

WHEN A PASSENGER TRAIN BURNS, HOW BIG IS THE FIRE?

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ABSTRACT

Fire safety design of rail vehicles and infrastructure such as tunnels requires development of design fires for scenarios of full carriage involvement, or especially in the case of tunnels, the possible involvement of multiple carriages. Despite the apparent importance of having an accurate estimate of the size of fires likely to occur in trains, there do not appear to be any consistently sound methods of determining likely fire sizes. In this paper, the authors review a number of approaches that have been used over the years, both experimental and computer modelling. Whilst mathematical modelling will play an increasingly important part in the design of both trains and tunnels, the lack of experimental data on post-flashover fires in trains against which models can be calibrated is a matter of concern. Computer modelling needs reliable data, which can only be obtained experimentally.

INTRODUCTION

In recent years there has been a worldwide increase in the number of metropolitan rail systems. In Asia we have seen the arrival of new rapid transit, or 'metro', systems in New Delhi, Nanjing, Bangkok and Kuala Lumpur, the expansion of existing metro systems in Hong Kong, Beijing and Seoul, and we are seeing new systems being planned or installed in Xian, Bangalore, Hanoi and Mumbai. We have also seen, unfortunately, disasters in tunnels such as Baku in 1995 and Daegu in 2003.

These rapid transit systems differ from the older urban rail networks in a number of ways; most significantly they contain significant underground sections. The fire safety issues are therefore twofold. The primary concern is the safety of passengers. A secondary concern is the impact of the fire on the tunnel structure.

In an above-ground rail system, the safe evacuation of passengers from a burning rail passenger saloon is primarily controlled by the design of the saloon, and the flammability and arrangement of the materials in the saloon. In an underground rail system, the safe evacuation of passengers is controlled primarily by factors associated with the tunnel. 'Safe evacuation', in this case, means escape from the tunnel system, or into a place of refuge.

To achieve fire safety we need to have a good understanding of the nature of fires in trains, in both above-ground and underground systems. At this stage, our knowledge in these areas is sadly lacking. Why is this so? The main reasons are:

- we are still assessing the flammability of the individual materials in a saloon rather than the flammability of the saloon,
- in some jurisdictions we are addressing the fire safety of new rail systems project by project, rather than establishing general guidelines,
- we are designing tunnels and their emergency ventilation systems not knowing how big a train fire really is.

This paper summarises current knowledge and practices in this area, and look at ways of answering the question: ‘When a passenger train burns, how big is the fire?’

CURRENT REGULATIONS AND STANDARDS

Currently, it is not unusual for fire safety in passenger vehicles and design fires for tunnels to be dealt with separately. Even when a connection is made between the two, the calculation methods used may be suspect, and there is often an unfounded assumption regarding the maximum of cars that will be involved in a fire. Very often regulations, and the standards they reference, treat the tunnel and the train as two separate entities. Whilst progress is being made in this area, there is still a long way to go.

Regulations for underground rail systems

Usually, the regulations for underground trains concentrate on containing the effects of a fire. Whilst there are controls on individual materials in some, perhaps many, rail systems, there are no requirements to limit total fire size, or even to determine accurately what size a train fire might be.

In Japan, for example, the regulations focus on having “adequate” ventilation in underground rail systems, a requirement that needs a knowledge of fire size. The controls on linings in passenger saloons are, however, not stringent¹.

In Hong Kong, safety committees oversee the development of each new rail tunnel project, whilst rail operators are mainly responsible for applying the requirements for fire properties of materials used in the passenger vehicles. This does allow for some feedback between likely fire sizes in trains and design fire sizes for tunnels, although there is no validation required on the prediction of likely fire sizes.

In Australia, there are no regulations for controlling fire growth on trains in tunnels.

Standards for rail passenger vehicles

There are a number of types of specifications and guidelines applicable to fire safety in rail passenger vehicles in tunnels, for example:

- some provide controls on individual materials and/or components in passenger saloons;
- some provide controls on fire growth in a passenger compartment; and
- some address issues external to the vehicle, such as ensuring adequate ventilation in a station or tunnel in the event of a train fire.

Some individual standards or sets of standards may contain provisions for all of these aspects of fire safety. For instance, NFPA 130, “Standard for Fixed Guideway Transit and Passenger Rail Systems”² provides a set of rules on design of emergency ventilation systems to ensure that passengers and crew can safely evacuate to a point of safety. Whilst the heat release rate of a saloon fire is needed for the design of these systems, NFPA 130 does not specify a method for determining fire size. It does contain a method for determining ‘fire load density’, but as this does not contain a rate factor, it cannot be used to estimate fire size.

The British standard, BS 6853, “Code of practice for fire precautions in the design and construction of passenger carrying trains”³, is used in many parts of Asia. It contains requirements for all individual components in both the interior and on the exterior of a passenger saloon, and links the requirements to the train ‘category’, i.e., whether it is for use above-ground; underground in a single-tunnel; or underground in a double-tunnel. It does not contain requirements for total fire size.

In Europe, CEN is progressing towards a suite of rail fire safety standards, EN 45545, “Railway applications. Fire protection on railway vehicles”⁴. These standards cover many aspects of rail fire safety, but do not provide a means to predict fire size.

SOME EXPERIMENTS

There have been a number of large- and full-scale experiments on rail passenger vehicles in the last few years. Most often the information of interest related to rates of fire growth within a compartment, and hence escape times of passengers.

EUREKA project

Nine European nations combined to run the EUREKA project between 1990 and 1992⁵. In this project various vehicles, including railway passenger saloons were burnt in a tunnel to obtain information related to safety and fire size for both intercity carriages and metro carriages. The railway carriages burnt were stripped of internal fittings and seats so that the influence of linings could be seen. Fire sizes for the metro carriages were calculated by a number of researchers using various techniques. The results ranged from 15-20 MW⁶ and 24⁷ to 35⁸.

FIRESTARR project

The need for large-scale or real-scale experiments has been acknowledged in the European FIRESTARR project⁹, funded by the European Commission. The FIRESTARR Project is part of a program for preparing a seven part European Standard for fire protection on railway vehicles (prEN 45545). One of the main objectives of the FIRESTARR Project is:

To propose a classification system for a range of railway products and to validate these proposals with real-scale tests on parts of European trains.

The ‘Real-scale tests’ were conducted inside a 9 m³ compartment inside a passenger rail vehicle, and do not include any attempt to estimate total fire size.

FRA project

NIST conducted a major research program on fires in trains on behalf of the US Federal Railroad Administration (FRA). The aim of the program was to demonstrate the efficacy of heat release rate-based test methods in conjunction with hazard analysis techniques in assessing fire safety in passenger trains. The program culminated in a series of full-scale experiments¹⁰. The passenger car used was an inter-city car 26 m in length. As the purpose of the program was to assess risk to passengers rather than fire size, none of the fires was let go to flashover, and hence no estimate of fire size was attempted. In addition, NIST found that the impact of passenger belongings had a significant effect on fire growth and maximum fire size due to the synergistic relationships between these “imported” fuels and those that comprise the saloon’s furnishings and linings. However, NIST did no detailed studies to quantify this effect.

CSIRO experiments

In conjunction with NSW rail authorities, CSIRO conducted a series of experiments on a mock-up of a portion of a railcar. These experiments demonstrated that the seats alone would not result in a flashover fire, and hence highlighted the need to conduct larger-scale experiments¹¹.

In 2003, CSIRO conducted a full-scale train fire experiment in the open on a typical Australian suburban carriage¹². The objectives of the experiment were to:

- study how a large fire develops and spreads in a typical rail passenger vehicle; and
- study the link between material flammability properties and fire size.

The rail carriage was recovered following a non-fire accident, and many re-usable components had been salvaged prior to it becoming available. Whilst the carriage was fully lined, only 1/3 of the carriage had seats.

Following the experiment, attempts were made to estimate fire size by ‘hindcasting’ with FDS. Although an approximate fire size of 9-10 MW was estimated, difficulties were found in matching predicted temperatures with those measured. This was believed to be due to inaccuracies associated with input data on material properties that had been measured in the cone calorimeter, and uncertainties related to the collapse of lining materials during the actual fire.

Other experiments

There have been other large-scale experiments in train carriages, none of which included measurements of heat release, such as the Japan National Rail (JNR) experiments in 1972¹³; the Japanese Railway Bureau experiments in 1992¹⁴; and the Korean Railroad Research Institute (KRRI) experiments in 2004¹⁵.

The JNR experiments were notable for two reasons:

- the fire was lit in a carriage that was part of a complete train set, thus allowing for the possibility of spread beyond the saloon of origin; and
- the train was set in motion once the fire was established.

This makes it one of the most complete train fire experiments ever performed. Unfortunately, techniques for measuring heat release had not then been developed.

FIRE SIZE ESTIMATION METHODS

In all compartments, including rail passenger vehicles, fire growth and fully developed fire behaviour are controlled by:

- ignition source properties;
- material properties;
- vehicle configuration; and
- ventilation

These factors, particularly materials and configuration, are significantly different for trains than for buildings.

Average heat release rate method

One of the earliest and simplest methods applied to estimate design fires for large fire scenarios where the fire spreads to involve the entire vehicle interior is the average heat release rate method¹⁶. This method sums the total fuel load of the interior material for the vehicle and divides it by assumed burn time eg.

$$\dot{Q}_{\text{ave}} \text{ (MW)} = \frac{\text{Total Fuel Load (MJ)}}{\text{Burn Duration (s)}} \quad [1]$$

This method assumes a constant fire size over the duration of the burn. The fuel load is often calculated from heat of combustion (MJ/kg) values for materials taken from literature or determined using a bomb calorimeter.

This method was first developed in 1975, and assumed burn times of the order of 1 hour. This was based on the observations of two Montreal subway fires, in 1971 and 1974. This approach was used when designing ventilation system for rail tunnels in Atlanta, Baltimore, Hong Kong and Pittsburgh. Following a more severe fire incident, with a shorter burning time, on the Bay Area Rapid Transit (BART) system in California in 1979, a burn duration of 20 minutes was used when designing the Los Angeles, Philadelphia and Atlanta systems.

With the introduction of NFPA 130² in 1983, it was expected that material fire performance would improve. Although the effect of NFPA 130 on burn times could not be quantified, the assumed burn time was increased from 20 minutes to about 30 minutes, and was used for the design of the Seattle, Shanghai, Singapore and Taipei transit systems.

The average heat release rate method does not produce a realistic design fire for the following reasons:

- the growth and decay phases of the fire are neglected;
- the average heat release rate is dependent on an arbitrary burn time;
- it is assumed that all materials burn to completion;
- material properties, configuration and ventilation are neglected; and
- the true peak heat release rate will be greater than the estimated average heat release rate.

Summation of heat release rates of individual materials

A method for estimating nominal fire sizes that uses the measured time-dependent heat release rate *per unit area* of each material has been proposed¹⁷. The purpose was to allow trade-offs between materials in saloons whilst limiting the overall flammability. There was no intention of using it to calculate design fires for tunnel design.

In this method, the time-dependent heat release rate *per unit area* of each surface material is measured in the cone calorimeter at the following irradiances:

- horizontal prone (ceiling-like) 50 kW/m²
- vertical (wall-like) 35 kW/m²
- horizontal supine (floor-like) 25 kW/m²

This data is multiplied by the exposed surface area to produce a theoretical heat release rate curve. The heat release rate curves for all materials are then summed to give a total heat release rate curve for the train interior. This calculation is summarised as follows:

$$\dot{Q}_{(t)} = \sum \left(\frac{A_i \dot{q}_{i(t)}''}{1000} \right) \quad [2]$$

where $\dot{Q}_{(t)}$ = time-dependent total heat release rate, MW; A_i = exposed area of material i , m²; and $\dot{q}_{i(t)}''$ = time-dependent heat release rate *per unit area* of material i measured in the Cone Calorimeter, kW/m².

The total heat release rate curve is smoothed using a 20-30 s running average to merge peaks which are close together. This smoothing is used to overcome apparent difficulties in having materials that are adjacent in the carriage reach their peak heat release rates at different times.

Assumptions implicit in this method are:

- the fire size in a saloon can be predicted by the summation of heat release rate data for individual materials;
- each material ignites instantaneously across its entire surface;
- each material ignites independently of adjacent materials;
- there is no ventilation control at any stage; and
- there is constant external heat flux on each material.

This method is held to be superior to the average heat release rate method. However, it has been shown experimentally that the method does not predict realistic fire sizes¹⁸. At best it is only useful for comparing alternative materials or differing surface areas.

A modification of this method attempts to consider fire spread along the train interior¹⁹. In this method it is assumed that ignition of sections of each material occurs at an arbitrarily chosen rate, for instance 10% per minute. The calculation, which is essentially the same as described above, is illustrated in equations [3] and [4].

$$\dot{Q}_m = \frac{A}{600} \int_0^t \dot{q}''(t - \tau) d\tau = \frac{A}{600} \int_0^t \dot{q}''(\tau) d\tau \quad \text{for } t \text{ (time)} < 600 \text{ s} \quad [3]$$

or

$$\dot{Q}_m = \frac{A}{600} \int_0^{600} \dot{q}''(t - \tau) d\tau = \frac{A}{600} \int_{600-t}^t \dot{q}''(\tau) d\tau \quad \text{for } t \text{ (time)} > 600 \text{ s} \quad [4]$$

where \dot{Q}_m is the contribution to the fire size of one material of area A .

This is like a moving average method, and takes 600 s to involve the entire surface. Apart from the staggered ignition, the assumptions are the same as above. Full-scale experiments have shown that fire spread along the interior of a carriage after flashover is much more rapid than 10% per minute¹². This method does not produce a valid estimate of fire size.

Despite this lack of validity, both of these summation methods have been applied in the design of rail vehicles in Australia, Hong Kong and elsewhere.

Fire modelling methods

Engineering practitioners, including fire engineers, are responsible for the design of specific rail tunnels. Therefore detailed information on how design fires are selected is not necessarily available in the open literature.

There are many reasons for modelling fire growth in train saloons. Sometimes it is to estimate escape times²⁰, sometimes to assess ventilation systems²¹, and sometimes to assess the structural stability of the tunnel²². Methods for estimating escape time model pre-flashover fires, and fire size is of no interest. Methods for assessing ventilation and structural integrity of the tunnel model post-flashover fires, and fire size is critical.

Probably the first computer fire model used in estimating fire sizes for use in tunnel design was COMPF2²³, the first post-flashover fire model. In 1991 COMPF2 was used, in conjunction with assumed additional data for floor and below floor combustibles, to develop design fires in which all the interior materials were assumed to have the properties of polycarbonate^{16,24}. The design fires

produced had peak fire sizes of 18 MW for one carriage, and 23 MW for two carriages burning at the same time, but not ignited together.

More recently, Lattimer and Beyler ²⁵ presented a model that used generic material data from the literature. Depending on ventilation conditions, they predicted fire sizes of 19-41 MW. Results from the model were compared with published data for compartment fires. The authors concluded that difference between predicted and experimentally measured trends could be due to the window fallout, or melting in the case of polycarbonate, and the resultant changes in ventilation. They noted that ventilation and opening sizes greatly influence the peak fire size and recommend that further work, experimental and modelling, on window breakage and fallout for glazing, or softening in the case of polycarbonate windows, is required.

ESTIMATES OF FIRE SIZE

Some estimates of fire size are given in Table 1. Whilst the carriages these figures were estimated for vary a lot in detail, they are all elongated metal square cylinders with potential openings provided by a limited number of doors, and rows of windows.

SUMMARY

Currently the design, specification and construction of tunnels and of trains are treated independently. Whilst a tunnel design might be based on an assumed fire size, there is no way of confirming that a burning train will not exceed that design fire size. This is a critical issue when designing for not only the structural integrity of the tunnel, but more importantly, for designing the systems that are needed for safely evacuating passengers.

In all these methods of estimating fire size, there is an assumption about the number of carriages that will be involved. In all the cases reviewed, the fire does not spread beyond a specific number of carriages (usually one) due to the properties of the carriages themselves, not external fire protection systems.

Whilst the ability of the ventilation systems to control smoke in tunnels has been well studied, there does not appear to be any studies of the impact of the tunnel on fire spread along the train.

Many computer fire models have been developed for use in building enclosures, which generally have aspect ratios very different to those in train saloons. These models usually assume flashover occurs at the same time throughout the enclosure. Experiments ^{5,12} have shown that in rail carriages, partial flashover is possible.

Another design aspect ignored is the 'hollow tube' design of many modern metro trains, where there is no fire separation between carriages. Yet, there are metro systems with such open train designs that have been built on the assumption of no fire spread between carriages.

Further work, both experimental and modelling, on window breakage and fallout for glazing is required to clarify the ventilation changes during a fire and the resulting change in fire size.

With fire size being so critical, it is time to reassess the need to conduct more full-scale experiments on complete trains in tunnels so that we can adapt our fire models to more really represent the real world in train fires in tunnels.

With our current technology, perhaps we could even revisit the Japanese experiment on a moving train, this time with heat release measurements.

TABLE 1. Some estimates of fire size in rail carriages

Reference	Method	No of carriages	Location (actual or theoretical)	Fire size, MW	Comments
Kennedy <i>et al</i>	calculation: (fire load/time)	1	underground	15	1 hr burning time assumed (1975)
Kennedy <i>et al</i>	calculation: (fire load/time)	3	underground	29	fire spread to next car at 20 min assumed (1983)
Kennedy <i>et al</i>	calculation: (fire load/time)	2	underground	22	fire spread to next car at 30 min assumed (1989)
Kennedy <i>et al</i>	modelling (post-flashover)	1	underground	18	all materials assumed to be polycarbonate COMPF2 (1991a)
Kennedy <i>et al</i>	modelling (post-flashover)	2	underground	23	all materials assumed to be polycarbonate COMPF2; fire spread to next car at 30 min assumed (1991b)
Duggan	calculation: summation of heat release rates	1	na	5	interior surface materials only
Lattimer and Beyler	modelling (post-flashover)	1	underground	19-41	model not experimentally verified for railcar geometry
White <i>et al</i>	experiment plus calculation (FDS with heat release data from cone calorimeter)	1	above-ground	9-10	compartment only 1/3 furnished
	experiment plus calculation (energy balance)	1	above-ground	10-12	compartment only 1/3 furnished
Haack (EUREKA project)	experiment plus calculation	1	underground	15-20	carriages stripped of internal fittings and seats
Steinert (EUREKA project)	experiment plus calculation (enthalpy flows of CO ₂ /CO mass flows)	1	underground	24	carriages stripped of internal fittings and seats
Ingason <i>et al</i> (EUREKA project)	experiment plus calculation	1	underground	35	carriages stripped of internal fittings and seats

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