºC up to 1365 ºC.

There are numerous ways to represent a design fire, using both peak HRR and different fire growth rates (e.g. linear, quadratic etc) and by combining fire growth rates with constant levels and a decay period. A short summary of these methods is given in this paper.

The UPTUN project is a European 5th framework research project which aims at providing a methodology for upgrading existing tunnels in terms of fire safety. The UPTUN programme included eight Work Packages (WPs), where WP2 was devoted to the analysis of fire development in tunnels and potential mitigation measures. Design fire scenarios and associated design fire curves were proposed by UPTUN WP2 [9, 10], and used as input to other work packages within UPTUN. These proposed design fires can also be used in more in general terms, since they are based on current knowledge about fire scenarios as well as information created within the UPTUN project.

The proposal as given by UPTUN WP2 is presented in this paper. More information on design fires can be obtained in overviews such as presented in references [9, 11].

2. SUMMARY OF HRR AND TEMPERATURE

Numerous measurements of the HRR of passenger cars and ceiling temperatures can be found in the literature. In Table 1, a summary of HRR measurements for passenger cars and other road vehicles (except tankers) is given [12-14]. Table 1 contains values of measured or estimated total energy content, peak HRR, time to reach a peak HRR and ceiling temperatures. All of the large vehicles have been burned in a tunnel, whereas passenger cars have either been burned under a calorimeter or in a tunnel.

The HRRs for single passenger cars (small and large) vary from 1.5 to 9 MW, but the majority of the tests show HRR values less than 5 MW. When two cars are involved the peak HRR varies between 3.5 and 10 MW. There is a great variety in the time to reach peak HRR, i.e., between 10 and 55 minutes. It has been shown that the peak HRR increases linearly with the total calorific value of the passenger cars involved in the fire. An analysis of all data available shows that the average increase is about 0.7 to 0.9 MW/GJ [4, 15].

There are not many bus tests performed. The two tests shown in the Table 1 indicate that the peak HRR is in the order of 30 MW and the time to reach peak heat release rate is less than ten minutes.

The highest peak HRRs were obtained for the HGV trailers (single), which were found to be in the range of 13 to 202 MW, depending on the fire load. The time to reach peak HRR was in the range of 10 to 20 minutes. The fire duration was less than one hour for all the HGV trailer tests presented in Table 1. The fire growth rate after reaching 5 MW was nearly linear during all the tests carried out in the Runehamar tunnel and it varied between 16.4 to 26.3 MW/min [2].

The literature describes very few measurements of HRRs for rail and metro vehicles. The majority of the tests available are from EUREKA 499 test series [16]. In Table 2, a summary of these tests is given. The tests results are based on large scale tests with single coaches. The peak HRR is found to be in the range of 7 to 43 MW and the time to reach the peak HRR varies from 5 to 80 minutes. If the fire were to spread between the train coaches, the total HRR and the time to reach peak HRR would be potentially much higher than the values given in Table 2.

The measured ceiling temperatures vary from 110 to 1365 ºC. These temperatures can be compared to standardized time-temperature curves (ISO 834) for load bearing design in buildings and underground constructions. After one hour of exposure the temperature exceeds 925 ºC. ISO 834 has been used in many countries for tunnels, but it can not represent all types of material, e.g. petrol, chemicals etc. Therefore a special curve, the hydrocarbon curve (the HC-curve) was developed in the 1970s, with a peak temperature of 1100 ºC after only a few minutes. It has mainly been used in the petrochemical and off-shore industries but it has also started to be used for tunnels. The main difference between these two curves is the rate of fire development and the peak temperature rise. Special temperature curves have been developed in some countries to simulate hydrocarbon fires in tunnels.

Examples of such curves include the RABT/ZTV Tunnel Curve in Germany (peak 1200 ºC), modified HC_{inc} in France (peak 1300ºC), and the Rijkswaterstaat Tunnel Curve (the RWS Curve) in the Netherlands (peak 1350 ºC). The highest gas temperatures from vehicle fires were obtained in the Runehamar test series. These fires resulted in gas temperatures in the range of 1281 – 1365 ^{o}C [1]. These high temperatures correspond to RWS and HC curves for tunnel fires.

The results in Tables 1 and 2 indicate that there is a correspondence between high HRR and high temperatures. Ingason [17] has showed that the highest temperatures (> 1300 ºC) are obtained with HRRs larger than 20 MW and low ceiling heights (~ 4 m to 5 m) in combination with intermediate ventilation rates. For high HRR the flames impinge on the ceiling and the combustion zone, where the highest temperatures are usually obtained, is situated close to the ceiling, even when the longitudinal ventilation deflects the flames. When the longitudinal ventilation rate increase further the cooling effects predominate and the temperature drops again. The geometrical shape and size of the fuel, the tunnel cross-section (especially the height) and the ventilation rate are thought to be the principal parameters that determine the temperature level at the ceiling.

Type of vehicle, model year, test nr, u=longitudinal ventilation m/s	Calorific value (GJ)	Peak HRR $(\dot{Q}_{max})$ (MW)	Time to peak HRR (min)	Peak temperatures in tunnel ceiling (ºC)	Reference
Passenger cars					
Ford Taunus 1.6 , late 70´s , test 1	4	1.5	12	NA	Mangs and Keski-Rahkonen [18]
Datsun 160 J Sedan , late 70´s , test 2	4	1,8	10	NA	
Datsun 180 B Sedan, late 70´s , test 3	4	2	14	NA	
Fiat 127, late 70´s, 0,1 m/s	NA	3,6	12	NA	Ingason e.t. al. [19]
Renault Espace J11-II , 1988, test 20, u=0,5 m/s	7	6	8	480	Steinert [20]
Citroën BX , 1986	5	4.3	15	NA	Ship and Spearpoint [21]
Austin Maestro, 1982	4	8.5	16	NA	
Opel Kadett, 1990 , test 6, u=1,5 m/s	NA	4,9	11	210	Lemaire et al [22]
Opel Kadett, 1990 , test 7, u=6 m/s	NA	4.8	38	110	
Renault 5, 80´s, test 3	2.1	3,5	10	NA	Joyeux [23]
Renault 18, 80´s, test 4	3,1	2,1	29	NA	
Small Car, 1995, test 8	4,1	4,1	26	NA	
Large Car, 1995, test 7	6,7	8,3	25	NA	
Trabant, test 1	3.1	3.7	11	NA	Steinert [24]
Austin, test 2	3,2	1,7	27	NA	
Citroen, test 3	8	4,6	17	NA	
Renault Laguna, 1999	13,7	8,9	10	NA	Marlair and Lemaire [9]
Two passenger cars					
Citroen BX + Peugeot 305, 80´s, test 6	8,.5	1,7	NA	NA	Joyeux [23]
Small Car + Large Car, test 9	7,9	7,5	13	NA	
Large Car + Small Car, test 10	8,4	8,3	NA	NA	
BMW+ Renault 5, 80´s, test 5	NA	10	NA	NA	
Polo + Trabant, test 6	5,4	5,.6	29	NA	Steinert [24]
Peugeot + Trabant, test 5	5,6	6,2	40	NA	
Citroen + Trabant, test 7	7,7	7,1	20	NA	
Jetta + Ascona, test 8	10	8,4	55	NA	
Three passenger cars					
Golf + Trabant + Fiesta, test 4	NA	8.9	33	NA	
Buses					
A 25-35 year old 12 m long Volvo school bus with 40 seats, EUREKA 499, u=0.3 m/s	41	29	8	800	Ingason [25]
A bus test in the Shimizu Tunnel, u=3-4 m/s	NA	30 **)	7	303	Kunikane et. al. [26]
HGV					
A trailer load with total 10.9 ton wood (82%) and plastic pallets (18%), Runehamar test series, Test 1, u=3 m/s	240	202	18	1365	Ingason and Lönnermark [27]
A trailer load with total 6.8 ton wood pallets(82%) and PUR mattrasses (18%), Runehamar test series, Test 2, u=3 m/s	129	157	14	1282	Ingason and Lönnermark [27]
A Leyland DAF 310ATi – HGV trailer with 2 tons of furniture, EUREKA 499, u= 3-6 m/s	87	128	18	970	Grant and Drysdale [28]
A trailer with 8.5 ton furnitures, fixtures and rubber tyres, Runehamar test series, Test 3, u=3 m/s	152	119	10	1281	Ingason and Lönnermark [27]
A trailer mock-up with 3.1 ton corrugated paper cartons filled with plastic cups (19%**), Runehamar test series, Test 4, u=3 m/s	67	67	14	1305	Ingason and Lönnermark [27]
A trailer load with 72 wood pallets, Second Benelux tests, Test 14, u=1-2 m/s	19	26	12	600	Lemaire et. al. [22]
A trailer load with 36 wood pallets, Second Benelux tests, Test 8, 9 and 10, u=1.5, 5.3 m/s and 5 m/s	10	13, 19 and 16	16, 8 and 8	400,290,300	Lemaire et. al. [22]
A Simulated Truck Load (STL), EUREKA 499, u=0.5 m/s	63	17	15	400	Ingason [29]

NA=Not Available

*) Small Car (SC) includes the following cars: Peugeot 106, Renault Twingo-Clio, Citroen Saxo, Ford Fiesta, Opel Corsa, Fiat Punto, WW Polo Large Car (LC) includes the following cars: Peugeot 406, Renault Laguna, Citroen Xantia, Ford Mondeo, Opel Vectra, Fiat Tempra, WW Passat **) This is estimated from the convective HRR of 20 MW derived by Kunikane et al [26] because a sprinkler system was activated when the convective HRR was 16.5 MW. We assume that 67 % of the HRR is convective and thereby we can estimate the HRR = 20/0.67=30 MW. ** mass ratio of the total weight

Table 1. Large scale experimental data on road vehicles [12-14]

Type of vehicle, test series, test nr, u=longitudinal ventilation m/s	Calorific value (GJ)	Peak HRR ($\dot{Q}_{max}$) (MW)	Time to peak HRR (min)	Peak temperatures in tunnel ceiling (ºC)	Reference
Rail					
A Joined Railway car; two half cars, one of aluminium and one of steel, EUREKA 499, u=6-8/3-4 m/s	55	43	53	980	Steinert [20]
German Intercity-Express railway car (ICE), EUREKA 499, u=0.5 m/s	63	19	80	830	Steinert [30]
German Intercity passenger railway car (IC), EUREKA 499, u=0.5 m/s	77	13	25	720	Ingason et al [30]
British Rail 415, passenger railway car*)	NA	16	NA	NA	Barber et al. [31]
British rail Sprinter, passenger railway car, fire retardant upholstered seatings*)	NA	7	NA	NA	Barber et al. [31]
Metro					
German subway car, EUREKA 499, u=0.5 m/s	41	35	5	1060	Ingason et al [30]
German metro steel car, EUREKA 499, u=0.3 m/s	33	NA	NA	630	[16]

*) The test report is confidential and no information is available on test set-up, test procedure, measurement techniques, ventilation, etc.

Table 2. Large scale experimental data on rail vehicles [12-14]

3. DESIGN FIRE CURVES

There are numerous methods available to mathematically represent a design fire curve in tunnels. These include different types of fire growth rates, e.g. linear growth ($\propto t$), quadratic growth ($\propto t^2$) or exponential growth ($\propto (1-e^{-t})$) rate. These growth functions can be combined with a peak HRR value ($\dot{Q}_{max}$) and a decay functions ($\propto -t$ or e^{-t}). In building fire safety design, usually the growth rate alone is considered whereas in tunnels the entire fire curve is considered. In the following a summary of four different methods, see Table 3) to describe a complete design curve for tunnels is given:

- ***Linear growth:*** The French tunnel recommendations [32] for fire ventilation assume a time dependency of HRR with a linear growth from zero to time t_{max}, a constant maximum value to the time t_D and finally a linear decrease from the maximum value to zero to the time t_d.
- ***Quadratic growth:*** Ingason [33] proposed time-dependent design fires for different types of vehicle with a quadratic growth from zero to time t_{max}, a constant maximum value to the time t_D and finally a exponential decrease from the maximum value to zero to infinity.
- ***Exponential growth – fuel control:*** Ingason [34, 35] has proposed a method to estimate the HRR given as a single exponential function of time instead of as three functions of time. It is based on original work by Numajiri and Furukawa [36] and it is only thought for fuel controlled fires. The design parameters are the peak HRR ($\dot{Q}_{max}$), the total calorific value, E_{tot} and the parameter n, which is arbitrary chosen parameter with no physical meaning. Based on these parameters, t_{max} and t_d can be calculated, see Table 3. Other parameters are r and k, which are calculated based on the information given.

- ***Exponential growth – ventilation control.*** Ingason [35] created a fire curve with a steady state period by summing up two exponential curves. This would apply in case of strongly ventilation-controlled tunnel fires or fully developed compartment fires in steel body type of coaches.

Method Reference	HRR as a function of time t (s)	Time interval (s)	Time to maximum HRR (s)	Time to decay starts, t_D, and/or fire duration, t_d (s)	Other conditions
Linear growth Lacroix [32]	$HRR = \alpha_{g,L} t$	$0 \le t_{\max}$	$t_{\max} = \frac{\dot{Q}_{\max}}{\alpha_{g,L}}$	$t_D = t_d - \sqrt{\frac{2}{\alpha_{D,L}}\left(\frac{\alpha_{g,L}}{2} t_{\max}^2 + \dot{Q}_{\max}(t_d - t_{\max}) - E_{tot}\right)}$	
	$HRR = \alpha_{g,L} t_{\max} = \dot{Q}_{\max}$	$t_{\max} < t < t_D$			
	$HRR = \dot{Q}_{\max} - \alpha_{D,L}(t - t_D)$	$t_D < t < t_d$			
Quadratic growth Ingason [33]	$HRR = \alpha_{g,q} t^2$	$0 \le t_{\max}$	$t_{\max} = \sqrt{\frac{\dot{Q}_{\max}}{\alpha_{g,q}}}$	$t_D = \frac{\chi E_{tot}}{\dot{Q}_{\max}} + \frac{2}{3} t_{\max} - \frac{1}{\alpha_{D,q}}$	If $t_D \le t_{\max}$ no constant period, then $\dot{Q}_{\max} \approx \chi \alpha_{D,q} E_{tot} \left(1 - \frac{\alpha_{D,q}^{3/2}}{6} \sqrt{\frac{\chi E_{tot}}{\alpha_{g,q}}}\right)^2$ and $t_{\max} = \sqrt{\frac{\dot{Q}_{\max}}{\alpha_{g,q}}} = t_D$
	$HRR = \alpha_{g,q} t_{\max}^2 = \dot{Q}_{\max}$	$t_{\max} < t < t_D$			
	$HRR = \dot{Q}_{\max} e^{-\alpha_{D,q}(t - t_D)}$	$t \ge t_D$			
Exponential growth (fuel control) Ingason [34, 35]	$HRR = \dot{Q}_{\max} \cdot n \cdot r \cdot (1 - e^{-k \cdot t})^{n-1} \cdot e^{-k \cdot t}$	$t \ge 0$	$t_{\max} = \frac{\ln(n)}{k}$	$t_d = \frac{1}{k} \cdot \ln\left(\frac{1}{1 - \beta_d^{\frac{1}{n}}}\right)$	$r = \left(1 - \frac{1}{n}\right)^{1-n}$ $k = \frac{\dot{Q}_{\max}}{E_{tot}} \cdot r$
Exponential growth (ventilation control) Ingason [35]	$HRR = \dot{Q}_{\max}(18.96 \cdot e^{-10 \cdot t / t_d}(1 - e^{-10 \cdot t / t_d})^7$ $+ 37.59 \cdot e^{-7 \cdot t / t_d}(e^{-7 \cdot t / t_d} - 1)^{20})$	$t \ge 0$	$t_{\max} = 0.24 \cdot t_d$	$t_d = 2.03 \times \frac{E_{tot}}{\dot{Q}_{\max}}$	

Table 3. Equations for different methods to describe a complete design curve for tunnels

In Table 3, index *max* refer to the peak values, *D* refers to the decay period, *d* refers to the total fire duration, *g* refers to the growth period, *L* refer to a linear period, *q* refers to a quadratic period and *tot* refers to the total. χ is the combustion efficiency and β_d is the ratio between the integrated energy at time t_d, (E_{tot,t_d}), and the total energy released in the fire (E_{tot}) and can be arbitrarily chosen (0.97 – 0.99). In Table 4 data on the French design curve is given, where the linear fire growth rate ($\alpha_{g,L}$) and linear decay rate ($\alpha_{D,L}$) have been calculated based on the given data.

Type of vehicle * E_{tot} modified to match equation in Table 3	E_{tot} * (GJ)	$\dot{Q}_{max}$ (MW)	t_{max} (min)	t_D (min)	t_d (min)	$\alpha_{g,L}$ (MW/min)	$\alpha_{D,L}$ (MW/min)
2-3 cars / height clearance $\leq$2.7 m	17	8	5	25	45	1.6	0.4
1 van / height clearance $\leq$3.5 m	38	15	5	35	55	3	0.75
1 HGV - clearance >3.5 m - no hazardous goods	144	30	10	70	100	3	1
1 HGV with high GJ - clearance >3.5 m	450	100	10	70	90	10	5
1 tanker - clearance >3.5 m - hazardous goods	960	200	10	70	100	20	6.7

Table 4. Complementary data on design fires based on French regulations [9, 32]

Note that the values in Table 4 have been re-calculated from the original paper in order to adjust the numbers to the presentation given in Table 3. Ingason [33] assumed that the design parameters for the quadratic method (see Table 5) should be considered as guidelines for the designers, and that they may need to be adjusted when more experimental data becomes available. No allowance was made for the possible spread of fire between the vehicles, nor for the possible effects of under-ventilation on heat release rate development. If necessary, these effects must be investigated separately.

Type of vehicle	$\dot{Q}_{max}$, (MW)	$\alpha_{g,q}$ (MW/min²)	$\alpha_{D,q}$ (min^{-1})
Car	4	0.036	0.06
Bus	30	0.36	0.042
Truck*	15 - 130	-	-
Train **	15	0.036	0.06
Subway car ***	35	1.08	0.06

* Since the fire load of a truck may vary greatly, no attempt was made to determine Q_{max}, $\alpha_{g,q}$ or $\alpha_{D,q}$.

** Steel construction *** Aluminium construction

Table 5. Proposed design parameters for creation of design fires for traffic tunnels by Ingason [33]

Note that the values in Table 5 have been re-calculated from the original paper in order to adjust the numbers to the presentation given in Table 3. In order to demonstrate the use of the equations given in Table 3, an example has been chosen from Table 4. It is a HGV with no hazardous goods, with a total calorific value of 125 GJ, peak HRR equal to 30 MW and fire duration of 100 minutes. This information was used for all the cases. The parameter n was chosen as 2, in order to adjust the growth rate to the linear fire growth rate. In Figure 1, the results are shown.

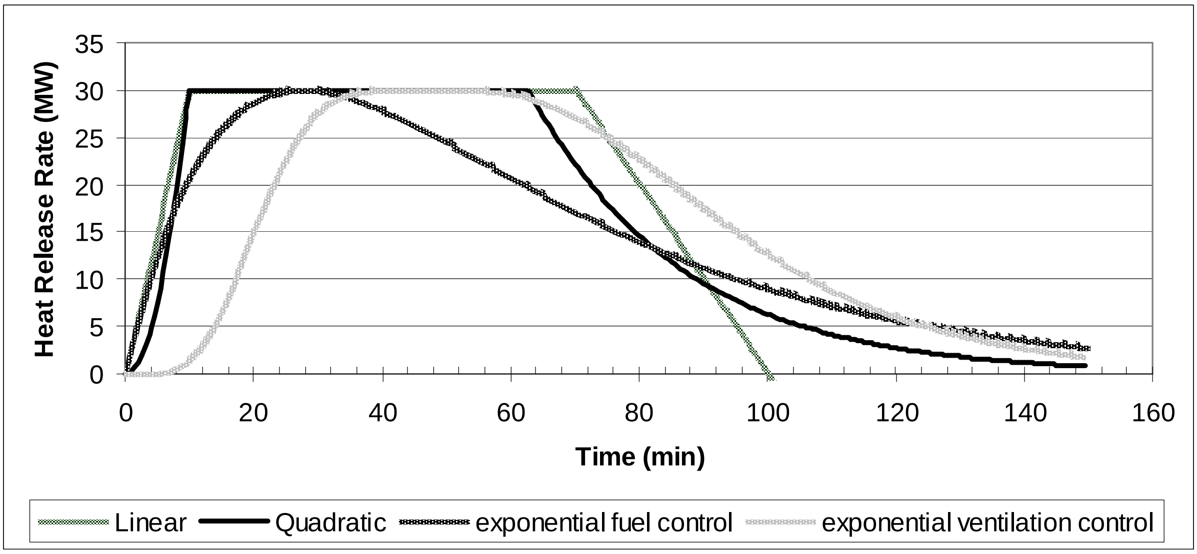

Figure 1. An example plotted for the HRR curves given in Table 3. The input was obtained from Table 4, E_{tot} =144 GJ and $\dot{Q}_{\max}$ =30 MW; Other parameter used where **linear**: t_d=100 min, $\alpha_{g,L}$ =3 MW/min, $\alpha_{D,L}$ =1 MW/min, **quadratic**: $\alpha_{g,q}$ =0.3 MW/min^2, $\alpha_{D,q}$ =0.042 MW/min^2, **exponential**: n=2, β_d =0.99.

The integrated area is the same for all curves. The exponential curves are more favourable to use since it gives a more realistic representation of a real fire curve.

4. UPTUN - WP2 PROPOSAL [10]

The following proposal is based on information obtained from test data such as that given in Tables 1 and 2. UPTUN - WP2 suggest distinguishing between:

A) fire scenarios where tunnel users, rescue teams and installed equipment necessary to provide safe evacuation and rescue operations (human safety) are at risk, and

B) protection of the tunnel boundary to avoid structural collapse, unwanted fire and smoke spread by ventilation ducts or fire doors (Fire resistance).

For A) human safety, fire scenarios in terms of HRR will be recommended, while for B) fire resistance, time-temperature curves are recommended. This approach follows how fire safety is regulated in the building regulations and allows the application of some commonly accepted methods for the documentation of fire resistance. In general UPTUN - WP2 recommends that several fire scenarios to be used for risk analysis of tunnels. Small fires may provide other problems than bigger fires. In risk analysis, it is significant to know how all possible scenarios contribute to the overall hazard. For A) human safety, all proposed scenarios from 5MW up to the actual design fire are recommended to be considered in risk analysis.

HRR MW			Road, examples vehicles	Rail, examples vehicles	Metro, examples vehicles	At the fire boundary
Risk to life		5	1-2 cars			ISO 834
		10	Small van, 2-3 cars, ++	Electric locomotive	Low combustible passengers carriage	ISO 834
		20	Big van, public bus, multiple vehicles		Normal combustble passengers carriage	ISO 834
		30	Bus, empty HGV	Passengers carriage	Two Carriages	ISO 834
	Risk to construction	50	Combustibles load on truck	Open freight wagons with lorries	Multiple carriages (more than two)	ISO 834
		70	HGV load with combustibles (approx. 4 tonne)			HC
		100	HGV (average)			HC
		150	Loaded with easy comb. HGV (approx. 10 tons)			RWS
		200 or higher	Limited by oxygen, petrol tanker, multiple HGVs	Limited by oxygen		RWS

Table 5. Fire scenario recommendation, UPTUN WP2 proposal [10]

The following fire growth rate ($\alpha_{g,L}$) is recommended by UPTUN – WP2:

Peak HRR of fire ≤ 30MW, => $\alpha_{g,L}$ = 10 MW/min

Peak HRR of fire > 30MW, => $\alpha_{g,L}$ = 20 MW/min

It is proposed that the duration of the fire be determined by the amount of available combustible material (E_{tot}), where 100% fuel consumption (80% combustion efficiency) is assumed. The amount of fuel should be evaluated for each study and will depend on the type vehicles, load and traffic pattern. In particular, stationary traffic can have a large influence on the amount and availability of combustible material.

For B) fire resistance, only three curves are recommended, ISO 834, Hydrocarbon Curve (HC) and RWS-curve. The same rule for duration applies as for type A) scenarios.

5. CONCLUSIONS

Design fire scenarios and associated design fire curves were proposed by UPTUN WP2 [9, 10], and used as input to other work packages within UPTUN. These proposed design fires can also be used in more in general terms, since they are based on current knowledge about fire scenarios as well as added information created within the UPTUN project.

Measured HRR and gas temperature development from all major large scale fire test series with vehicles are presented, as well as fire tests with vehicles in other types of applications. These values support the proposed design fires given by UPTUN project.

Mathematical tools for representation of complete design fire curves were presented. A comparison was made between different methods. It is recommended to use the exponential representation using one single function since it gives more realistic shape of the fire curves. It is also robust and easy to use.

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