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Article

Traffic-based methodology to develop peak Heat Release Rate probability distributions for sizing road tunnels ventilation systems when using a probabilistic approach

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Abstract: Road tunnels are a crucial part of today's transport infrastructures worldwide. Among the installed systems, the tunnel ventilation is key, as in the case of fire, it establishes and keeps appropriate conditions for self-evacuation and emergency services operations. Recent works propose using a probabilistic approach to assess road tunnels ventilation systems' capacity for fire scenarios. Under this approach, key design variables are defined based on probability distributions. From these distributions, the analysis uses the different possible values of the variables, including lower and upper limits as well as mean and characteristic values. The results obtained with this proposed probabilistic approach allow not only designers, but also tunnel operators and administrations, to quantify the reliability of the capacity of the ventilation system, assess its probability of failure, and define safety levels. This paper illustrates a methodology to define the design fire as a probability distribution for sizing road tunnels ventilation systems when applying the above-mentioned probabilistic approach. The methodology uses traffic information (crucial in road tunnels) and correlates it to peak Heat Release Rate (HRR) values from published reports by PIARC to obtain the design fire variable in terms of peak HRR probability distributions. The methodology is applied to two case study tunnels with different characteristics. The obtained results for the two tunnels are then compared and analyzed to peak HRR values normally recommended and used when sizing road tunnels ventilation systems to understand the uncertainty and sensitivity of the results.

Keywords: road tunnels; tunnel ventilation; stochastic analysis; probability distributions; design fire; traffic statistics

1. Introduction: Overview of important previous research

Road tunnels are a crucial part of today's transport infrastructures, contributing to the transportation system both from the economic and practical point of view.

To operate a road tunnel safely and efficiently, an integrated design of Mechanical, Electrical and Intelligent Transportation Systems (ME&I) is required. Among these ME&I systems, the tunnel ventilation system is key, as in case of fire it establishes and keeps appropriate conditions for self-evacuation and emergency services operations.

Traditionally, a deterministic approach has been adopted when sizing road tunnels ventilation systems, using prescriptive requirements and design criteria from standards and industry guidance to obtain an acceptable design solution from a fire safety point of view. The result of this design approach is given as a single outcome (for the most onerous design scenario considered) in terms of the capacity of the ventilation system to be installed.

Recent works propose the use of a probabilistic approach when sizing road tunnels ventilation systems (refer to references [1–5]). Under this approach, key design variables are defined using probability distributions to quantify the reliability of the system, assess its failure probability, and define safety levels. One of these critical variables is the design fire expressed as peak Heat Release Rate (HRR).

The outcome of the probabilistic approach documented in a recent published work from the corresponding author [4] for sizing road tunnel longitudinal ventilation systems provides an indicator of the residual risk associated with the capacity of the system expressed as a failure probability. This probabilistic approach uses a 1D steady-state model based on pressure loss calculations, supported by a Monte Carlo Simulation (MCS) method to perform a large number of simulations. For each of the simulations a deterministic calculation using the balance equation in Equation (1) is carried out for the different combinations of the design variables values, including those traditionally considered in a deterministic analysis (most onerous design scenario).

$$\Delta H_v \geq \Delta H_f + \Delta H_s + \Delta H_p + \Delta H_{ch} + \Delta H_{atm} \quad (1)$$

where:

- ΔH_v: Jet fans thrust;
- ΔH_f: Pressure loss generated by air friction along the tunnel;
- ΔH_s: Pressure loss generated by the air drag along the tunnel because of shape changes (turbulence zones);
- ΔH_p: Resistance generated by the stopped traffic;
- ΔH_{ch}: Pressure loss generated by the hot smoke buoyancy along the tunnel (upwards propagation of smoke);
- ΔH_{atm}: Natural draught (combined effects of wind and pressures).

The model used considers both the conservation of mass and the air as an ideal gas, it also accounts for the fire effects through air density changes (inversely proportional to those in the absolute temperature), and provides the air temperature downstream of the fire as the result of the balance of the heat released from the fire and the absorbed heat by the tunnel walls.

This probabilistic approach is an extension of the traditional deterministic one, as it considers and provides outcomes not only for the most onerous design scenario but also for all other possible combinations. It gives the result of the analysis as a failure probability function associated with the ventilation thrust, providing crucial information about the design criteria to assist administrations, tunnel operators, and designers.

The defined failure function (Equation (2)) depends on the installed ventilation thrust and the pressure losses. It defines the unsafe zone ($g(x) < 0$) as all those situations where the ventilation thrust is not enough to prevent smoke back-layering upstream of the fire (critical velocity not achieved). And the safe zone ($g(x) > 0$) is those situations where the capacity of the ventilation system is greater than the losses, and therefore there would be no back-layering as the obtained air velocity would be equal to or greater than the critical velocity.

$$g(x) = \Delta H_v - (\Delta H_f + \Delta H_s + \Delta H_p + \Delta H_{ch} + \Delta H_{atm}) \tag{2}$$

With this in mind, the failure probability is defined as the percentage of times that the pressure losses exceed the capacity of the installed ventilation system.

Figure 1, extracted from reference [4] and obtained with the mentioned probabilistic approach, shows the results for different tunnel lengths in terms of the installed ventilation thrust for different failure probability curves. In the figure, results show how the estimated probability of failure, based on the same design requirements, is different for the different tunnel lengths.

Length (m)	Inst. Thrust (Pa)	Pfail(%)
500	78	2.30
1000	110	2.40
2500	213	1.35

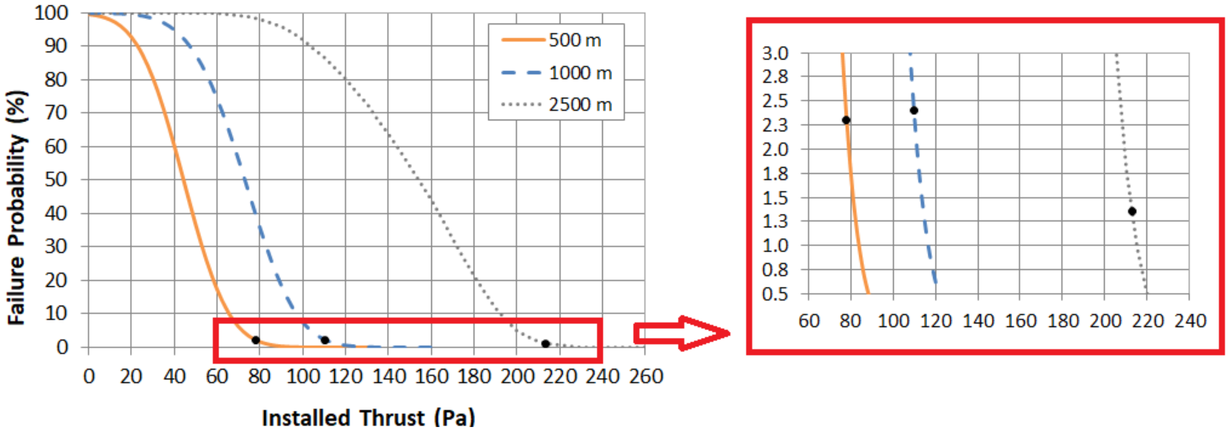


Figure 1. Failure probability curves for tunnel lengths.

Reproduced from reference [4].

For more detail on this probabilistic approach for sizing road tunnel longitudinal ventilation systems (and its comparison with the traditional deterministic approach), please refer to reference [4].

2. Design variables for tunnel ventilation sizing: Design fire

The design variables to evaluate the terms shown in Equation (1) for the pressure loss calculations in the 1D steady-state model to size a longitudinal ventilation system are:

- Geometry variables: Length, grade, friction and singular losses coefficients, cross section, number of lanes, hydraulic diameter.
- Fans: Installed thrust under ambient air conditions (with installation efficiencies), location and jet fan outflow velocity (at full speed).
- Traffic variables: Density, volume, percentage of each type of vehicle, aerodynamic coefficient of the stopped vehicles and their cross-sectional area (for each type of vehicle).
- Atmospheric/ambient conditions: Air temperature, air density and specific heat Cp.
- Fire scenario-related variables: Peak Heat Release Rate (HRR), critical velocity and fire location.

From these variables, the choice of the design fire is key, as it affects not only the design of the ventilation system but also the structural design and other systems designs, such as traffic management, fire detection, alarm, and suppression, as well as operations (incident response plans and evacuation strategies).

When sizing ventilation systems, the design fire can be considered as a time-dependent fire curve (refer to reference [6]) or as a single constant value defined as the peak HRR (refer to references [7–9]). And, generally, the selection of the fire HRR must be done accounting for the traffic fleet and whether the transport of Dangerous Goods is allowed or not.

A summary of peak HRR values from different international standards and guidelines is captured in **Table 1**.

Table 1. Peak HRR (MW) & vehicle type. International standards/recommendations.

Vehicle type	French Guid. [10]	German Stand. [11]	USA Stand. [7]	UPTUN WP2 fire scenarios [12]	PIARC [8]
Car	---	5–10	5–10	5	5–10
Several cars	8	5-10	10-20	10-20	---
Light duty vehicle	15	---	---	---	15
Bus, coach	---	20–30	20–30	30	20
HGV (< 25 T), lorry	30	30–30	70–200	50–150	30–50
HGV (25–50 T)	30	20–30	70–200	50–150	70–150
Tanker	200	50–100	200–300	200 or higher	200–300

3. Traffic-based peak HRR probability distribution development methodology

Based on the probabilistic approach mentioned in Section 1, the work presented in this paper shows a methodology to define the design fire variable as a peak HRR probability distribution, based on traffic information, to be used in that approach.

The analysis presented in the paper is applied to a case study for two different tunnels. It uses real traffic data from the two tunnels, including traffic volume (and its relationship with speed), the percentage of Heavy Goods Vehicles (HGV) and the allowance of Dangerous Goods (DG) traffic, which is correlated to peak HRR values collected from the literature [8] and fitted using the @Risk Distribution Fitting tool to four different probability distributions.

It is worth noting that the work is focused only on defining design fires to assist in road tunnel ventilation systems sizing. Other tunnel features/systems' designs (e.g., suppression or detection systems) where other parameters of the design fire (e.g., growth rate, species production, gas temperatures, etc.) would need to be considered separately are not within the scope of this paper.

It is not the intent of this work to provide standardized design fire probability distributions, but rather to demonstrate the application of the proposed traffic-based methodology using the data compiled for the analysis in a case study for two different tunnels.

When applying the probabilistic approach for sizing a tunnel ventilation system, the probability distribution of the design fire is one of the input design variables and it helps to understand the uncertainty and sensitivity of the peak HRR values to be used in the analysis. Additionally, when applying a deterministic approach, this aid is also valid, as discussed in Section 4.

For this case study, traffic data from two tunnels, including a total of 744 traffic data points per tunnel (vehicles/h and HGV percentage for each hour of each day of a whole month), was analyzed.

Note that an extended amount of data, in terms of the number of tunnels and time (more than one month of traffic data), should be explored in future work in order to obtain standardized design fire probability distributions.

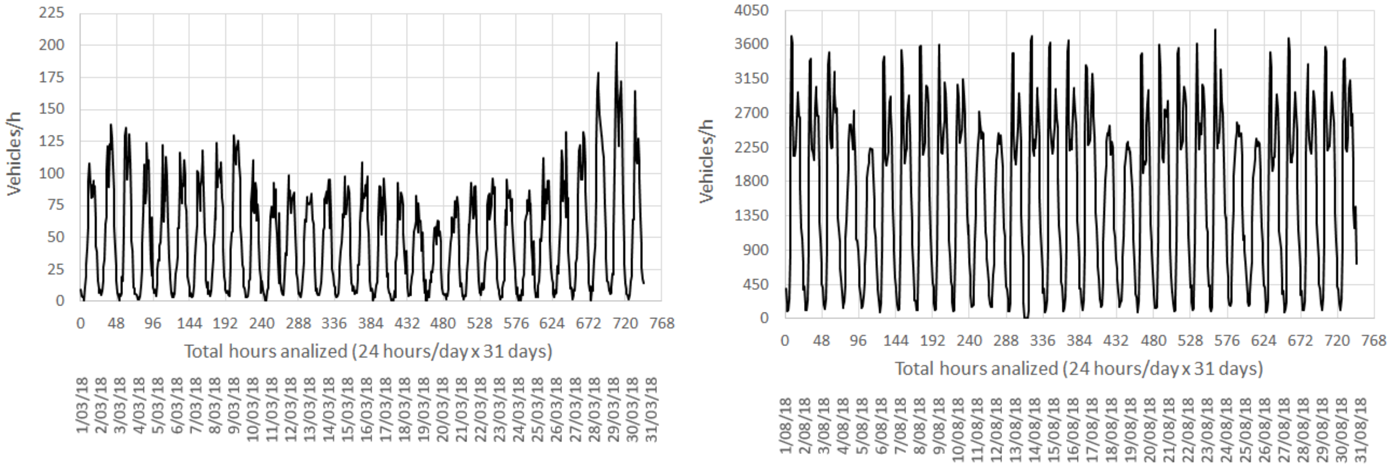
3.1. Traffic data analysis

Tunnel operators were approached to provide real traffic data from tunnels with different characteristics, including location (rural/urban), traffic direction (bidirectional/unidirectional), and Dangerous Goods presence (allowed/not allowed). Real traffic data obtained from two tunnels was analyzed. Although the source (and therefore the name of the tunnels) cannot be disclosed, **Table 2** presents the main characteristics of the two tunnels (Tunnel A and Tunnel B).

Table 2. General characteristics of analyzed tunnels.

	Tunnel A	**Tunnel B**
Length (km)	8.5	2.5
Number of tubes	Single	Twin
Number of lanes (per tube)	2	3
Traffic type	Bidirectional	Unidirectional
Dangerous Goods (DG) allowed	Yes	No

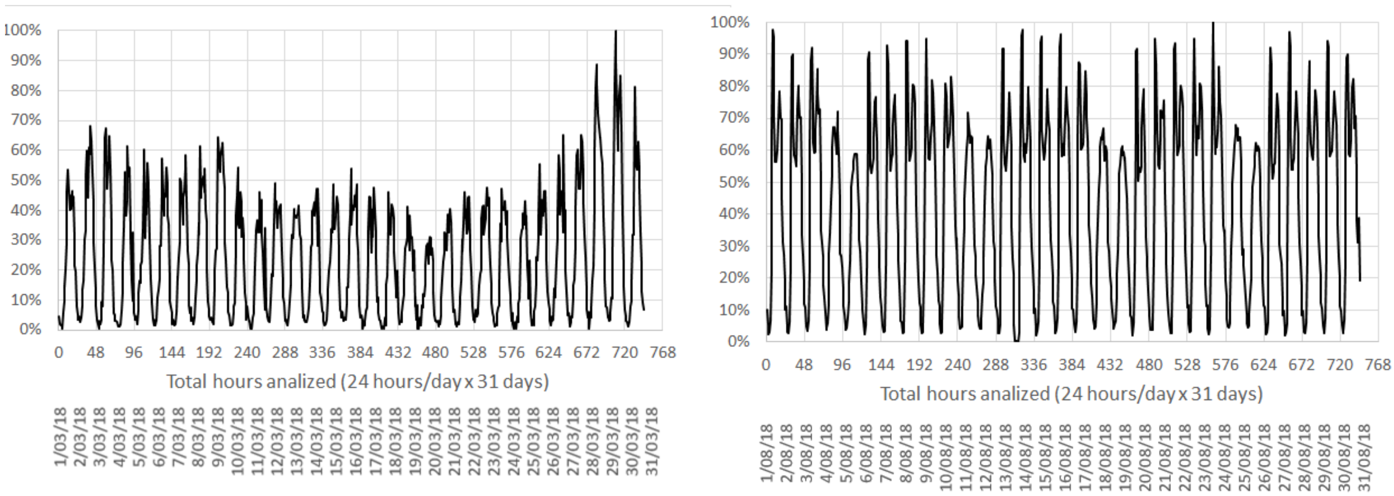
For this study, traffic data from one month during the end of the winter season with no holiday periods was analyzed. The analyzed traffic data included hourly numbers of total vehicles, Passenger Cars (PC) and Heavy Good Vehicles (HGV). **Figure 2** presents hourly total numbers of vehicles during the whole month. The graphs in **Figure 2** show the difference in the number of vehicles driving through each of the tunnels, which aligns with the different locations of the tunnels (Tunnel A, mountain rural tunnel and Tunnel B, urban tunnel).



(a) **(b)**

Figure 2. Number of vehicles per hour per day during a month, **(a)** Tunnel A; **(b)** Tunnel B.

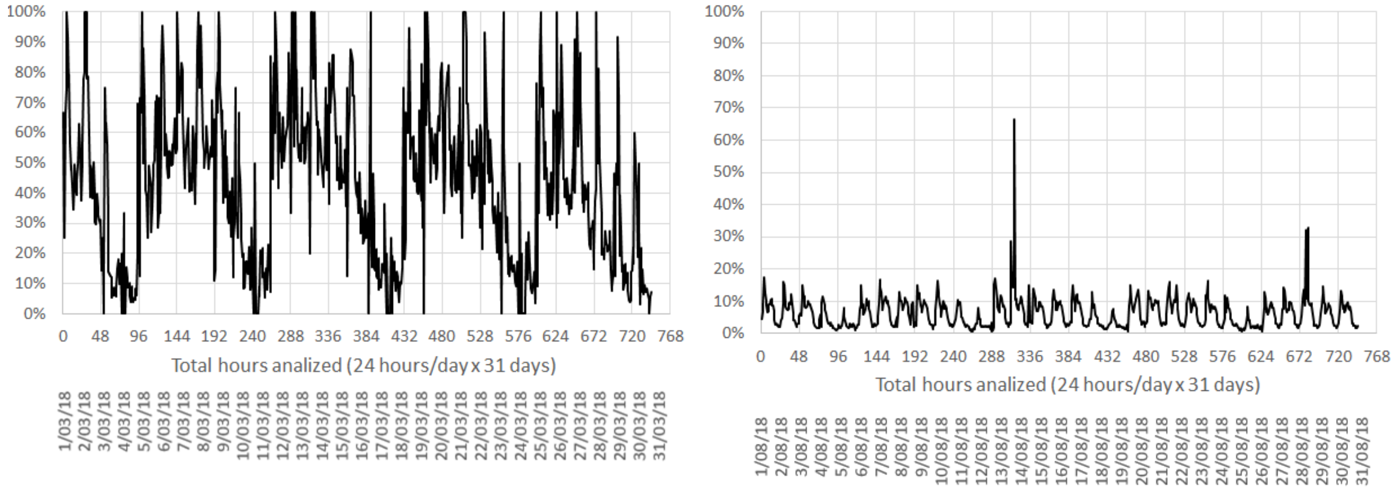
The proposed framework analyzes the traffic volume in terms of percentage instead of the traffic numbers, as these can be significantly different between tunnels (e.g., a maximum of 202 vehicles/h in Tunnel A and 3798 in Tunnel B). The percentage of traffic volume is calculated in relation to the maximum hourly total traffic value for each hourly total traffic value during the period of time analyzed (a total of 744 h, or data points included in the analysis). This standardization of the traffic volume in terms of percentage for the two tunnels analyzed is presented in **Figure 3**. These percentages of traffic volumes were the ones used during the peak HRR fitting step (as per **Table 3**).



(a) **(b)**

Figure 3. Standardized traffic volume per hour in %, **(a)** Tunnel A; **(b)** Tunnel B.

The other traffic data analyzed was the percentage of HGV driving through the tunnel. As shown in **Figure 4** for each of the tunnels.



(a) **(b)**

Figure 4. Standardized % of HGV per hour, **(a)** Tunnel A; **(b)** Tunnel B.

The graphs in **Figure 4** show the difference between the tunnels, with the average percentage of HGVs in Tunnel A around 45% while in Tunnel B is around 6%. This difference in the percentage of HGV aligns with the fact that Tunnel A is a rural tunnel, part of a freight transport route, and Tunnel B is a city tunnel.

3.2. Probability distribution fitting process

Over the years, fire tests on different road vehicles burned under different conditions (calorimeter hood, inside a tunnel, or in a car park) have been carried out to estimate the peak HRR and the time to reach the peak. An overview of peak HRR values for vehicle fires in road tunnels (including PC, HGV, buses and Dangerous Goods vehicles) is captured in the literature (refer to references [6,9,12–14,15]).

In this section, different probability distributions have been fitted to peak HRR values using the @Risk Distribution Fitting tool. @Risk is a commercial piece of software for risk analysis that uses the Microsoft Excel environment. It is a tool that provides features to help assess the fitting results (i.e., comparison, P-P and Q-Q plots) and includes delimiters on graphs to allow quick assessment of the probabilities associated with the values in the fitted distributions. The fact that the software is a commercial one, the data used for the fitting was in Excel, and @Risk Distribution Fitting automatically updates the distribution when the data is updated were the main reasons to select this fitting tool.

The HRR values correlated to the traffic data that are captured in **Table 3** have been based on the following:

- Incident frequency/occurrence. The frequency/occurrence of a fire incident is not variable. The probability distributions are meant to be used to size road tunnel ventilation systems and therefore the fact of a fire is taken as the starting point.
- Peak HRR value. The peak HRR values used for fitting the probability distributions are based on data captured in the literature and shown in **Table 1** (e.g., car fires HRR between 5–10 MW). It is not part (nor the aim) of the study

to analyze the conditions, physics or how the tunnel configuration influences/affects the HRR (fire size) when obtaining the peak values.

- Percentage of traffic volume. The traffic volume in tunnels is not constant; it varies along the day and with the day of the week (traffic volume is not the same on weekends or holidays or working days, nor during peak or low hours). To help understand the traffic profile, an average hourly percentage of total vehicles during the weekdays and the weekend days was calculated for both tunnels, as shown in **Figure 5**.

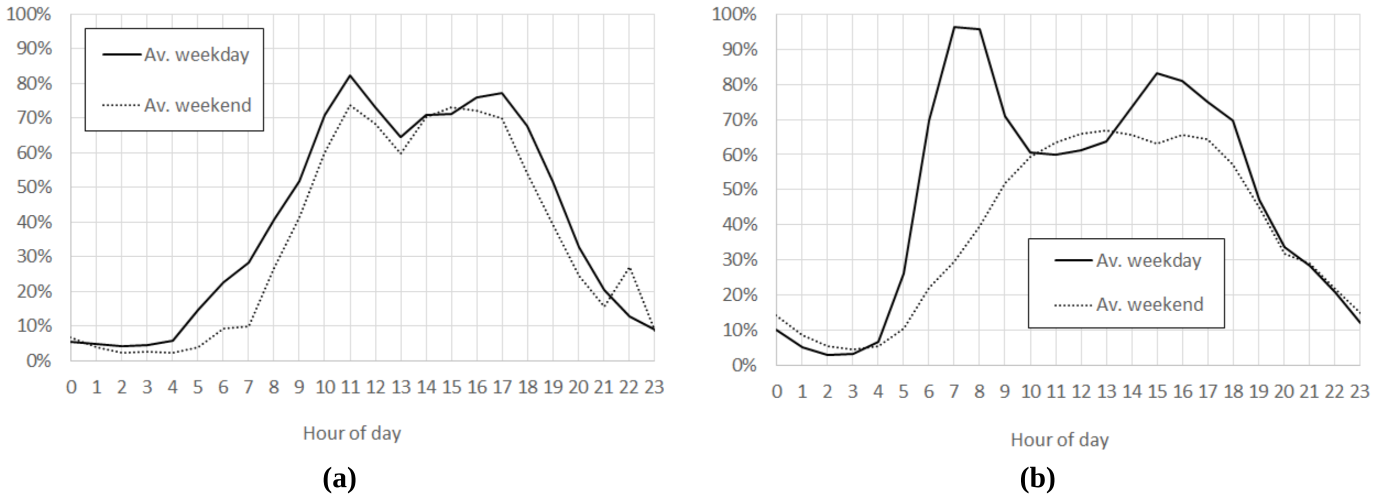


Figure 5. Average % of traffic volume per hour, **(a)** Tunnel A; **(b)** Tunnel B.

Based on these profiles, the analysis divided the percentage of traffic volumes into five bands to cover the different traffic volumes (as per **Table 3**). For example, for Tunnel B's weekday profile, traffic volumes less than 5% correspond to the early hours of the day (1:00–4:00), while traffic volume percentages between 80%–100% correspond to the morning and evening peaks (7:00–9:00 and 16:00–18:00, respectively).

- Traffic speed in relation to traffic volume as shown in **Figure 6**. Based on the fundamental relations of traffic flow, the flow is zero either because there are too many and they cannot move or because there are no vehicles. On the other hand, when the flow is maximum, the speed is between zero and free flow speed [16].

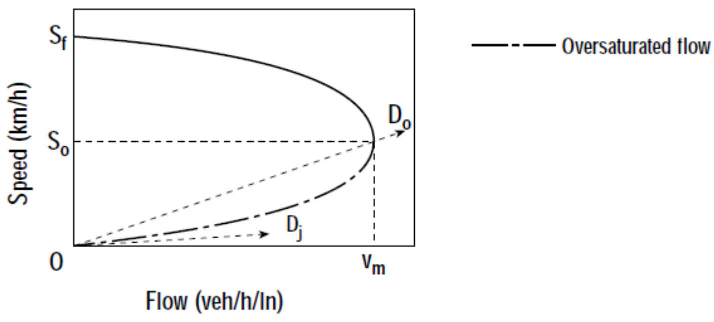


Figure 6. Generalized speed-flow curve.

Reproduced from reference [16].

Since high traffic volumes tend to reduce traffic speeds and with it the nature of the incidents tends to be less serious [17], the correlated peak HRR values for higher traffic volume percentages have been considered to be less than those with smaller traffic volumes.

- Percentage of HGV. The analysis has divided the percentage of HGV in six bands (as per **Table 3**). Since the HRR value for fires involving HGV is higher than for those involving Passenger Cars, the peak HRR has been considered to be larger for higher HGV percentages.
- Allowing or not allowing DG traffic. The assumed peak HRR value is greater when the traffic of DG vehicles is allowed (as per **Table 3**). The maximum peak HRR value considered when DG is allowed goes up to 300 MW, while when DG is not allowed, it goes up to 200 MW.
- DG traffic through the tunnel. Based on information provided by the tunnel operators of the tunnel allowing DG's traffic analyzed for the case study, if the traffic volume is high, then the traffic of DG vehicles is less likely to be allowed during that time.

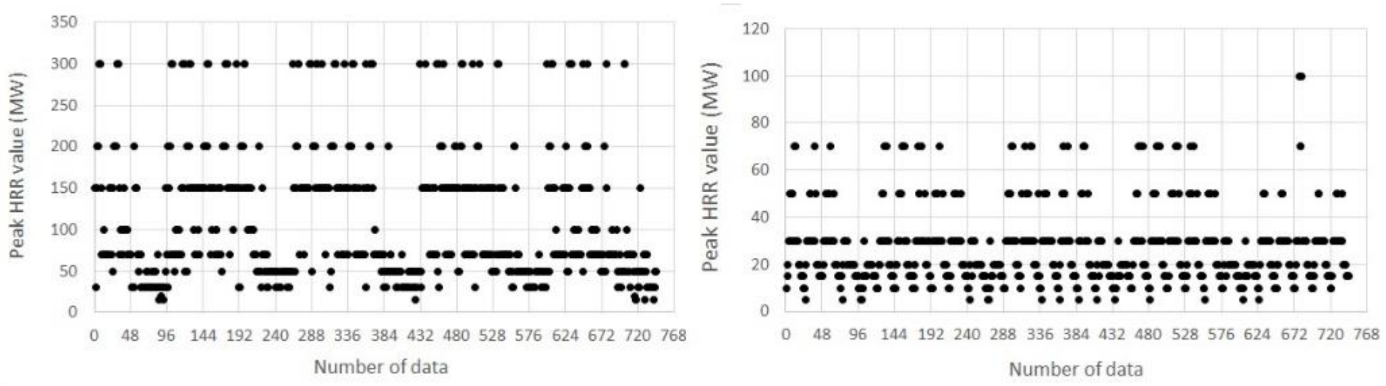
Table 3. Peak HRR based on the proposed traffic-based framework for the case study.

Traffic Volume (%)	HGV (%)	HRR (MW)	
		DG allowed	DG not allowed
< 5%	< 5%	30	5
	5%–< 10%	30	20
	10%–< 25%	30	30
	25%–< 50%	50	50
	50%–< 70%	150	70
	70%–100%	200	150
5%–< 15%	< 5%	30	10
	5%–< 10%	50	15
	10%–< 25%	50	30
	25%–< 50%	70	50
	50%–< 70%	150	70
	70%–100%	300	200
15%–< 50%	< 5%	15	15
	5%–< 10%	30	30
	10%–< 25%	50	50
	25%–< 50%	70	70
	50%–< 70%	150	150
	70%–100%	300	200

Table 3. (*Continued*).

Traffic Volume (%)	HGV (%)	HRR (MW)	
		DG allowed	**DG not allowed**
50%–< 80%	< 5%	20	20
	5%–< 10%	30	30
	10%–< 25%	70	70
	25%–< 50%	100	100
	50%–< 70%	150	150
	70%–100%	200	150
80%–100%	< 5%	30	30
	5%–< 10%	50	50
	10%–< 25%	70	70
	25%–< 50%	100	100
	50%–< 70%	150	150
	70%–100%	200	150

Each of the traffic data points, which include traffic volume percentage, HGV percentage and criteria of allowance of DG traffic was correlated/assigned a peak HRR value. This correlation was based on the above considerations (as per **Table 3**) and generated a 744 peak HRR database for each tunnel of the study case (as shown in **Figure 7**).



(a) **(b)**

Figure 7. Correlated peak HRR values database for distribution fitting, **(a)** Tunnel A; **(b)** Tunnel B.

To clarify the process followed and the peak HRR values in **Table 3**, a few points of the obtained database are presented and compared below:

- For a percentage of traffic volume of 2%, with 0% of HGV and DG traffic allowed, the peak HRR value correlated is 30 MW. Meanwhile for a percentage of traffic volume of 41%, with 4% of HGV and DG traffic allowed, the peak HRR value correlated is 15 MW. The difference in these cases is based on the traffic volume percentage (2% vs. 41%) and its relationship with the traffic speed and the likelihood of DG being allowed to drive through. It has been assumed that with low traffic volume the traffic speed and the likelihood of DG passing through will be higher.

- For a percentage of traffic volume of 4.8%, with 4.9% of HGV and no DG traffic allowed, the peak HRR value correlated is 5 MW. It has been assumed that even if the traffic speed could be high with the low traffic volume and low percentage of HGV it is likely that the possible incident would involve a passenger car.
- For a percentage of traffic volume of 41%, with 4% of HGV and DG traffic allowed, the peak HRR value correlated is 15 MW. Meanwhile, for a percentage of traffic volume of 25% (the same traffic volume band as for 41%) but with 59% of HGV and DG traffic allowed, the peak HRR value correlated is 150 MW. The difference in these cases is based on the percentage of HGV (4% vs. 59%) and the HRR values for PCs and HGVs. It has been assumed that with a low percentage of HGV it is more likely in the case of a fire occurrence to be related to PCs and therefore the difference in HRR value.
- For a percentage of traffic volume of 65%, with 33% of HGV and DG traffic allowed, the peak HRR value correlated is 100 MW. For a percentage of traffic volume of 71%, with 33% of HGV and no DG traffic allowed, the peak HRR value correlated is 100 MW. The HRR value assumed in these two cases is the same, as both the traffic volume and HGV percentages are similar, and it has been assumed that when the traffic volume is high, the traffic of DG vehicles would be less likely to be allowed.

This database represented in **Figure 7** was used with @Risk Distribution Fitting tool to fit four probability distributions for each tunnel. The reason for assessing different types of distributions was to see the differences based on the type of distribution and which distribution would give a better fit of the data. The fitted distributions are Beta, Weibull, Gamma and Lognormal distributions. For the fitting process in @Risk, the fitting options used for all the distributions included fixing the lower bound at zero. For the Beta distribution, also a fixed upper bound at 500 MW was used. The rest of the fitting options were the ones by default in @Risk.

To compare the fit from these four distributions, @Risk provides a goodness of fit measurement to see how the fitted distribution matches the data, and therefore the goodness of the fit. For continuous data, @RISK provides five methods for obtaining the goodness of the fit: The Bayesian Information Criteria (BIC), the Akaike Information Criteria (AIC), the Chi-Squared (Chi-Sq), the Anderson-Darling (AD) and the Kolmogorov-Smirnov (K-S).

The A-D, K-S and Chi-Sq methods were developed as tests for fit validation but not as tools for deciding between different distributions (although they can be used for this purpose when the number of data values is very large). The AIC and BIC methods ("Information Criteria" methods) were developed for model selection and they consider, among other criteria, the number of free parameters of the fitted distribution. Both AIC and BIC methods are very similar and rely on Bayesian analysis, although the AIC method tends to penalize less the number of parameters than the BIC method. Based on this, in this paper the AIC method has been chosen for comparing each potential distribution, where a smaller AIC value indicates a better fit.

Tunnel A peak HRR distribution fitting:

A summary of the outcomes of the @RISK Distribution Fitting process is captured in **Table 4** and shows the parameters defining each distribution, the mean, standard deviation, percentiles (5th and 95th) and the obtained AIC values.

Table 4. @Risk outcomes summary (Tunnel A).

	Mean	Std. Dev.	5% Pert	95% Pert	AIC Value	Rank based on AIC
Beta (1.62, 4.87, 0, 450)	112	71	18	247	8301	4
Weibull (1.53, 122.79)	111	74	18	252	8296	3
Gamma (2.24, 49.13)	110	73	22	252	8261	2
Lognorm (110.68, 88.68)	111	89	27	275	8228	1

Figure 8 shows the frequency data and fitted distributions (density and cumulative functions) for the peak HRR (MW) values related to the traffic for Tunnel A.

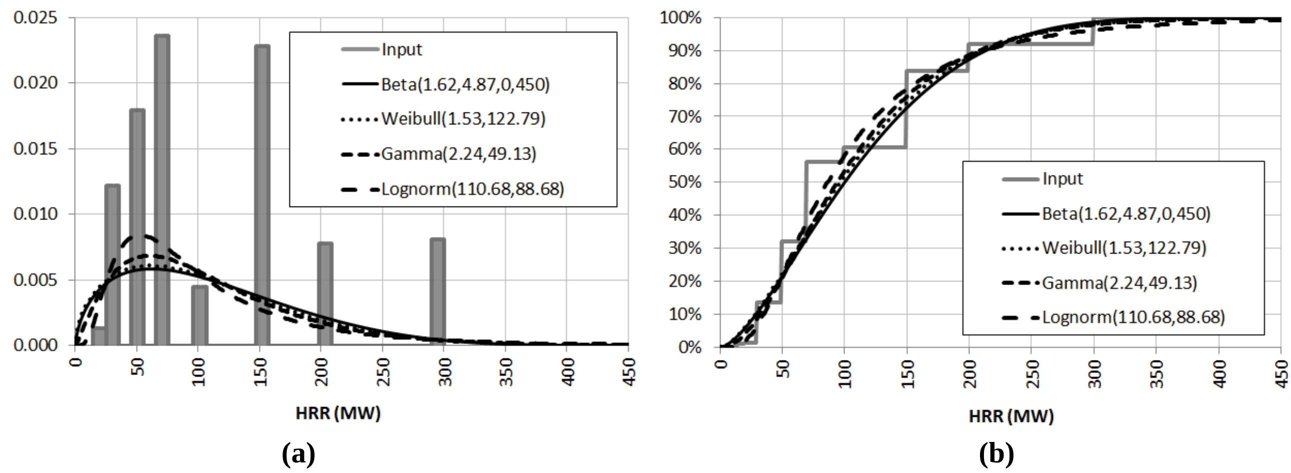


Figure 8. Frequency data and fitted distributions (Tunnel A), **(a)** density function; **(b)** cumulative function.

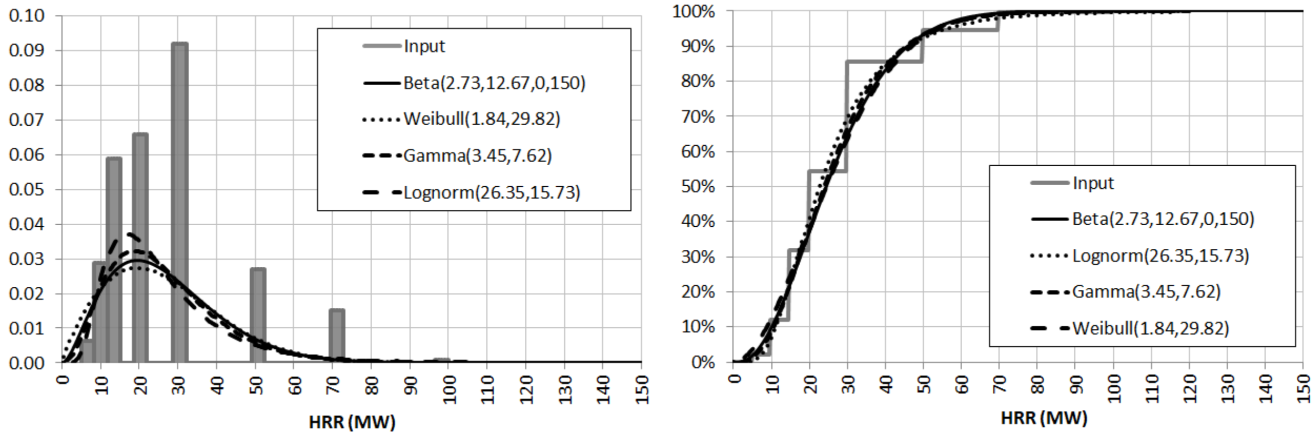
Tunnel B peak HRR distribution fitting:

A summary of the outcomes of the @RISK Distribution Fitting process for Tunnel B is captured in **Table 5** and shows the parameters defining each distribution, the mean, standard deviation, percentiles (5th and 95th), and the obtained AIC values.

Table 5. @Risk outcomes summary (Tunnel B).

	Mean	Std. Dev.	5% Pert	95% Pert	AIC Value	Rank based on AIC
Beta (2.73, 12.67, 0, 150)	27	14	7	53	5947	3
Weibull (1.84, 29.82)	26	15	6	54	5982	4
Gamma (3.45, 7.62)	26	14	8	53	5905	2
Lognorm (26.36, 15.73)	26	16	9	56	5873	1

Figure 9 shows the frequency data and fitted distributions (density and cumulative functions) for the HRR (MW) values related to the traffic for Tunnel B.



(a) **(b)**

Figure 9. Frequency data and fit distributions (Tunnel B), **(a)** density function; **(b)** cumulative function.

4. Discussion

A comparison between the design fire probability distributions (obtained with the proposed methodology) and representative peak HRR values normally used when sizing road tunnels ventilation systems applying a deterministic approach (see **Table 1**), can be made to help understand the sensitivity of the values.

This has been done with the results obtained for the case study presented in this manuscript. **Table 6** compares the representative peak HRR values, and their corresponding probability based on the results obtained for the two tunnels assessed.

Table 6. Probability distributions and representative peak HRR values comparison.

Representative peak HRR value when sizing road tunnel ventilation systems design	Tunnel A probability distributions	Tunnel B probability distributions
10 MW	0%–2%	7%–13%
20 MW	2%–6%	37%–42%
30 MW	7%–11%	63%–70%
50 MW	20%–22%	92%–93%
100 MW	50%–59%	99%–100%
200 MW	87%–88%	100%

Note that when sizing the ventilation system based on a deterministic approach, the probability distributions on their own don't dictate the specific value to be used. When statistical information is available for a design parameter (like the one provided by the probability distributions), the designer selects the specific percentile to use in the design (percentile approach). Generally, when considering upper values, the recommended percentile varies from 80th (refer to reference [18]) to 95th (refer to references [10,18,19]).

Assuming a 95th percentile approach and based on the obtained probability distributions (refer to **Tables 4** and **5**), for Tunnel A this would mean a design fire value of 247–275 MW (per PIARC's recommendations in the middle range of the peak

HRR for petrol tanker fires) and for Tunnel B 53–56 MW (per PIARC's recommendations, the upper bound of the peak HRR for HGV up to 25 T).

This comparison shows how the obtained probability distributions would cover the different peak HRR values that are normally recommended and used when sizing road tunnels ventilation systems with a deterministic approach.

Note that a comparison between the obtained distributions with other probability distributions used and/or proposed in/for other frameworks (e.g., risk assessments/models) where other properties or features are considered (e.g., time to reach peak HRR and frequency and consequences of the events) has not been done and is not within the scope of the study. The distributions obtained based on the proposed methodology are meant as an input for sizing tunnel ventilation systems following a probabilistic approach as the one presented in recent published works (refer to reference [4]).

Defining the design fire in terms of a probability distribution and using a probabilistic approach to size the tunnel ventilation system assesses the capacity of the system based on the different design fire values covered by the distribution (i.e., lower and upper limits as well as mean and characteristic values), not only the most onerous one (as per a deterministic approach-based design).

The outcome obtained from using a probabilistic approach gives an indicator of the residual risk associated with the capacity of the system expressed as a failure probability (refer to reference [4]).

In other engineering fields, such as structural engineering, the use of a probabilistic approach is widely used, and it is an entire field of research in performance-based safety engineering.

Note that it is not the aim of the work to provide standardized probability distributions, but rather, to demonstrate the application of the proposed traffic-based methodology using a limited amount of data. An extended amount of data, in terms of the number of tunnels and time (more than one month of traffic data), should be explored to obtain standardized design fire probability distributions.

5. Conclusions

This paper illustrates, through a case study, a methodology to define design fires (peak HRR) for sizing road tunnel ventilation systems in terms of probability distributions based on traffic data.

Peak HRR data obtained from the literature has been correlated to real traffic data for two tunnels following assumptions based upon the percentage of total traffic volume, percentage of HGVs, traffic speed in relation to the traffic volume and whether DG traffic is allowed or not. Using the @Risk Distribution Fitting tool, four probability distributions have been fitted to characterize the design fire.

The analysis shows how the probability distributions would cover the different peak HRR values that are normally recommended and used when sizing road tunnels ventilation systems with a deterministic approach, which helps to understand the uncertainty and sensitivity of the values.

The results presented in this paper are based on a case study and are intended only for illustrating the proposed process to obtain design fire probability distributions for sizing road tunnel ventilation systems based on traffic data. It is not the intent of the study to provide standardized probability distributions for general road tunnel assessments, nor propose the use of a specific design fire percentile value.

It is worth noticing that the probability distributions on their own don't dictate the design fire value to be used. As per Section 4, when sizing the ventilation system based on a deterministic approach, the designer can select a specific percentile to be used in the design (percentile approach).

When using a probabilistic approach (as the one captured in reference [4]), the capacity of the system is based on the different design fire values covered by the distribution (i.e., lower and upper limits as well as mean and characteristic values), not only the most onerous one (as per the deterministic approach). The probabilistic approach is an extension of the traditional deterministic one, as it considers and provides outcomes not only for the most onerous design scenario but also for all other possible combinations.

Although in both approaches the peak HRR values represent the same, in terms of sizing the ventilation system, the probabilistic one provides important information about the design criteria to assist administrations, designers, and tunnel operators.

Based on the results obtained from recent published works [4], the information obtained with the probabilistic approach can compensate for unbalances derived from the application of the common deterministic practice (where for similar conditions and the same design criteria, different residual risk is allowed). This is important for national highway administrations and/or tunnel operators, since the fact of not having a comparative and consistent criterion (residual risk) for all the tunnels can imply an uneven and inefficient use of resources.

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