Modelling Fire Size and Spread in Tunnels

ALAN BEARD, RICHARD CARVEL, and PAUL JOWITT
Civil Engineering Section
School of the Built Environment
Heriot-Watt University
Edinburgh EH14 4AS
Scotland, United Kingdom

ABSTRACT

The heat release rate (HRR) of a fire in a tunnel is a crucial factor, both in terms of fire spread and smoke production. Key factors which influence the HRR are: {1} the nature of the burning item, {2} the tunnel geometry, {3} the ventilation conditions and {4} vehicle separation. This paper reports on work which has been undertaken over a number of years to model the dependence of HRR on these factors; the work is continuing. Specifically, Bayesian probabilistic models have been devised to model the dependence of the HRR of a fire on tunnel geometry and longitudinal forced ventilation and deterministic models have been devised to model fire spread from one item to another in a tunnel similar to the Channel Tunnel; again with longitudinal ventilation. Key interim results are presented.

KEYWORDS: fire, risk, tunnels, heat release rate

INTRODUCTION

Over recent years the issue of fire in transport tunnels has become an important concern, not only for tunnel designers, operators and regulators, but also for the general public. The fires in the St Gotthard Tunnel in Switzerland, the Tauern Tunnel in Austria, the Mont Blanc Tunnel and the Frejus Tunnel joining France to Italy, the Channel Tunnel joining the UK to France and the underground railway in Baku, Azerbaijan have highlighted the issue and shown the devastating effects of such fires in terms of loss of life, damage to facilities and destruction of vehicles.

Even though fatal fires in tunnels are relatively rare and the majority of fires that do occur in tunnels are small, rarely involving more than one vehicle, there is always the need to increase our level of understanding of the behaviour of fires in tunnels. This is because traffic density in tunnels is increasing all the time and tunnel systems are continuing to grow in size, length and complexity.

The heat release rate (HRR) of a fire may be considered to be the principal factor contributing to the severity of a fire. It is dependent on a number of factors including the composition of the fuel, ventilation conditions and the geometry of the tunnel. The size of a fire in a tunnel would be expected to be significantly greater than the size of a similar fire in the open because of the effects of enclosure. That is, there is a dependence upon the geometry of the tunnel. In addition to the tunnel's geometry it is to be expected that the heat release rate of a fire will vary with any forced ventilation velocity in the tunnel. In many tunnels one of the most important parts of fire safety management is control of the ventilation system, the main concern usually being to control the smoke in the event of a fire to such an extent that there is a smoke free escape route from the fire location. Tunnel ventilation systems fall into two main categories; transverse and longitudinal. In

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transversely ventilated tunnels, fresh air is supplied from a duct (either under the roadway or above the ceiling) at periodic points along the length of the tunnel. In some cases the exhaust air is only extracted at one or two points at or near the portals, this is described as "semi-transverse ventilation". In other cases there is a separate duct to extract air at periodic points along the length of the tunnel, this is described as "fully transverse ventilation". In longitudinally ventilated tunnels, air is forced along the tunnel, often by jet fans installed on the ceiling at periodic points along its length. Jet fans are a comparatively recent invention, so older tunnels tend to be transversely ventilated. However, installation of longitudinal ventilation systems tends to cost less than transverse ventilation, so many recently constructed tunnels are equipped with longitudinal ventilation. In the USA the majority of tunnels are transversely ventilated, in the far east the majority are longitudinally ventilated, whereas in Europe both types of system are commonplace.

In tunnels with longitudinal ventilation the concern in the event of a fire is generally to control the smoke so that there is no smoke flow upstream of the fire location, this is in order to prevent "backlayering" or "back-flow." Although it has been shown that the "critical" ventilation velocity required to prevent backlayering varies with fire size and with tunnel shape, an international recommendation is that a fixed ventilation rate of 3 ms^{-1} be maintained in the event of any fire, to prevent the smoke backlayering [1].

Although a number of studies have been carried out to investigate the behaviour of smoke from fires in tunnels under a range of different ventilation conditions, few studies have been carried out to investigate the behaviour of the fires themselves, so the variation of the HRR of a fire in a tunnel with ventilation velocity is not adequately known. In 1976, Heselden estimated the HRR of a heavy goods vehicle (HGV) fire in a tunnel to be approximately 20 MW and this figure has tended to become an accepted value. Some tunnels have been built with a "design fire" of approximately 20 MW in mind (although other tunnels have been designed to withstand fires with HRRs of 50-100 MW). However, the only well documented fire test of a HGV in a tunnel, carried out in a longitudinally ventilated tunnel, exhibited a HRR well in excess of 100 MW [2]. Opinion is divided as to whether the huge difference between these two figures is due to underestimation in the first instance, or the dramatic intensifying effect of the longitudinal ventilation in the experimental results. Further, tests carried out on a 'simulated HGV' in the Runehamar tunnel in Norway found heat release rates in excess of 200 MW; with longitudinal ventilation [3].

In order to assess the risk in vehicle tunnels it is necessary to understand how fires behave in tunnels with longitudinal ventilation systems. Specifically it is important to understand how fires involving vehicles will respond to changes in the ventilation velocity. This is particularly significant as the majority of fire experiments in tunnels have been carried out with fuel pools rather than with solid fuels or actual vehicles, and while test series like the Memorial Tunnel Fire Ventilation Test Program have greatly increased the level of understanding of smoke behaviour in tunnels with different ventilation configurations, they reveal nothing about how vehicle fires will respond to forced ventilation. The mechanism of burning of a fuel pool is very different to a solid fuel. For a vehicle fire or a wooden crib fire, for example, forced ventilation may blow *through* the fire load, causing the fire to spread and grow in intensity in a very different manner than if there were no forced ventilation. It is not the same for a pool fire where all the combustion occurs at (or above) the surface, not inside the load. That is not to say that the influence of longitudinal ventilation on a pool fire is not important or significant, just that it is different to the influence of ventilation on a vehicle fire. Pool fires have been considered in a separate part of this study and the results have been published elsewhere [4].

There have been very few fire tests of real vehicles in tunnels, and the tests that have been carried out have used a number of different tunnel sizes, vehicle types and ventilation conditions, which give no coherent picture of fire behaviour overall. It would be desirable to use all the experimental data that are available to investigate the relationship between fire size (HRR) and ventilation velocity. There is no way to use such a diverse set of data using conventional statistical analysis, but one method that may be used is to consider the problem probabilistically and use Bayes' Theorem. This has been done as part of this work.

Beyond the influence of tunnel geometry and forced longitudinal ventilation on HRR another crucial issue is associated with the question: "what size does a fire need to be to 'jump' to a neighbouring item, e.g., a vehicle?" This question has been tackled by constructing a deterministic non-linear model to predict the HRR at which an initial fire would be expected to spread to a neighbouring object, given a longitudinal forced ventilation. All three issues are reported on briefly in this paper, i.e.: {1} the dependence of HRR on tunnel geometry, {2} the dependence of HRR on forced longitudinal ventilation and {3} the HRR necessary for fire spread from one item to another, given a longitudinal forced ventilation. This covers a considerable amount of research and there is insufficient space here to go into details. Full details are given in the journal and conference papers referred to and readers who wish to find out more are advised to refer to them.

DEPENDENCE OF FIRE SIZE ON GEOMETRY OF THE TUNNEL

Bayesian methodology has been used, first to determine which geometrical factor most influences HRR, and then to predict the actual variation of HRR with tunnel geometry. By considering the heat release rate (HRR) coefficient ψ, defined by $Q_{tun} = \psi Q_{open}$ (where Q_{tun} is the HRR of a fire in a tunnel with natural ventilation and Q_{open} is the HRR of a similar fire in the open air), "*prior*" estimates of the probability of various hypotheses about ψ may be refined by considering the "*likelihood*" of a set of experimental test results using Bayes' formula. The refined probabilities are known as the "*posterior*" probabilities. These can be refined further by considering the likelihood of additional experimental sets. After several refinements the most plausible hypothesis may be predicted.

Following an extensive literature study it was determined that data from the following naturally ventilated experimental fire tests, carried out in tunnels, were relevant to understanding the interaction between fire size and tunnel geometry; further references are given in reference [5].

- Car, wooden crib, and pool fire tests in the Hammerfest tunnel, Norway
- Car and wooden crib fire tests in a "blasted rock tunnel," Sweden
- Pool fire tests carried out by SP in Sweden
- Medium scale kerosene pool fire tests in a mine roadway tunnel, Londonderry, Australia
- Heptane and methanol pool fire tests in lab-scale wind tunnel, Japan
- Pool fire tests in the Ofenegg tunnel, Austria
- 20 and 50 MW natural ventilation pool fire tests in the Memorial Tunnel, USA

These have been compared to experimental data from the following open air fire tests:

- Three car fire tests carried out at VTT in Finland
- Wooden crib fire test carried out by FOA, Sweden
- A comprehensive study of wooden crib fire tests carried out by Gross, USA
- Lab-scale pool fire tests carried out in Japan
- Pool fire tests carried out by SP in Sweden
- A comprehensive survey of pool fire burning rates presented by Babrauskas

For each tunnel fire experiment, a value of ψ was determined by comparing experimental data from the tunnel fire experiment with experimental data from similar fires in the open air. From an examination of the experimental data it was determined that ψ (and hence fire enhancement) might vary with the following factors:

i. Distance from fire load to ceiling (tunnel height)
ii. Distance from fire load to walls (tunnel width)
iii. Blockage ratio (fire item cross-sectional area/tunnel cross-sectional area)
iv. Mean hydraulic diameter

No other geometrical factor appeared to be significant from the database. A Bayesian methodology was used to systematically test each of these four hypotheses using sets of data from the database. Initially each hypothesis was considered to be equally likely, i.e. $P(H_i) = P(H_{ii}) = P(H_{iii}) = P(H_{iv}) = 0.25$, where H_n represents a hypothesis and $P(H_n)$ is the probability of that hypothesis being true. Each “set” of evidence comprised two or more tunnel fire experiments from the database being considered together; generally within a set there would be fire loads of significantly different blockage ratio in similar tunnels or there would be similar fire loads in different tunnels.

Using all the experiments in the database, a good estimate of the dependence of ψ upon the width of the tunnel and the width of the fire object was found to be:

$$\psi = 24\left(\frac{W_f}{W_t}\right)^3 + 1 \qquad \text{where: } W_f = \text{width of fire object ; } W_t = \text{width of tunnel}$$

This relationship appears to give a very good agreement with the experimental data for all wooden crib, car and pool fires in tunnels except:

i. Fires starved of oxygen
ii. Pool fires involving methanol
iii. Fires in tunnels with concave ceilings
iv. The smallest kerosene pool fire carried out in the Australian mine tunnel (Labelled as ‘Unexplained result’.)

With the exception of the ‘Unexplained result,’ which remains a mystery, these may be interpreted in the following way:

i. The HRR of any fire is highly dependent on the availability of oxygen. If a tunnel restricts the inflow of air, the HRR of a fire will be significantly lower than expected.
ii. Methanol is very different to all the other fuels (heptane, kerosene, wood, cars, etc.) in that it doesn’t produce significant amounts of smoke. As heat transfer from the smoke layer above the fire, both back to the fuel and out to the surrounding

environment, are important factors in determining the HRR of a fire, it is not surprising that ψ is very different for fires that produce significant amounts of smoke and fires that do not.

iii. Concave ceilings appear to enhance HRR by an additional 10%, this may be due to the lens effect of the ceiling geometry "focussing" the re-radiated heat back to the fire location in the centre of the tunnel, or it may be due to the fact that there is more smoke in the centre of the tunnel (above the fire) than nearer the sides.

The overall implication is that, in situations where the airflow is not restricted, the wider the tunnel the better with respect to fire risk. The HRR of a fire in a tunnel, and hence the smoke production rate, will tend to be less in a wide tunnel compared to a narrow one of the same height.

This is not to say that the heat release rate does not depend upon height, a dependence upon height would be expected; however, given the results of the research conducted, the width appears to have a greater effect.

DEPENDENCE OF FIRE SIZE UPON FORCED VENTILATION

To describe the variation of HRR with ventilation velocity, the heat release rate coefficient, k , has been used, defined by: $Q_{vent} = k\ Q_{nat}$ where Q_{vent} is the HRR of a vehicle fire in a tunnel with forced ventilation and Q_{nat} is the HRR of a similar fire in a similar tunnel with natural ventilation. For the purposes of this study it is assumed that "natural" ventilation has a fairly low velocity, this would not necessarily be the case on a windy day or in a tunnel with a significant slope. By considering the coefficient k, rather than the absolute HRR of a fire, factors such as the composition of the vehicle may be bypassed. Thus if $k = 1.5$ for a car fire in a certain tunnel with a 2 ms^{-1} airflow, then a small car, which would be expected to burn at 2 MW in a tunnel with natural ventilation, would be expected to burn at about 3 MW whereas a larger car, which might burn at 5 MW in a naturally ventilated tunnel, would be expected to burn at about 7.5 MW. It should be noted that Q_{nat} for a vehicle fire would probably not be the same as the HRR of a fire involving a similar vehicle carried out under a calorimeter hood in a laboratory; when fires in tunnels are compared to similar fires outside of tunnels a significant enhancement of HRR, due to the confining geometry of the tunnel, is generally observed [6], unless the fire is underventilated, in which case Q_{nat} may be significantly reduced. Vehicles that pass through tunnels come in all shapes and sizes; however experimental fire testing of vehicles in tunnels has not yet covered the whole range of vehicle sizes, so it was decided to consider only passenger cars and HGVs in this study. Pool fires have been considered elsewhere [3].

Results from the HGV case, in the fully developed phase, are given here; for other cases see Ref [7]. A number of experts were asked to estimate values of k at the maximum heat release rate. On average the expectation of the experts was that the HRR would probably be between 2 and 4 times greater for all ventilation velocities considered. The following experimental tests were considered to be relevant to this case:

- EUREKA simulated truck load test in the Hammerfest tunnel (full scale, natural ventilation)
- EUREKA HGV fire test in the Hammerfest tunnel (full scale, forced ventilation)
- FOA wooden crib tests in the "blasted rock tunnel" (reduced scale, natural ventilation)
- Wooden crib test in the HSE tunnel (reduced scale, forced ventilation)

- Simulation of HGV fire in the HSE tunnel (reduced scale, forced ventilation)
- Second Benelux tunnel tests; the Netherlands
- Runehamar tunnel tests, Norway

Although the wooden crib tests carried out in the Hammerfest Tunnel were considered to be relevant to the initial stages of fire development on a HGV, the cribs used were not large enough to give any information of the fire behaviour of a HGV, so these tests have not been used in this part of the study. After consideration of the experimental evidence, posterior estimates for k were found as shown in Fig. 1.

It appears that the higher the ventilation velocity, the larger the fire. For example, at a velocity of forced ventilation of 4 m/s, a HGV fire would be expected to be about 4 times larger in terms of HRR than a similar fire subject to natural ventilation. If there is a HGV fire in a tunnel then a sensible ventilation strategy would be to use the minimum velocity of forced ventilation necessary to control the smoke.

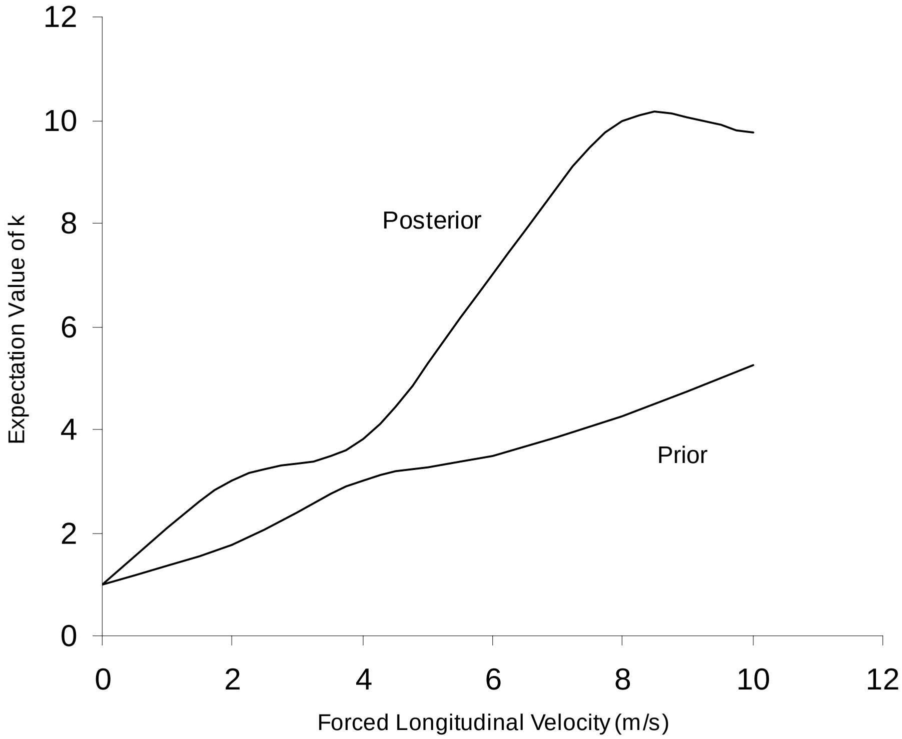

Fig. 1. The expectation value for *k* for a fully involved HGV fire,
as a function of forced ventilation velocity.

FIRE SIZE NECESSARY TO ‘JUMP’ TO A SECOND OBJECT

A different approach was adopted to tackle this issue. A deterministic non-linear model FIRE-SPRINT A3 has been created to calculate the critical HRR necessary for a fire to jump from an initial fire to a second object in a tunnel, given no flame impingement but with longitudinal forced ventilation.

The model assumes that the tunnel has ‘sides’ and ‘ceiling’ which form a partial circle. It is assumed that there is a burning object in the tunnel and that a longitudinal forced ventilation of ambient air pushes smoke to one side of the fire, partially or wholly surrounding a rectangular cuboidal target object. Flame is assumed to extend beyond the downstream edge of the fire and to go over the target object.

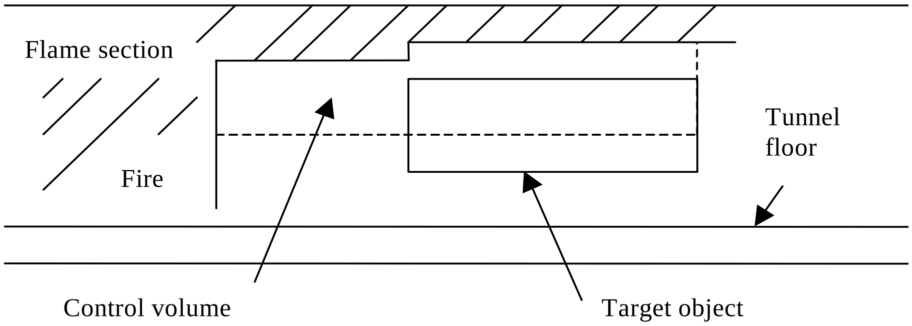

Fig. 2. Simplified diagram illustrating model (forced flow L to R).

A control volume, which hot gases enter and leave, is indicated by the dashed lines. In Fig. 2 a simplified version of the model is illustrated; for full details see references [8,9]. A single state-variable model has been created with the state-variable corresponding to temperature of the gases in the control volume. Equilibrium points have been found for the system and the onset of thermal instability is associated with fire spread from the initial fire to the target object. The illustrative case of fire spread from an initial fire to a HGV in the Channel Tunnel has been considered. A system with one state-variable has one eigenvalue and the onset of instability is given by the point at which the eigenvalue becomes positive. FIRE-SPRINT A3 does not include flame impingement. Although smoke is assumed to move downstream of the initial fire, the model is not necessarily restricted to the case where the longitudinal velocity is less than the critical velocity to prevent backlayering of smoke. This is because of a compensating effect: if some of the smoke were to move upstream then there would be less radiation feedback from the downstream smoke to the fire base. However, there would be an additional radiation contribution from any upstream smoke to the fire base. The model may therefore be regarded as applicable to velocities lower than the critical velocity, although for lower velocities it should probably be regarded as less reliable than for higher velocities.

A second non-linear model, FIRE-SPRINT B1, which assumes flame impingement to take place, has also been created. This is similar to the FIRE-SPRINT A3 model but assumes a small ‘tongue’ of flame to impinge persistently on the target object and involves two control volumes.

Key results are:

{1} The critical rate of heat release for spread from an initial fire to a target HGV is predicted to be approximately between 30 and 40 MW, at a forced ventilation velocity of 2 m/s and separation of 6.45 metres; assuming flame impingement not to exist.

{2} The critical rate of heat release for spread increases with increasing velocity, presumably due to a cooling effect. (NB: The effect of increasing longitudinal forced ventilation on HRR needs to be borne in mind, as described above.)

{3} Assuming flame impingement to exist reduces the calculated critical rate of heat release for spread to about one quarter or one third of the critical HRR found assuming flame impingement not to exist.

CONCLUSION

Research has been undertaken to investigate the dependence of heat release rate in a tunnel on the geometry of the tunnel and on forced longitudinal ventilation; as well as to estimate the heat release rate necessary for spread to a second object.

Tentative results indicate:

{1} For a wide range of fires, which are not oxygen starved and for a given tunnel height, the wider the tunnel the better with respect to fire risk.

{2} For vehicle fires a forced longitudinal ventilation may increase the heat release rate very considerably.

{3} The critical heat release rate necessary for fire to spread from an initial fire to a second object, downstream of the initial fire, increases with the velocity of forced ventilation.

{4} If flame impingement exists then the critical HRR for spread reduces to about one quarter or one third of that assuming no flame impingement to take place.

REFERENCES

[1] Nordmark, A., “Fire & Life Safety for Underground Facilities: Present Status of Fire & Life Safety Principles Related to Underground Facilities,” *Tunnelling & Underground Space Technology*, **13**: 217-269 (1998).

[2] Grant, G.B. and Drysdale, D.D., “Estimating Heat Release Rates From Large Scale Tunnel Fires,” *Proc 5th International Symposium on Fire Safety Science*, Melbourne, Australia, pp. 1213-1224, March 3-7, 1997.

[3] Ingason, H., SP Report 2004:05, *Proceedings of the International Symposium on Catastrophic Tunnel Fires*, *November 20-21, 2003*, 2004.

[4] Carvel, R.O., Beard, A.N., and Jowitt, P.W., “A Bayesian Estimation of the Effect of Forced Ventilation on a Pool Fire in a Tunnel,” *Civil Engineering & Environmental Systems*, **18**: 279-302 (2001).

[5] Carvel, R.O., Beard, A.N., and Jowitt, P.W., “A Method for Making Realistic Estimates of the Heat Release Rate of a Fire in a Tunnel,” ISBN 1 901808 18, *3rd International Conference on Tunnel Fires & Escape from Tunnels*, Washington, DC, October 9-11, 2001, pp. 137-144.

[6] Casale, E. and Marlair, G., “Heptane Fire Tests with Forced Ventilation,” ISBN 91 7848 513 4, *Proceedings of the International Conference on Fires in Tunnels*, Boras, Sweden, October 10-11, 1994, pp. 36-50.

[7] Carvel, R.O., Beard, A.N., Jowitt, P.W., and Drysdale, D.D., "Variation of Heat Release Rate with Forced Longitudinal Ventilation for Vehicle Fires in Tunnels," *Fire Safety Journal*, **36**: 569-596 (2001).

[8] Beard, A.N., "Modelling Spread of Fire in a Tunnel," *Journal of Applied Fire Science*, **10**: 29-40 (2001).

[9] Beard, A.N., "A Model for Predicting Fire Spread in Tunnels," *Journal of Fire Sciences*, **15**: 277-307 (1997).