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A New Methodology of Design Fires for Train Carriages Based on Exponential Curve Method

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Abstract. Design fires have great influences on the fire safety concepts and safety measures, and are the basis for any assessment and calculation in tunnel fire safety design. A new methodology of design fires for individual train carriages is proposed based on the exponential design fire curve method and state-of-the-art fire research. The three key parameters required for construction of a design fire are the maximum heat release rate, time to maximum heat release rate, and energy content. An overview of the full scale train carriage fire tests is given and the results show that the maximum heat release rate is in a range of 7 MW to 77 MW and the time to reach the maximum heat release rate varies from 7 min to 118 min. The method could be employed to one single train carriage or several carriages, and alternatively one carriage could be divided into several individual sections. To illustrate the use of the methodology, several engineering applications are presented, including design fires for a metro train carriage with a maximum heat release rate of 77 MW, a double-deck railway train carriage with a maximum heat release rate of 60 MW and a tram carriage with a maximum heat release rate of 28 MW. The main objective is to provide practicing engineers with a flexible and reliable methodology to make design fires for individual train carriages in performance-based tunnel fire safety design.

Keywords: Design fire, Train carriage, Metro, Tram, Heat release rate, Engineering application

1. Introduction

Mitigation systems are installed in tunnels to improve safety of tunnel users and to prevent damages to the construction [1]. The systems installed vary in type and cost. A design fire is needed when these mitigation systems are engineered for a specific tunnel project, and it represents the load of the mitigation systems during the incident. Therefore a design fire has a great influence on the fire safety concepts and safety measures, and is the basis for any assessment and calculation in tunnel fire safety design.

Full scale fire tests are the best way to obtain valuable information about realistic carriage fires. However, the huge cost and the resulting limited number of tests

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make the full scale tests impossible to run in every project. Despite this, the limited data obtained are very valuable for fire safety design, especially in design fires. CFD tools could be an option. However, CFD modelling of fire development is complex and generally not reliable, and thus it could only be used in qualitative study, or be used when modelling of similar scenarios has been well validated, see for example [2].

In engineering applications, the design fire is most commonly represented as a single value of a maximum heat release rate (HRR) in megawatt (MW) or a time dependent heat release rate curve.

For vehicle fires in road tunnels, fixed design fire values can be found in different guidelines or standards for road tunnels, depending on type of the vehicle. These values are based on experimental data and consensus among members of technical committees working with these documents. However, for train carriage fires (train, subway, metro or tram), the guidelines only define time–temperature curves but not the heat release rate as a single design value or as a function of time [3]. The focus is on requirements on the fire resistance of the materials used in rolling stocks, to prevent the fire to develop or at least retard its growth and spread [4]. Example of such standard is the EN 45545-2:2013 [5] which defines a classification system that specifies requirements for fire behaviour of materials and products used in trains. The classification system has been prepared by Technical Committee CEN/TC 256 ‘‘Railway applications’’ on behalf of the European Commission, based on the requirements of the EU Directive 2008/57/EC. Another well-known standard for design of fixed guideway transit and passenger rail systems (rolling stock) is NFPA 130 [6].

Initially the design fire for a train carriage was expressed using an average heat release rate that was calculated using the energy content and the duration, see for example [7]. However, a more common way to create a design fire curve is to combine the maximum heat release rate with different types of fire growth rates and decay rates, e.g. the linear curve by Lacroix [8] and the quadratic curve proposed by Ingason [9]. While using constant design values for maximum heat release rates in tunnels, the design fire curves tend to include long periods with constant maximum heat release rates. From a physical point of view these curves may appear unrealistic but they do provide the designer with a useful tool to test their design. The use of these discontinuous equations also means that the design curve is not convenient to apply in the design process.

A new methodology of design fires for individual train carriages is proposed in this paper. A simple and flexible design fire method with a single mathematical expression is applied and the key parameters are discussed based on the state-of-the-art research. To illustrate the use of the methodology, several engineering applications are presented, including design fires for a metro train carriage, a double-deck railway train carriage and a tram carriage. The main objective of this paper is, therefore, to provide practicing engineers with a flexible and reliable methodology to create design fires for individual train carriages in performance-based tunnel fire safety design.

2. Overview of Full Scale Train Carriage Fire Tests

In order to put the results of the study into a context of real fires, an overview of full scale train carriage fire tests is presented here. There are quite few measurements of heat release rates for rail and metro vehicles (rolling stock) [1]. The majority of the tests available are from the EUREKA 499 test series. In Table 1, a summary of these tests is given. A list of the Eureka tests is given in the main test report [10].

The test results presented in Table 1 are based on tests with single carriages. The maximum heat release rate is found to be in a range of 7 MW to 77.4 MW and the energy content in a range of 23 GJ to 77 GJ. The time to reach the maximum heat release rate after ignition varies from 5 min to 118 min. Note that the time to maximum heat release rate from the metro test in the EUREKA 499 tests is much shorter than the others. The reason is that the aluminium roof was burnt away completely during the test. If the fire spread between the train coaches, the total heat release rate would be much higher than the values given here although one cannot simply add the heat release rate for each coach to obtain an estimate of the total heat release rate. This is due to that the first coach would not

Table 1
A Summary of Full Scale Carriage Fire Tests

Type of vehicle, test series, test nr, u = longitudinal ventilation m/s	Calorific content (GJ)	Maximum HRR (MW)	Time to maximum HRR (min)	References
Rail				
A Joined Railway car; two half cars, one of aluminium and one of steel, EUREKA 499, test 11, u = 6–8/3–4 m/s	55	43	53	[12]
German Intercity-Express railway car (ICE), EUREKA 499, test 12, u = 0.5 m/s	63	19	80	[13]
German Intercity passenger railway car (IC), EUREKA 499, test 13, u = 0.5 m/s	77	13	25	[13]
British Rail 415, passenger railway car[a]	NA	16	NA	[14]
British Rail Sprinter, passenger railway car, fire retardant upholstered seatings[a]	NA	7	NA	[14]
Carleton intercity train	50	32	18	[15]
Metro				
German subway car, EUREKA 499, u = 0.5 m/s	41	35	5	[13]
METRO Test 2, X1	60	76.7	12.7	[16]
METRO Test 3, Refurbished X1 (simulating C20)	60	77.4	118	[16]
Carleton subway car	23	52.5	9	[15]

[a] The test report is confidential and no information is available on test set-up, test procedure, measurement techniques, ventilation, etc. NA—Not Available

necessarily reach the maximum heat release rate at the same time as the later ones. This problem, however, will be solved in this paper. The EUREKA 499 tests show that there are many parameters that could affect the fire development in a train carriage. These include the body type (steel, aluminium etc.), the quality of the glazed windows, the geometry of the openings, the amount and type of combustible interiors and their initial moisture contents, the construction of wagon joints, the air velocity within the tunnel and the geometry of the tunnel cross-section [11]. All these parameters could need to be considered in a design process of a rail or metro tunnel. A very important factor for the development of the fire is the quality and mounting of the windows. As long as the windows do not break or fall out (and there are no other large openings), the fire will develop slowly. On the other hand, if the windows break the fire can spread and increase in intensity very quickly. In the METRO project, much higher heat release rates were measured. Part of the reason is that the luggage was considered as part of the fuel loads in the metro carriages. Further, large ignition sources were used to simulate arson fires. Moreover, the openings for a metro carriage were larger than those in a rail carriage, which suggests that the heat release rates could be higher for fully developed fires. This can also be seen from the comparison of the Carleton train test to the subway car test. In METRO Test 3, the fire development was delayed for around 107 min due to the aluminium lining. This indicates the importance of the wall and ceiling linings on the fire development.

In Figure 1, time-resolved heat release rate curves are given for the tests presented in Table 1 (with the exception of the British tests). A comparison of the t-squared ultra-fast fire curve and the test results in Figure 1 with time up to 25 min is presented in Figure 2. Based on the above analysis and the data shown

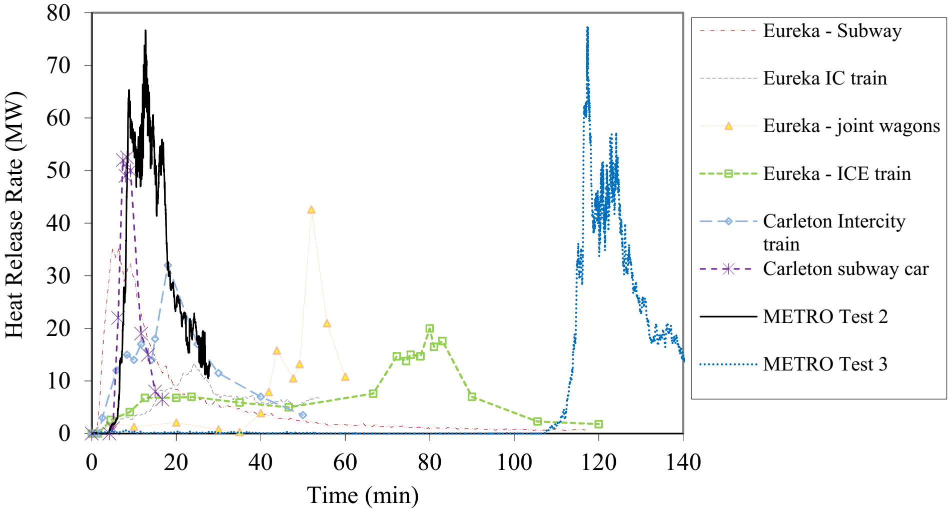

Figure 1. Time-resolved HRR curves for the carriage fire tests presented in Table 1.

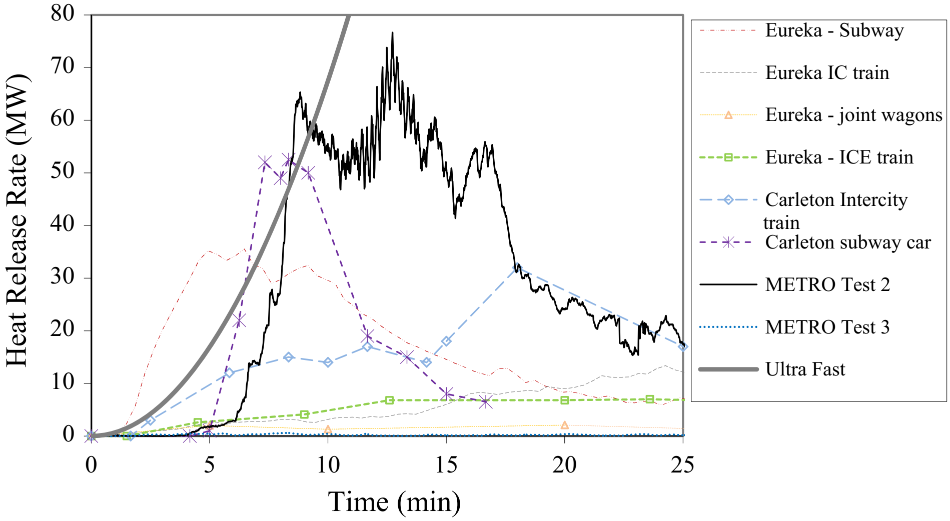

Figure 2. Comparison of the t-squared ultra fast curve with the HRR curves at early stages of the carriage fire tests presented in Table 1.

in this figure, it can be expected that for a carriage with combustible linings the time to maximum heat release rate could probably be around 10 to 20 min. These key values can be used as references in the design and will be discussed further in the following.

3. Methodology

3.1. Determination of Typical Fire Scenarios

The determination of typical scenarios has a great influence on the design fire. The choice mainly depends on the severity of a possible fire and the targeted safety level for a specific vehicle or tunnel. The key relevant parameters include ignition source, fuels available and geometry of the carriage.

In some scenarios, the fire could not become fully developed and the maximum heat release rate could be very low. For example, a 150 kW gas burner placed beside a seat consisting of fire retardant materials according to EN 45545-2:2013 [5] could be ignited but probably not continue to burn after the gas burner is removed 10 min later. However, in case of a large ignition source, e.g. in an arson fire, the fuels directly contacted to the ignition source could probably be ignited immediately and the fire could spread to the neighboring fuels after a short time. This fire spread from the ignition source to neighboring fuels (seats or luggage not directly contacted) is defined as the critical fire spread for train carriage fires [17, 18]. The main mode of this critical fire spread is the radiation heat transfer from the ceiling flame and also the vertical flame. The critical fire spread strongly depends on the fuels adjacent to the ignition source, such as luggage and combustible wall linings. Only if the initial heat release rate reached a certain level, could the spread to the neighboring targets occur. A minimum heat release rate for this critical fire spread was estimated to be in the range of 2 MW to 3 MW for train carriage fires [17, 18]. The critical fire size, the combustible wall linings and the luggage are necessary for the fire to spread in the carriages investigated [17]. After the critical initial fire spread occurred, the fire is mostly able to spread easily along the carriage [17, 18].

From the safety point of view, it could be assumed in most engineering applications that the critical initial fire spread occurs and the train carriage fire finally becomes fully developed, especially while lacking of information. This is, therefore, defined as the typical fire scenarios for the train carriages discussed in this paper.

3.2. Design Fire Curves

Ingason [19–21] carried out a series of study on the method of design fire curves and found a convenient way to describe the design fire curve for tunnels with simple mathematical expressions, which makes the design fire process much more simple, flexible and reliable. The main findings and methods are summarized here.The heat release rate of a fire curve can simply be expressed as follows:

$$Q(t) = Q_{\max} nr(1 - e^{-kt})^{n-1} e^{-kt} \tag{1}$$

where $k = \frac{Q_{\max} r}{E_{tot}}$ and $r = \left(1 - \frac{1}{n}\right)^{1-n}$ where the transient heat release rate is $Q(t)$ (kW), the maximum heat release rate $Q_{\max}$ (kW), the total energy content E_{tot} (kJ), the time after ignition t (s), the retard index n, the amplitude r and the time width k (s^{-1}).The time to maximum heat release rate after ignition, $t_{\max}$ (s), can be expressed in the following form:

$$t_{\max} = \frac{\ln(n)}{k} \tag{2}$$

The above two equations are enough for a design fire, however, Equation (2) needs an iterative calculation. Instead of using Equation (2), the retard index, n, could be approximately estimated using the following equation:

$$n \approx 0.74294 e^{(2.9 Q_{\max} t_{\max} / E_{tot})} \tag{3}$$

More detailed information about this method can be found in the literature [19–21].

Note that Equation (3) is only an appxoimate solution of parameter n. Therefore, Equation (2) should always be checked after one estimation. For large values of n or t_{max}, large errors could be introduced. In such cases, only Equation (2) should be used.This design fire curve method could be employed to one single train carriage or several train carriages. Alternatively, one train carriage could be divided into several sections after which the superposition method can easily be applied. The choice of the methods depends on the information available.

This set of equations provides a very simple and flexible way to construct a design fire curve for a specific train carriage. Despite this, the key parameters including the maximum heat release rate, the time to maximum heat release rate after ignition, and the energy content need to be provided as inputs, which will be discussed in detail in the following.

3.3. Maximum Heat Release Rate

A fully developed train carriage fire is assumed, as discussed previously. Li et al. [17, 18] investigated the correlations between different scales of metro carriage fire tests in the framework of the METRO project, and proposed a simple theoretical model to estimate the maximum heat release rate for a fully developed metro carriage fire, which has been proved to be able to correlate all the test data in different scales very well. The maximum heat release rate in a carriage fire is mainly related to the type and configuration of the fuels, effective heat of combustion, heat of pyrolysis and the openings. The maximum heat release rate for a fully developed carriage fire, Q_{max} (MW), is expressed as [17, 18]:

$$Q_{\max} = \sum_i \min\left(1.85\dot{m}_a \frac{\chi_{r,i}\Delta H_{c,i}}{L_{p,i}}, \dot{m}''_{f,i}A_i\Delta H_{c,i}\right) \tag{4}$$

where the fraction of heat absorbed by the ith surface, $\chi_{r,i}$, in the above equation is defined as [17, 18]:

$$\chi_{r,i} = \chi_r \frac{A_i}{A_t} \tag{5}$$

and the maximum possible mass flow rate through openings [17, 18]:

$$\dot{m}_a = 0.5\sum_i A_{o,i}H_{o,i}^{1/2} \tag{6}$$

where $A_{o,i}$ and $H_{o,i}$ are the area (m^2) and height (m) of the ith opening respectively. χ_r is the fraction of heat absorbed by the fuel surfaces in the total energy released inside the carriage, which has been found to be 0.23 for train carriages. $\chi_{r,i}$ is the fraction of heat absorbed by the ith fuel surfaces A_i, $\dot{m}_a$ is the maximum mass flow rate through opening (kg/s), $\dot{m}''_{f,i}$ is the fuel mass burning rate for the ith fuel surface (kg·m^2/s), ΔH_c is the heat of combustion (MJ/kg), L_p is heat of pyrolysis (MJ/kg), A_i is the ith surface area and A_t is the total surface areas exposed to the internal flame and it is the sum of the individual surface area A_i. The total surface area includes all exposed fuel surfaces and interior wall surfaces. The physical meaning of $\chi_{r,i}$ is the fraction of the heat from the combustion flame inside the carriage that is absorbed by the ith fuel surface. The fraction of heat absorbed by the ith fuel surfaces could be zero at some location where no fuel is available, e.g. a wall fully covered by insulating materials.Note that based on the term on the right hand side of Equation (4), the heat release rate per unit fuel area (HRRPUA) for the *i*th fuel can be defined as:

$$HRRPUA = \dot{m}''_{f,i} \Delta H_{c,i} \tag{7}$$

In estimation of the maximum heat releases rate for one specific fuel, the exposed heat flux generally needs to be pre-determined. Note that in fully developed carriage fires, the maximum gas temperature is normally in a range of 800°C to 1000°C, corresponding to an incident radiation heat flux of around 75 kW/m^2 to 150 kW/m^2. The value of 75 kW/m^2 could be used as an average effective value for all the exposed fuel surfaces, which is also partly due to that data corresponding to this heat flux can be easily obtained from cone calorimeter tests. In case of lack of information, the values of HRRPUA for different fuel types proposed by Ingason et al. [1] could be used.

The availability of doors and windows is a key parameter for design fires. The windows could break up while exposed to high heat intensity. Windows breakage due to fires has been studied by many researchers [22–25]. These studies suggest that the failure of the glazing doors and windows depends on many factors including glazing material (including different types of glass and polymer materials and different construction or treatments such as lamination and tempering/toughening), glazing thickness and surface area, glass defects (particularly micro cracks that are influenced by edge treatment) and edge frame material. The failure of a modern tempered glass used in a train carriage could be expected to occur after exposure to a gas temperature over 600°C, or an incident heat flux over 40 kW/m^2. The values could be lower for some windows. While lacking of information in design fires for carriages, the windows and doors can be assumed to fail after being exposed to such high temperatures. The effect of window breakage is accounted for by Equation (6).

3.4. Time to Maximum Heat Release Rate

The time to maximum heat release rate after ignition indicates how fast the fire grows up, that is, how fast the fire spreads along the carriage. The time to maximum heat release rate differs significantly from one scenario to another, see Table 1. The time to maximum heat release rate can be expected to be sensitive to type, location and size of the ignition source and fuels, and geometry of the carriage. This parameter could be determined from the full scale test data.

According to the full scale tests data shown in Table 1, the time to maximum heat release rate is in a range of 7 min to 120 min. The time to maximum heat release rate in the metro test in EUREKA 499 programme is much shorter since the aluminium roof was burnt down completely during the tests. This test data is excluded, assuming that the carriage body of interest is made of steel or similar material that will not be burn down during a fire. The time to maximum heat release rate is mainly in a range of 15 min to 120 min for train carriage fires in those tests. The full scale metro carriage tests in Brunsberg tunnel recently carried out by SP indicates that the time to maximum heat release rate is approximately

13 min and the fire curve in the growth period could be represented using the *t* squared ultra fast curve although it could tend to be conservative. Note that the ignition source corresponded to that commonly used in an arson fire, which resulted in rapid increase in the growth period. In summary, the time to maximum heat release rate could be chosen as 15 min for this type of train carriage fires, to be slightly on the safe side, while lacking of information.

Information about the fire spread in carriages can also be used in estimation of the time to maximum heat release rate. Li et al.'s work [17] shows that the fires in the Brunsberg tunnel tests in the METRO project behaved as traveling fires after the critical fire spread occurred. In other words, the fire travelled along the carriage at a quite constant speed. The flame spread rate along the carriage is around 1.5 to 2 m/min. Use of this information for estimation of time to maximum heat release rate in the design fire will be shown in the engineering applications in Sect. 4.

3.5. Energy Content

The total energy content of the fuels determines the duration of a fire, and is also correlated with the maximum heat release rate. The fuels in carriages mainly consist of seats, wall linings, floor linings, ceiling linings and luggage. After a summation of the fuels inside the carriage, the total energy content can be easily obtained.

3.6. Luggage

The luggage in the carriages should be considered in estimation of maximum heat release rate and energy content. In the framework of the METRO project, a field study was conducted to investigate the carried fuel load in the Stockholm metro lines and also on the commuter trains, and lab sample tests were thereafter carried out [26, 27]. The results showed that in the metro carriages approximately 82% of the passengers carried luggage, and the average weight of each carried piece constituting a fire load in a metro carriage was around 4.2 kg. The luggage ranged from small bags to pram, with each producing a heat release rate of 100 kW to 850 kW. On average two prams were brought per carriage set during 75% of the studied time (rush hours and daytime). Further, it was found that 28% of the passengers asked carried some sort of pressurized cans, like hairspray or other cans, mostly pressurized with flammable gas, which could significantly increase the heat release rate. In case of a fire, it is difficult to estimate how many passengers will leave their luggage. However, we may expect that the passengers carrying suitcases, large rucksacks and other heavy bags may have to discard their luggage during evacuation. Lab sample tests show that the heat of combustion for the luggage varies from 17 MJ/kg to 35 MJ/kg. The heat output for each luggage on average could be assumed to be in a range of 150 to 250 kW. As a rough estimation, we may assume that 82% of the passengers carry some sorts of luggage and 50% of them will abandon their luggage in case of a fire. The average heat release rate for each luggage could be assumed to be 200 kW and an average heat of combustion of 25 MJ/kg could be used in estimation of the energy content.

4. Engineering Applications

Several examples of using the methodology proposed above for design fires in different carriages are presented. From the safety point of view, it is assumed that in all the examples discussed below, the critical fire spread occurs and the carriage fire finally becomes fully developed. Therefore, Equation (4) can be used to estimate the maximum heat release rate and also the information about fire spread rate can be used to estimate the time to maximum heat release rate.

4.1. Metro Train Carriage

Here we try to construct the fire curve in the METRO test 3. Based on the data obtained from the METRO test 3, the maximum heat release rate is 77 MW and the time to maximum heat release rate is around 118 min. From the fuel load, the energy content is estimated to be 60 GJ. The design fire for the METRO test 3 can therefore be constructed using Equation (1) and the result is shown in Figure 3. Note that the average time to maximum heat release rate of 121 min is used rather than the realistic time to maximum heat release rate for better correlation. It should be pointed out that a metro carriage fire could develop much more rapidly, however, in the METRO test 3, the fire development was delayed for around 107 min due to the aluminium lining. It can be seen from Figure 3 that the estimated fire curve correlates very well with the measured fire curve. The maximum heat release rate could also be estimated using Equation (4) and similar results can be obtained [17, 18]. The use of Equation (4) is explained in Sect. 3.3. It requires a detailed analysis of the fuels and their configurations, and the openings of the carriage. The fuel parameters including average burning rate under an estimated heat flux, heat of combustion and heat of pyrolysis need to be known. Detailed calculations of the heat release rates in the METRO tests and some other tests can be found in the literature [17, 18]. At the beginning of the fire, a heat release rate of 1 MW is added as the output from the initial ignition source and

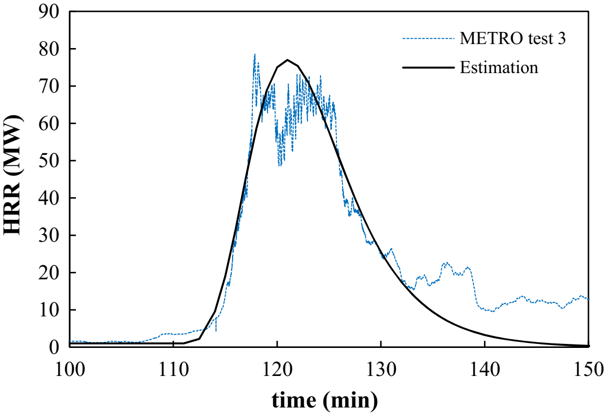

Figure 3. Design fire for the METRO Test 3.

limited fuels nearby. Note that a heat release rate of around 2 MW to 3 MW was identified as the critical condition for rapid fire spread and sharp increase in the fire curve for carriage fires [17]. The initial fire stage before reaching this critical heat release rate could be expressed using the t-squared fire and the growth rates could be found in the literature [28].

4.2. Double-Deck Train Carriage

A double deck modern train carriage is 25 m long and 4.5 m high. In these types of train carriages, the fire is normally ventilation controlled as large amounts of fuels are available. In design fire, the ignition source should be assumed to be in the lower deck rather than in the upper deck as the lower deck case is worse from the point of view of both fire development and evacuation. The energy content is assumed to be 50 GJ in the lower deck and 30 GJ in the upper deck. The maximum heat release rate can be estimated using Equations (4) to (6) based on information about geometry and fuels for a specific train carriage. The maximum heat release rate for a typical intercity train could be estimated to be, e.g. 45 MW for the lower deck and 25 MW for the upper deck, using Equations (4) to (6). These parameters are highly dependent on the fuels and openings for a specific carriage. A detailed analysis of the fuels and openings needs to be carried out as depicted in Sect. 4.1. The time to maximum heat release rate is estimated to be approximately 15 min for the lower deck, which, as discussed previously, could be used as the time to maximum heat release rate for one single carriage. The time to maximum heat release rate for the upper deck depends on how fast the fire spreads to the upper deck. Given that in most cases the combustible materials outside the carriage are quite limited, the fire could spread to the upper deck only if the fire in the lower deck increases to a certain level, that is, significant external flame exists or ceiling flame in the lower deck extends to the upper deck along the staircases. In both cases, the average gas temperature in the lower deck should reach approximately 600°C (indicating window breakage and local flashover

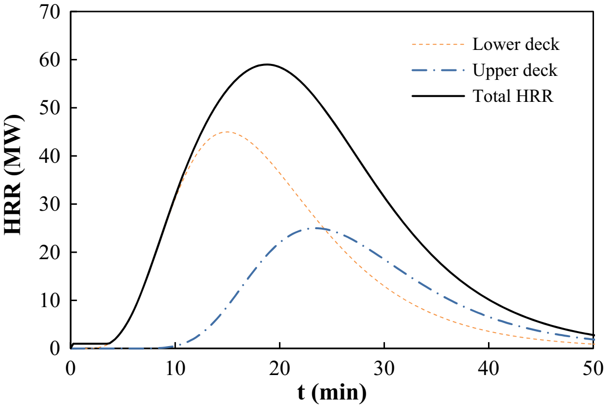

Figure 4. The design fire for a double-deck train carriage.

[17, 18]). Meanwhile, the heat release rate in the lower deck should be of a significantly large value, which could be estimated to be approximately 50% of the maximum heat release rate for the lower deck based on analysis of carriage fire tests with significant external flames from openings. At first the design fire curve for the lower deck is plotted (see Figure 4), based on which the starting time for the fire spread to the upper deck can be estimated to be approximately 8.5 min corresponding to 50% of the maximum heat release rate in the lower deck. Therefore the time to maximum heat release rate for the upper deck could be estimated to be 23.5 min (plus 15 min).

Figure 4 shows the design fire curve for the double deck train carriage constructed using Equation (1). The total maximum heat release rate is 60 MW at 18.8 min. At the beginning of the fire, a heat release rate of 1 MW is also added as the output from the initial ignition source and limited fuels nearby.

4.3. Tram Carriage

A modern tram carriage consists of 6 sections with each having a length of 6 m. Note that a tram fire involves quite limited fuel load and thus it is generally fuel controlled. Equation (4) is used for estimation of the maximum heat release rate for each section of a typical tram carriage. The key parameters for individual sections in a tram are listed in Table 2. For each section, the maximum heat release rate could be estimated to be 12 MW using Equation (4) and the energy content is calculated to be 5 GJ. These parameters are highly dependent on the fuels and openings for a specific carriage. A detailed analysis of the fuels and openings needs to be carried out as depicted in Sect. 4.1. The difference in time to maximum between neighbouring sections depends on the fire spread speed along the carriage. As mentioned earlier, it has been found that for the travelling fires in a similar carriage, the flame spread rate along the carriage is around 1.5 m/min to 2 m/min [17, 18]. Here the value of 2 m/min is selected for safety reasons. Therefore the difference in the time to maximum heat release rate between the two neighbouring sections can be estimated to be 3 min. The key parameter left is the time to maximum heat release rate for the first section. This time is chosen to be around 10 min to assure that the heat release rate approximately reaches the maximum heat release rate level at around 15 min.

Table 2
A Summary of Key Parameters for Individual Sections in a Tram

Section no.	Energy content, E (GJ)	Maximum HRR, Q_{max} (MW)	Time to maximum HRR, t_{max} (min)
Section 1	5	12	10
Section 2	5	12	13
Section 3	5	12	16
Section 4	5	12	19
Section 5	5	12	22
Section 6	5	12	25
Sum	30	28	20.3

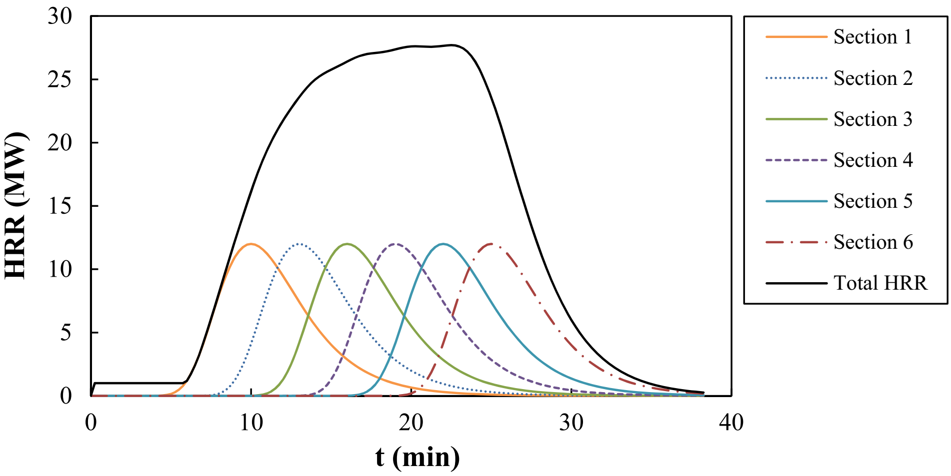

Figure 5. The design fire for a tram.

Figure 5 shows the design fire for the tram constructed using Equation (1). The total maximum heat release rate is 28 MW at 20.3 min. At the beginning of the fire, a heat release rate of 1 MW is also added as the output from the initial ignition source and limited fuels nearby. It also shows that after around 15 min the design fire reaches a plateau, that is, the heat release rate reaches 25 MW and keeps at this level for around 10 min. This indicates that an extended carriage length has limited influence on the design fire, that is, the maximum heat release rate for a longer carriage with limited fuels distributed inside is approximately the same. We can also compare the design fire curve obtained in Figure 5 to the standard *t*-squared curve and it can be found that the design fire approximately follows the fast curve before the plateau (25 MW). Note that the choice of the time to maximum heat release rate for the first section only affects the time to total heat release rate but not affect the total heat release rate and the shape of the design fire curve.

The above applications show the capability and flexibility of the methodology to construct design fires for different carriages. It should, however, be kept in mind that the design fires obtained are only suitable for the specific carriages in the design scenarios defined above, rather than for all carriages of the same type or all scenarios, although they can indeed serve as references. For other carriages and other scenarios, the method proposed can be used to construct their own design fires, based on the information obtained and some reasonable assumptions. The above examples are therefore mainly used for illustration purposes.

5. Conclusion

A new methodology of design fires for individual carriages is proposed for performance-based tunnel fire safety design. The design fire curve method with a simple mathematical expression provides a convenient and flexible way for design fires. The three key parameters required for construction of a design fire are the maximum heat release rate, time to maximum heat release rate, and energy content. The design fire curve method could be employed to one single train carriage or several carriages. Alternatively one carriage could be divided into several individual sections and this method could be considered as a better solution. The choice of the methods depends on the information available.

Based on the severity of a possible fire and the targeted safety level, typical fire scenarios can be defined for a specific carriage or tunnel. The key parameters related include ignition source, fuels available and geometry of the carriage. From the safety point of view, it could be assumed in most engineering applications that the critical initial fire spread occurs and the train carriage fire finally becomes fully developed, especially while lacking of information.

The accuracy of design fires strongly depends on how well the knowledge about fire development in carriages is known. A simple equation for the maximum heat release rates in fully developed train carriage fires, Equation (4), is introduced. It can easily be used to estimate the maximum heat release rate for the whole carriage or each section of the carriage. This parameter is a key to the design fire. Further, the energy content can be easily estimated based on lab test data or data from literature. The last parameter needed to determine is the time to maximum heat release rate, which differs significantly from one scenario to another. The time to maximum heat release rate could be determined from a full scale test similar to the specific design scenario if available. In most cases, a conservative value of around 15 min could be chosen for the time to maximum heat release rate or the time to the plateau of a design fire curve. The flame spread speed along the carriage can be used to estimate the difference in time to maximum between neighbouring sections or carriages. The design fire curve method, Equation (1) together with Equation (4), could be used to construct design fire curves for any fully developed carriage fires.

To illustrate the use of this methodology, three engineering applications are presented, including design fires for a metro train carriage with a maximum heat release rate of 77 MW, a double-deck railway train carriage with a maximum heat release rate of 60 MW and a tram carriage with a maximum heat release rate of 28 MW. The estimated fire curve for the METRO test 3 correlates very well with the measured heat release rate curve.

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