International Journal on Engineering Performance-Based Fire Codes, Volume 9, Number 3, p.111-117, 2007

AN EXAMINATION OF VEHICLE FIRES ACCORDING TO SCALING RULES

J.C. Jones, T. Noonan and M.C. Riordan
School of Engineering, University of Aberdeen, Aberdeen AB24 3UE, UK

(Received 11 July 2008; Accepted 18 December 2008)

ABSTRACT

Die-cast model vehicles of various scales have been burnt and heat-release rates deduced from temperature measurements. Scaling factors from the models to full size vehicles have been determined.

1. INTRODUCTION

Vehicular fires have been studied in a number of ways [1,2] including the measurement of heat-release rates of whole vehicles ignited in a large calorimeter. Such experiments on motor cars have peak heat-release rates of the order of 3000 kW (3 MW). Equivalent information for other sorts of vehicle – buses, trucks, motor cycles – is fairly scarce.

As the present author has recently pointed out elsewhere [3], such heat-release rates are obviously sufficient for flashover but if the vehicle which is on fire is out of doors there is nothing for it to flash over to. Of course, if the vehicle was in a repair workshop or an enclosed parking area flashover would be possible.

In thermal ignition and indeed many other topics in fire safety, scaling rules from laboratory size to full size have been developed and subsequently used in a predictive way. In this paper we attempt to develop such rules for vehicles by burning scale models and taking temperature measurements. A preliminary note [4] was put out after the earliest results had been obtained. Herein we give a full account of the programme, starting with the related theory.

2. THEORY

Fig. 1, reproduced from [3], is a generalised form of a heat-release history for a burning car from experiments of the type which were described in the previous section. The maximum varies from one sort of car to another and can be as high as 8 MW though most peak in the 2-4 MW range. A value of 3 MW has been chosen as a reference value ('pivot point') in this work.

A maximum heat-release rate of 3 MW for a real vehicle will therefore be used in the scaling from model cars to real cars according to the theory which follows.

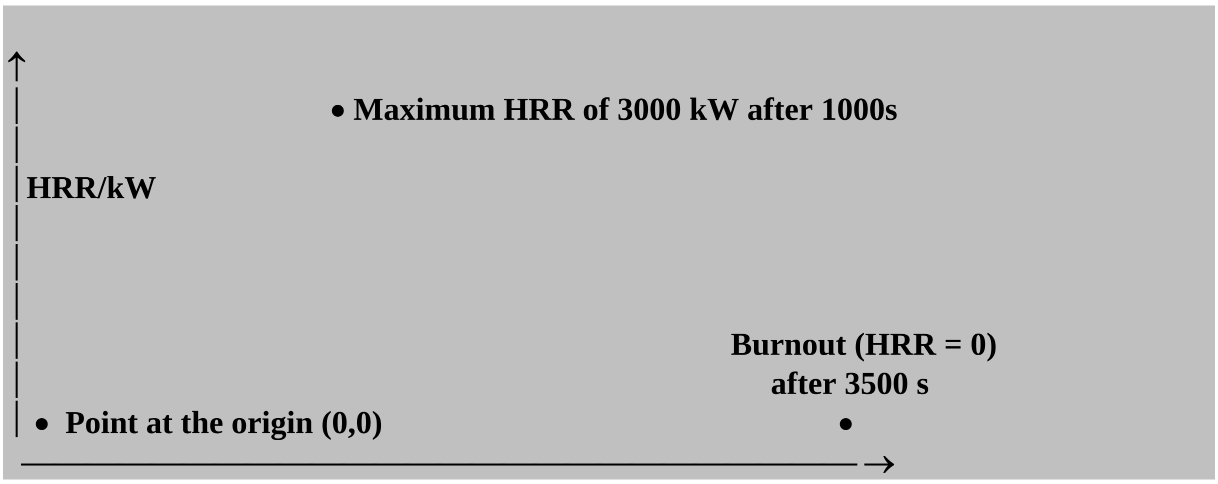

Fig. 1: Simplified and adapted heat-release history for a burning car. Taken from [3] and initially prepared from information in [2].

Model cars come in scales including 1/24, 1/43 and so on. Often the scale is given but if it is not it can be deduced from easily accessible information on the dimensions of an actual car of the same type as the model. With one exception (discussed in the Results section) this was in fact found to be quite straightforward not only for saloon cars but also for the model buses, coaches and motorcycles used in this study.

In calorimeters of the genre of the cone calorimeter the heat release measured is predominantly radiative, possibly to the total exclusion of convection. Accordingly, to measure temperatures during the experiments with model cars and convert the highest recorded temperature to a peak heat-release rate according to the 'solid flame' principle for comparison with calorimetric results such as those in Fig. 1 is sound. Let the peak temperature observed during the burning of a model car of scale 1/n be T K:

heat flux from the model (q, units Wm^{-2}) = σT^4

where σ is the Stefan-Boltzmann constant (5.7×10^{-8} $Wm^{-2}K^{-4}$). Our postulate is that the flux from a real car will be:

$3000/(\phi L)^2$

where L is the length of the vehicle and ϕ a geometrical factor. If the model car being examined has length L the above expression becomes:

$3000/(\phi nL)^2$

If the fluxes from a model and real car of the same type are equated we have:

$q = 3000/(\phi nL)^2 \Rightarrow \phi = \sqrt{[3000/qn^2L^2]}$

Qualitative or semi-quantitative arguments might be made in favour of the idea of equating the fluxes for the real car and the model one. For example, one might argue that the proportion of flammable material in a real car and in a model one composed principally of die-cast metal with fittings (upholstery, tyres) made of plastic are comparable. One might also make the point that the vapour-phase pyrolysis products which form the fuel in the flame from a model or a real car which has ignited will not differ greatly in nature even if they originate from different polymer materials and that the concentration of these in a fire will not vary by much between the two scales of interest. Notwithstanding such views we prefer our equating the two fluxes to be seen as a postulate to be tested experimentally. The postulate stands or falls on the consistency of ϕ values obtained for different models. This point will be made another way in the paragraph which follows.

In [5] 1/10 scale models of a vehicle structure are being used to examine fire behaviour. In this piece of work scales range from 1/12 to 1/170, many models being 1/43. Together they provide guidance to those examining the acceptability or otherwise of using scale model vehicles in such work.

3. EXPERIMENTAL

Die-cast metal model vehicles – cars, light commercials, motorcycles, coaches and buses – were obtained from retail outlets. Often the scale was given: if it was not it was estimated in the way described earlier. As previously stated, scales ranged from 1/12 to 1/170. After weighing and measurement of length a model was supported between two pieces of steel on a metal tray and ignited by placing a candle on one of the flammable parts, often a tyre. Once burning was established two thermocouples – type K, metal sheathed with bare junctions – were placed in the flame. The thermocouple signal went to a recorder (Yokogawa) with internal cold-junction compensation appropriate to type K which gave a continuous digital and analogue trace. The experiments were carried out in a room with powerful smoke extraction. In some of the experiments the weight after burning was determined.

A transparent guard (previously in use with a piece of heavy machinery) was placed in front of the burning model and usually the thermocouples were hand held close to their points of attachment to extension cable by an operator wearing eye protection. Having regard to the fact that the flame could not possibly have got out of control, there being nothing within its reach which could ignite, safety measures were in fact very stringent. Smoke masks were available, but it was usually found that the room's extraction capability was sufficient. The time between ignition and burnout to the extent that temperature readings had diminished to hundreds of degrees below the peak values was usually 15-20 minutes. At that point the model was doused with cold water, and a model having been burnt was left fully immersed in water overnight so as to eliminate the possibility of redevelopment of combustion through incomplete extinguishment. A total of about 35 model vehicles were examined in the way described.

Anticipating the results section, usually a burnt out model had retained most of its initial weight and was recognisable as whatever vehicle type it originally was in spite of heavy staining of the metal. The exception was the model motorcycles, which always fragmented during burning. Buses and coaches unlike cars and light commercials tended not to retain their initial shape but to 'cave in'. These observations do of course reflect the fire behaviour of real vehicles. The steel from which vehicle bodies are made is oxidisable but although there is weakening there is not total destruction of a body shell in a vehicle fire as temperatures are not high enough and, as with the models, a burnt out vehicle usually retains its visible identity in terms of make and type. So in this respect the model vehicles have behaved similarly to real ones.

4. RESULTS

In Table 1 results are given for the passenger cars and light commercials. In the boxed area following the table a sample calculation of ϕ is given for the results in the first row of the table.

Table 1: Results for model cars and light commercials

Description of model	Weight before burning/g	Length before burning/cm	Weight after burning/g	Peak temperature /^{o}C	Flux (q) /kWm^{-2}	ϕ
Mercedes Benz, 280GE 1/67	42	6.8	30.5	520	23	2.5
Mini, new type, 1/32	133	10.5	118	740	60	2.1
Mercedes, 1/24	n.d.	20	346	600	33	2.0
Ford Mustang, 1/24	330	20	274	615	35	1.9
London FX4 Taxi, 1/40	109	11.3	92.5	730	58	1.6
London FX4 Taxi 1/40	108.5	11.3	94.5	590	32	2.1
London FX4 Taxi, 1/40	106.5	11.4	-	522	23	2.5
London FX4 Taxi, 1/37	150	12.3	-	620	36	2.0
Mercedes Police Car, 1/43	70	9.8	-	710	53	1.8
BMW Police car, 1/32	170	11.7	165.5[1]	695	50	2.1
Mercedes 280GE, 1/67	42	6.8	-	578	30	2.2
BMW Z8, 1/65	47	6.9	-	740	60	1.6
Ferrari Spider, 1/65	38.5	6.8	35.5	565	28	2.3
Ambulance, unspecified 'make', 1/32	181	12.7	160	670	45	2.0
Police car, 1/50 est.	30	7.3	-	580[2]	30	2.7
Classic Mini 1/35	65	8.5	-	562	28	3.5
Toyota MR2, 1/31	127	12.7	-	610	35	2.4

[1] This model self-extinguished part way through the test when the light display went 'pop'. This presumably signified implosion and the resulting movement of air caused extinction.

Peak temperature 520^{o}C = 793 K $\Rightarrow$ q = 23 kWm^{-2}

n = 67, L = 0.068 m

Inserting into: $\phi = \sqrt{[3000/qn^2L^2]}$

gives: ϕ = 2.5

The ϕ values in the table can be summarised thus:

Number of values: 17
Range: 1.6 to 3.5
Mean: 2.2
Standard deviation: 0.4

The consistency of values of ϕ is reasonable and it is therefore suggested that a burning car will radiate with flux:

$$3000/(2.2L)^2$$

where a plus-or-minus on the factor of 2.2 can be incorporated according to the statistical processing of the results above.

Table 2a shows the results for buses and coaches.

The ϕ values for these can be summarised as follows.

Number of values: 5
Range: 0.6 to 1.2
Mean: 1.0
Standard deviation: 0.2

Though showing a good degree of consistency, the ϕ values are significantly different from those in Table 1. Intuitively we see no reason why radiative flux, referred to the area of the source, should differ between the two classes of vehicle. The explanation almost certainly is that the pivot point of 3000 kW for cars is too low for the coaches and buses. In Table 2b a value for the corrected pivot for each of the five vehicles is given. Assigning the pivot the symbol P kW, this is calculated as:

$$P = (2.2)^2\ qn^2L^2$$

meaning that the factor ϕ for the cars is being used to obtain a better pivot point for the buses and coaches. This will give an indication of the rate at which such vehicles will release heat if ignited.

Table 2a: Results for buses and coaches

Description of model	Weight before burning/g	Length before burning/cm	Weight after burning/g	Peak temperature /^{o}C	Flux (q) /kWm^{-2}	ϕ
Articulated airport transit bus, estimated 1/95 scale	165.5	18.6	-	579	30	0.6
London Routemaster double-decker bus, estimated 1/70 scale	192	11.6	-	610	35	1.1
London Routemaster double-decker bus, estimated 1/70 scale	193.5	11.6	-	600	33	1.2
London Routemaster double-decker bus, Estimated 1/73 scale	169.5	11.2	-	620	36	1.1
Police bus, estimated 1/170 scale	33	7.6	28.5	470	17	1.0

Table 2b: Calculated values of the total heat release of burning buses and coaches from the equation developed in the main text

Description of model	P/kW
Articulated airport transit bus, estimated 1/95 scale	45336
London Routemaster double-decker bus, estimated 1/70 scale	11619
London Routemaster double-decker bus, estimated 1/70 scale	10531
London Routemaster double-decker bus, Estimated 1/73 scale	11647
Police bus, estimated 1/170 scale	13734

Four of the five results in the table are very consistent, giving a mean value of P of 12000 kW. This indicates that a bus or coach on fire has a total heat-release rate about four times that of a car, which is a reasonable result. The one outlier is the articulated airport transit bus which gives a P value almost four times this. This however might be a consequence of the plus-or-minus on the ϕ value of 2.2 used. If instead of the mean value of 2.2 the lowest value of 1.6 for ϕ was used to calculate P for this model, the result would be 24000 kW, just twice the value for the other four models in the table. Moreover, of all the models for which the scale had to be estimated this one had the greatest uncertainty and that might in fact be in part the reason for the difference.

Turning now to the motorcycles, results for these are given in Table 3a.

The values of ϕ for these can be can be summarised:

Number of values:	10
Range:	2.1 to 4.9
Mean:	3.5
Standard deviation:	0.8

Table 3a: Results for model motorcycles[2]

Description of model	Weight before burning/g	Length before burning/cm	Peak temperature /°C	Flux (q) /kWm^{-2}	ϕ
Vulcan motorcycle, 1/18	64	13.4	670	45	3.4
BMW motorcycle, 1/18		13.4	690	49	3.2
Motorcycle, unspecified 'make', 1/28	28	9.5	695	50	2.9
Motorcycle, unspecified 'make', 1/28	27.5	9.5	710	53	2.8
Motorcycle, unspecified 'make', 1/28	29	8.9	690	49	3.1
Motorcycle, unspecified 'make', 1/28	28	9.0 est.	560	27	4.2
Motorcycle, unspecified 'make', 1/28	28	9.0	582	30	4.0
Police m/cycle, 1/35	-	7.3	880	101	2.1
Police m/cycle with sidecar, estimated 1/55 scale[3]	-	5.5	510	21	4.0
Police motor cycle 1/12 scale	-	16.2	600	33	4.9

[2] It was never possible to determine the weight of these after burning because of the fragmentation.
[3] Side car did not burn and perhaps acted as a fire break.

Results are more scattered than for either of the other vehicle types but the ϕ values are higher indicating that a lower pivot than 3000 kW applies. Values of the total heat release adjusted in the same way that they were for buses in Table 2b are given for the motorcycles in Table 3b, below.

The indication is that a motorcycle on fire will have a total heat-release rate of the order of 1 to 2 MW. There is one outlier. This particular model however was the only one in all of those used in the programme – cars, buses and motorcycles – to display such a high temperature; this was noted at the time of the experiment and might be due to some unusually reactive material in one of its components.

Table 3b: Calculated values of the total heat release of burning motorcycles from the equation developed in the main text

Description of model	P/kW
Vulcan motorcycle, 1/18	1267
BMW motorcycle, 1/18	1380
Motorcycle, unspecified 'make', 1/28	1712
Motorcycle, unspecified 'make', 1/28	1815
Motorcycle, unspecified 'make', 1/28	1473
Motorcycle, unspecified 'make', 1/28	830
Motorcycle, unspecified 'make', 1/28	922
Police m/cycle, 1/35	3191
Police m/cycle with sidecar, estimated 1/55 scale	930
Police motor cycle 1/12 scale	604

In considering the wide range of values for the calculated heat-release rates for the actual buses and motorcycles from results for the model ones we must remember that real cars show a spread of a factor of two or more in this quantity as mentioned in the Introduction. Though it is believed that the range of heat-release rates given for the full-scale buses and motorcycles is in each case a good estimate it could perhaps be refined in the following way. If we chose a higher pivot point for the model cars – say 5 MW – and put a plus or minus of about 60% on it, we could be confident of establishing by calculations of the type performed the precise range for the other types of vehicle. A reader interested in such a refinement has all of the necessary data to hand but the authors' view is that such refinement would not add much to the value of the work at this stage.

5. CONCLUSIONS

A postulate that heat-release rates from burning cars can be scaled from a model car to an actual one on the basis that heat flux will be the same in the two and be characteristic of a black body having an area the square of some multiple of the length is broadly confirmed. From the experiments, the multiple for cars and light commercials has a mean value of 2.2.

Whereas such a vehicle in full size is known to radiate at about 3000 kW, predictions from scaling are that motor buses and coaches will radiate at about four times this and that motorcycles will radiate at about half this.

Scaling principles for such fires having been attempted some promise is evident. There is scope for refinement in a number of ways including a range of pivot points from the real vehicles, according to information in [2], instead of selection and use of a single one.

REFERENCES

1. M.L. Janssens, "Heat release rate of motor vehicles", Fifth International Conference on Performance-Based Fire Codes and Fire Safety Design Methods, Luxembourg, October 2004, 22pp. (2004).
2. V. Babrauskas, "Heat release rates", Handbook of Fire Protection Engineering, 3rd Edition, SFPE, Quincy, MA, USA, pp. 3-1 to 3-37 (2002).
3. J.C. Jones, "Numerical examples in fire protection engineering", Whittles Publishing, Caithness, 80pp. approx. (2006).
4. J.C. Jones, T. Noonan and M. Riordan, "Combined photographic and gravimetric evidence of the destructive potential of fire", Journal of Fire Sciences, Vol. 23, pp. 189-192 (2005).
5. W.K. Chow, K.C. Lam, N.K. Fong, H. Dong, G.W. Zhou and Y. Gao, "Scale modeling results on smoke spreading and control in a double-deck bus", International Journal on Engineering Performance-Based Fire Codes, Vol. 8, No. 4, pp. 145-151 (2006).

ADDENDUM - EFFECT OF THE ABSENCE OF FUEL FROM THE MODEL VEHICLES

A reader of this paper in draft form pointed out that in a fire involving a real vehicle fuel (gasoline, diesel, LPG) adds to the fire hazard. There is of course no fuel in that sense in the models. This is undoubtedly a valid point which the authors willingly accept. It is examined quantitatively in the boxed area below.

The proportion of the weight of a car which is combustible – seats, carpets, interior fittings – is usually about 20% of the total weight of the car [3]. There will therefore be 200 kg of such materials in a car weighing a tonne. Taking the Ford Focus as an example, it weighs 1.18 tonne and will therefore on the basis of the above figure contain 236 kg of combustibles in its structure. Its petrol tank holds 55 litre. Assigning a reasonable value of 780 kg m^{-3} to the density of gasoline, this means that a full tank contains 43 kg of petrol. The calorific value of the gasoline is likely to be about 20% higher than those of the breakdown products of the upholstery and plastic fittings, which will be largely oxygenated. The proportion of the fire load due to the gasoline is then:

$$(43/236) \times 1.2 = 22\%$$

This is by no means negligible and has to be noted. The following points can however be made:

- A car will have a full tank only for quite a small part of the time.

- Ethanol, neat or in a blend, is coming into widespread use in spark ignition engines. This has a lower calorific value than gasoline and will bring down the factor of 1.2 in the above equation to below 1.0 if neat ethanol or a blend such as ‘E85’ is used.

- There is scope for discussion as to whether breakdown products could, irrespective of their calorific values, display the same combustion phenomenology as rapidly leaked liquid fuel.

Note added in proof.

The author has become aware of recently published work in which 1/10 scale passenger railcars were used to simulate the behaviour in full size ones. This is:

H. Ingason, “Model scale railcar fire tests”, Fire Safety Journal, Vol. 42, pp. 271-282 (2007).