DESIGN FIRE CHARACTERISTICS FOR ROAD TUNNELS

Technical Committee 3.3 Road tunnels Operations
World Road Association
STATEMENTS

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World Road Association
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Fire safety in tunnels depends on an amalgam of systems and procedures designed to achieve the best outcome in the event of an incident. The “Design Fire”, defined in terms of its magnitude, growth rate and duration, provides a basis for sizing the required systems and anticipating the operational measures that need to be in place. In the case of new tunnels, it may influence the choice of tunnel configuration or the use of additional systems to mitigate consequences.

A prescriptive approach has generally been adopted with design fires, formerly in a range up to a peak heat release rate of 30 MW. However, the experience of actual large tunnel fires and full-scale tests indicates that much larger fires may occur. The report presents the standards currently adopted in different countries, which vary from 20 to 300 MW.

Full scale test results for small commercial vehicles indicate fire sizes of about 15 MW. Tests on HGV’s show a broad spread from 50 to 200 MW. The duration of these fires ranges from 20 to 40 minutes, with gas temperatures in the region of 1300°C. Actual fires have been estimated to peak at up to 100 MW, but the durations have, in some cases, been much longer due to fire spreading to multiple vehicles.

Given the wide range of fire sizes experienced, it is evident that the selection of a design fire size for a particular tunnel is not straightforward. A consideration of several factors, such as the type of traffic allowed, the ventilation system, tunnel geometry and fire mitigation systems has to be taken into account. Even in a prescriptive approach, such considerations are weighed. To give more guidance on the process of choice, a methodology for a performance-based approach is presented in the report.

The impact of the design fire on smoke management systems is also reviewed.
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INTRODUCTION

The purpose of this report is to provide guidance and recommendations on the choice of design fires for road tunnels. A design fire is defined as a Heat Release Rate (HRR), in MW, as a function of time. It provides the fire characteristics that are used to establish the sizing of equipment in tunnels and the scenarios to consider when developing emergency response plans.

The fire growth period of the design fire affects the conditions in the tunnel during the “self-rescue” phase. An understanding of how fast a fire might grow, and the subsequent spread of smoke and hot gases, is a factor in the design of ventilation, suppression, and detection systems as well as the determination of evacuation strategies. The peak HRR is the main parameter in determining the capacity of the ventilation system. The peak HRR is of concern for the life-safety of the fire service during the fire-fighting phase. The objective during this phase is to provide tenable conditions with respect to smoke control and radiation from the fire: if the fire grows beyond a certain size, direct radiation may prevent fire fighters from approaching the fire.

Structural design and classification of technical equipment for fire protection utilize a “temperature versus time” concept for the analysis, rather than a heat release rate. By evaluating the temperature distribution in a structure, the structural resistance can be estimated and steps taken in the design to manage the risk appropriately. The structural impact of temperature is obviously a consequence of the heat release from a fire. For small fires, the impact on structure would be minimal as the fire plume is diluted and cooled with entrained air. For large fires the fire plume impinges on the structure, exposing it to temperatures corresponding to the combustion process, normally in the range 1200-1360 °C. This document does not address the time-temperature effects on the tunnel structure; PIARC report “Systems and Equipment for Fire and Smoke Control in Road Tunnels” [1] provides further details.

A prescriptive approach has generally been adopted in which a specific fire size is chosen as a basis for the tunnel fire-life safety design. These have been peak heat release rates of the order of 5 MW to 30 MW depending on the type of vehicle. However, as a consequence of the serious fires in European road tunnels since the late 1990’s, much work has been undertaken to assess the risk of fires and the possible fire sizes (peak HRRs) that can occur from different vehicles. The magnitudes of the largest possible fires far exceed the aforementioned heat release rates. This has raised the question of the adequacy of the design fire sizes used for the design of ventilation, suppression and detection systems in road tunnels, and has promoted much debate in the tunnel fire safety community.

Recent European studies have provided further insight into the general aspects of fires in tunnels, in particular the FIT [2] and UPTUN [3] projects, and full scale experiments that have been carried out to explore the potential magnitude of larger vehicle fires that can occur in tunnels.

Some authorities have adopted these larger fire sizes into codes and standards: see appendix 1. However, the design fire is generally not the worst possible fire that may occur, but a conscious choice between a probable fire that may arise and the ability to achieve practical design solutions for a less probable fire of larger magnitude. As a consequence of this and the complexity of the issues involved, not all codes and standards reflect the larger design fires.
Experimental data is generally the most reliable source of information. However, much of the available data has been obtained in tunnels that have smaller cross-sections compared to average road tunnels, leading to higher ventilation velocities and radiation feedback from the walls of the tunnel. These data tend to show high peak HRR with a rapid fire growth rate, and should be assessed in the context of larger cross-sections. The boundary effects due to geometry and ventilation are discussed in appendix 2 of this report.

The larger fire sizes considered as a result of these incidents and tests lead to a wider consideration of the approach to choosing a design fire. The prescriptive approach is based on broad requirements that are declared in terms of fixed values. In practice, a prescriptive approach also embodies some of the elements of a performance-based approach, where design fires may be adjusted depending on the design approach.

In contrast, a purely performance-based approach is usually based upon explicitly stated objectives that allow the freedom to develop innovative designs that satisfy these objectives. The performance-based design approach can be used for both new and existing tunnels, to achieve stated fire and life safety objectives, to support the development of alternatives to prescriptive-based code requirements, or to evaluate the tunnel fire safety as a whole.
1. PREVIOUS WORK BY PIARC

The Road Tunnel committee report of the Brussels Congress in 1987 [4] makes reference to peak HRRs representing a design fire. The report discusses the large-scale fire tests carried out at Offenegg [5], Heselden [6] and the work of PWRI in Japan. HRRs of approximately 20 MW for a bus or truck and 100 MW for a fuel spill are quoted. Information on smoke propagation velocity, smoke production and maximum temperatures for different fire sizes is also provided.

In its 1999 document “Fire and Smoke Control in Road Tunnels” [7], PIARC recommended a design fire size of 30 MW. For Heavy Goods Vehicles (HGV) and vehicles with dangerous goods this report indicated the possibility of higher levels of peak Heat Release Rate, based on the EUREKA HGV fire test [8] which indicated a peak HRR of approx. 100-120 MW. However, the impact of the high air velocity in the HGV test raised doubt that the EUREKA tests were sufficiently representative of actual tunnel fires to provide new realistic design values on their own. The HRRs from fires arising from petrol tanker fuel spills depend on the leakage rate and drainage and are in the range of 200 – 300 MW.

The PIARC report “Fire and Smoke Control in Road Tunnels” [7] discusses the tenability in the tunnel environment; tolerable air temperatures are noted as 80 °C for 15 minutes in humid conditions; the “Large Scale Fire Tests in the Rutehamar Tunnel – Gas Temperature & Radiation” [12] report shows that radiation is tolerable at a level of 2-2,5 kW/m2 for users and 5 kW/m2 for fire fighters, depending on the time of exposure. A well-equipped fire fighter might tolerate a radiation level of 5 kW/m2 for about 4 to 5 minutes. A visibility of 7 to 15 meters was a recommended target for evacuation and fire fighting operations. Whilst visibility tends to be the most restrictive criterion for tenability, temperature, toxicity and radiation have to be considered when evaluating the environmental conditions during the self-evacuation phase. No recommendations were given with regard to toxic gas concentration due to lack of reliable data. However the view was expressed that if the minimum visibility is maintained, then it would be expected that toxic gas concentrations would be under the tolerable limit for evacuation.

The report “Systems and equipment for fire and smoke control in road tunnels” [1] written in the 1999-2003 cycle and published in 2007 restated the previously established peak heat release rates for different types of vehicle and also discussed the fire growth in the context of emergency exits.
2. DESIGN FIRES

This section presents information relating to design fires used in different countries and discusses data from full-scale fire tests. A risk-based approach to establishing design fire size is also discussed.

2.1. SUMMARY OF PRACTICES ADOPTED IN DIFFERENT COUNTRIES

The following table summarizes the typical design-fire assumptions used in different countries. More complete details are to be found in appendix 1.

<table>
<thead>
<tr>
<th>Country</th>
<th>Design Fires (MW)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>50</td>
<td>With FFFS (deluge system), for ventilation only</td>
</tr>
<tr>
<td>Austria</td>
<td>30</td>
<td>High risk category: 50 MW</td>
</tr>
<tr>
<td>France</td>
<td>30 – 200</td>
<td>200 MW when transports of dangerous goods allowed but only applied for longitudinal ventilation</td>
</tr>
<tr>
<td>Germany</td>
<td>30 – 100</td>
<td>Depending on length and HGV in tunnel</td>
</tr>
<tr>
<td>Greece</td>
<td>100</td>
<td>Longitudinal ventilation</td>
</tr>
<tr>
<td>Italy</td>
<td>20 – 200</td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Netherlands</td>
<td>100-200</td>
<td>100 MW if tankers are not allowed, otherwise 200 MW for ventilation system</td>
</tr>
<tr>
<td>Norway</td>
<td>20 – 100</td>
<td>Depending on risk class, always longitudinal ventilation</td>
</tr>
<tr>
<td>Portugal</td>
<td>10-100</td>
<td>Based on traffic type</td>
</tr>
<tr>
<td>Russia</td>
<td>50-100</td>
<td></td>
</tr>
<tr>
<td>Singapore</td>
<td>30-200</td>
<td>Depends on vehicle types allowed</td>
</tr>
<tr>
<td>Spain</td>
<td>≥30</td>
<td></td>
</tr>
<tr>
<td>Sweden</td>
<td>100</td>
<td>Longitudinal ventilation</td>
</tr>
<tr>
<td>Switzerland</td>
<td>30</td>
<td>Smoke extraction equals 3.3-4 m/s times cross section</td>
</tr>
<tr>
<td>UK</td>
<td>30 – 100</td>
<td></td>
</tr>
<tr>
<td>USA</td>
<td>30 – 300</td>
<td>300 MW if dangerous goods allowed</td>
</tr>
</tbody>
</table>

It is evident from table 1 that:

- Several countries adopt a range of fire sizes depending on the type of vehicle admitted to the tunnel, recognizing the possibility of larger fires with HGV and dangerous goods;
- Countries that only utilize longitudinal ventilation allow for higher HRR design fires.

The use of higher heat release rates for longitudinally ventilated tunnels reflects that this mode of ventilation can generally be designed to deal with higher fire sizes at reasonable expense, while transverse ventilation would require very expensive increases in tunnel structure and equipment.

2.2. BASIS FOR THE CONSIDERATION OF DESIGN FIRES

The design fires given in Section 2.1 are based on the expected magnitude of different vehicle fires, ranging from smaller trucks and buses, to HGVs and fuel tankers. This section presents the HRR levels in relation to the vehicle type and established data obtained from recent experimental work.
2.2.1. Data Based on Vehicle Type

The choice of a design fire depends on the type of traffic allowed in the tunnel. Table 2 summarises the generally accepted ranges of potential peak HRR for different vehicle types. Clearly, for tunnels allowing only light duty vehicles, the fire size would be correspondingly smaller.

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Peak HRR (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger car</td>
<td>5 – 10</td>
</tr>
<tr>
<td>Light duty vehicle</td>
<td>15</td>
</tr>
<tr>
<td>Coach, bus</td>
<td>20</td>
</tr>
<tr>
<td>Lorry, heavy-goods vehicle up to 25 tonnes*</td>
<td>30 – 50</td>
</tr>
<tr>
<td>Heavy-goods vehicles typically 25-50 tonnes*</td>
<td>70 – 150</td>
</tr>
<tr>
<td>Petrol tanker</td>
<td>200 – 300</td>
</tr>
</tbody>
</table>

*Depending on the quantity and nature of the load: see Ingason [10] for more specific data

Design fires in road tunnels are usually based on the assumption of a fire development in a single vehicle. However, based on recent experience and fire tests, it has become evident that this assumption may be too low for certain types of vehicle fire. Some of the more serious fires that have occurred in tunnels are due to collisions involving vehicles with considerable amounts of combustibles. The consequence has often been that the fire has spread to adjacent vehicles: see appendix 3.

2.2.2. Summary of Data Based on Full Scale Tests

A number of full-scale experiments have been carried out in tunnels, and details of the more recent ones are given in appendix 2. These are the EUREKA 499 Project [8], Benelux [9], Runehamar [11] & [12], Memorial Tunnel [13], and the RWS Fire Suppression Tests at Runehamar [14]. This section provides a brief summary of these tests. As with any large-scale test, there is little opportunity to perform identical repeated set-ups: since the fuel sources are mainly vehicles, it is quite possible that repeatability would be elusive. Also, since the tests are carried out in different tunnels, there are variations due to tunnel cross-section and ventilation as well as the fire load itself. Nevertheless, some reasonable generalizations can be made with regard to the tests as a whole.

Table 3 provides a brief compilation of the average durations of the fire and the range of peak HRR. With regard to the HRR, it can be seen that the values found for different types of vehicle are consistent with the general guidelines given in Table 2.

<table>
<thead>
<tr>
<th>Test</th>
<th>(t_{inc}) (min)</th>
<th>(t_c) (min)</th>
<th>(t_s) (min)</th>
<th>(t_d) (min)</th>
<th>(t_T) (min)</th>
<th>Peak HRR (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[18] à [20]</td>
<td>Vehicles</td>
<td>5</td>
<td>7</td>
<td>36</td>
<td>15</td>
<td>64</td>
</tr>
<tr>
<td>Wood cribs</td>
<td>4</td>
<td>9</td>
<td>62</td>
<td>2</td>
<td>77</td>
<td>9.5 – 27</td>
</tr>
<tr>
<td>Eureka [8]</td>
<td>Heptane</td>
<td>0</td>
<td>46</td>
<td>35</td>
<td>17</td>
<td>98</td>
</tr>
<tr>
<td>Vans/Bus</td>
<td>3</td>
<td>5</td>
<td>48</td>
<td>41</td>
<td>97</td>
<td>6.1 – 28</td>
</tr>
<tr>
<td>Benelux [9]</td>
<td>Vans</td>
<td>5</td>
<td>4</td>
<td>12</td>
<td>9</td>
<td>30</td>
</tr>
<tr>
<td>Eureka [8]</td>
<td>HGV</td>
<td>8</td>
<td>4</td>
<td>30</td>
<td>15</td>
<td>57</td>
</tr>
<tr>
<td>Runehamar [11], [12]</td>
<td>HGV</td>
<td>3</td>
<td>7</td>
<td>30</td>
<td>13</td>
<td>53</td>
</tr>
</tbody>
</table>
where:

\[ t_{\text{inc}}: \text{time from ignition until the fire is producing flame (smouldering or incubation region)} \]
\[ t_g: \text{time from end of incubation to maximum heat release (fire growth region)} \]
\[ t_s: \text{duration time of the steady-state region} \]
\[ t_d: \text{time from the start of the decay of the HRR to the end of it (decay region)} \]
\[ t_f: \text{duration time of the fire from ignition} \]

In these full scale tests, fires have typical durations from 30 to 40 minutes with a few extending up to 2 hours, see appendix 2. Fires from real accidents may have considerably longer duration, as described in appendix 3. This is mainly because of the fire spreading from the initial fire to other vehicles inside the tunnel. In all these cases the fire services were not able to control the fire spread, and this explains the high levels of HRRs in these accidents. In addition, special considerations should be given to whether the experimental setup (simulated loads) is representative of current road traffic in tunnels.

As discussed in appendix 2, the fire-growth rate increases with the longitudinal ventilation velocity. Therefore, only the longitudinal velocity required for smoke control, e.g. the critical velocity, should be used in order to avoid a potential increase in the fire growth rate.

As indicated in table 3, the fire tests generally display a number of phases in their behaviour. The fire initially smoulders for a period of time after ignition. At the end of this “incubation” or “smouldering” phase, the fire will spread and rapidly grow. This period is known as the “fire growth” phase. At the end of the growth phase, the fire will sustain a peak HRR at the end of which the fire will decay and eventually extinguish. This similarity in the behaviour of the experimental results suggests that an “idealized” curve might be a useful concept for design. Appendix 2 establishes a possible set of idealized design fire curves based on the experimental data for different possible fire loads in road tunnels. Illustration 1 shows the general form of this curve.

The use of an idealized curve may be useful for a particular design situation. However, due to the variability of the experimental results the parameters that define the idealized curve for any class of vehicle would have to be determined for the specific tunnel configuration, traffic etc.
2.3. SELECTION OF DESIGN FIRE

2.3.1. Prescriptive Design

Prescriptive design involves the application of a design fire given by a code or standard. In some countries either a single value or a range of values is prescribed for the design fire: see table 1 and appendix 1. Historically, these have been quite low. A design fire embodied in a country’s standard implies a generally accepted risk level applied to all tunnels. However, particular projects may have different risk profiles. Also, the realization of the possibility of larger fires requires more thought to be applied to the risks involved in different kinds of tunnels, which may lead to larger prescriptive design fire sizes. Prescriptive values may vary depending on the traffic type, density and tunnel length and location, and the designer or authority would choose the appropriate value for a given case.

In an existing tunnel the situation may arise through a requirement for refurbishment; design values may have changed since the original construction and require a reconsideration of the implicit risks. Operational changes such as increased traffic over a period of years may also alter the risks and may thus promote a reconsideration of the design fire size. This is usually delivered through a risk assessment or cost benefit analysis.

Certain standards allow a reduction of the prescribed values of fire size based on a risk assessment or the consideration of mitigation measures.
2.3.2. Non-Prescriptive Approaches

In a non-prescriptive approach, the design fire size is specifically established to meet an accepted level of risk. A starting point would usually be the design fires given in codes and standards. Adjustments may then be made to achieve the desired residual risk; for definition of terms see the PIARC report “Current Practice for Risk Evaluation for Road Tunnels” [15].

For example, the magnitudes of design fires for particular vehicle types, already discussed in the PIARC report “Fire and Smoke Control in Road Tunnels” [7] and broadly outlined in table 2, can provide a starting point for this assessment. Information from the standards adopted in different countries, table 1, can also provide a basis. However, experience of real fire events and the evidence of experiments would indicate that more conservative values could be adopted for tunnel design.

The acceptance of the possibility of larger fires in tunnels leads to a need to consider the risks of these events and to address the feasibility and cost of a project. In this regard, several broad factors need to be considered, as outlined below:

- Frequency and magnitude of fires: car fires are relatively frequent in tunnels and rarely present any problem for the systems or the operator. Minor truck fires occur, although they are less frequent and do not present major problems. Large fires are rare, and do challenge the systems, the structure and operation.
- The consequences for ventilation: in longitudinally ventilated tunnels with moderate gradients (< 4%) an increase of the HRR can be accommodated by simply adding a few jet fans. In short tunnels there may be a problem as to where to install these additional fans.
- In a transversely ventilated tunnel the increase of the HRR requires a corresponding increase of the smoke extraction rate to ensure confinement of the smoke region. This requires more ventilation plant and associated infrastructure, larger duct sizes to avoid undue pressure drop, and these two factors alone have an impact on the cost of civil works.
- The possibilities for mitigation: it may be possible to reduce the risk of a large fire occurring through operational measures, e.g. escorting dangerous goods, or monitor and immobilize dangerous goods vehicles (e.g. HTVTS system in Singapore), or enhanced response, or additional systems such as fixed fire suppression systems and fast detection.

2.3.3. Considerations for Performance-Based Design

Determination of the worst-case fire event that may occur in a tunnel will always depend on the type of traffic allowed. It may not, however, be the design fire scenario, as the designer may accept a risk that is at an acceptably low level or employ a number of measures to reduce the fire risk. These measures can include strategies such as the use of fixed fire fighting systems, improved fire detection, improved response methods, operational measures such as the prohibition of certain dangerous products, and traffic management. At some point a decision is made to accept a certain risk level, when the cost of further mitigation measures become disproportionate to the benefit achieved. This implies that an acceptable level of residual risk, i.e. the risk level applicable after the mitigation measures have been implemented, has been achieved.

In a performance-based approach an analysis of potential fire hazards is the first step in the evaluation of risk. This will consider the range of vehicles that could use the tunnel, and the
anticipated vehicle numbers based, for example, on traffic volume modelling. Data such as that in PIARC report “Fire and Smoke Control in Road Tunnels” [7] or other data can be used to determine the fire scenarios which may occur during the design life of the tunnel.

If a performance-based design approach is used, the designer must be aware of the fact that the adoption of a reduced design fire does not mean that a larger fire will not occur, rather that the probability or the consequence of this event is acceptable from a design perspective. Furthermore, on the basis of a risk assessment approach, the designer may decide to use more than one design fire, for example, one for structure, to accommodate asset protection, and another one for the life safety systems such as the ventilation system. However, as noted in the Introduction, structural design normally adopts a time-temperature approach and is not discussed further here. The primary function of the ventilation system is to provide a tenable environment for both the user evacuation and emergency response phases. A performance-based approach would generally follow the steps outlined in illustration 2.
Illustration 2 - Outline of performance-based considerations
Step 1: is the definition of the main characteristics of the tunnel. Those characteristics are generally fixed and constant for the design, as they correspond to the aim of the transportation infrastructure. The potential fire hazard depends on the types vehicles permitted and the volume of traffic.

Step 2: is based on the establishment of safety objectives and operational requirements. For a fire hazard, safety objectives are commonly focused on, for example:

- Users, where the objective is to bring the probability of injuries and fatalities in line with safety level policies,
- Safe access for fire fighting,
- Minimise the damage to structures and equipment

Those safety objectives are generally fixed and defined by local policy, regulation and the level of risk assumed by the tunnel operator and tunnel owners.

Operational requirements are generally focused on the time and the cost allowed for closing and repairing the tunnel in case of a fire. Aspects that have to be considered includes requirements such as:

- The total capital cost to repair,
- The risk exported on diversion roads,
- The geological properties of the surrounding soil that can in some cases severely affect the time and the cost to repair in case of collapse of the tunnel structure,
- Operation losses during tunnel closure (toll tunnel),
- Financial impact on local economy during tunnel closure especially when the transit time on diversion roads is significantly increased.

Step 3 is the design process and focuses on the definition of the design fire. This is generally in line with the tunnel and traffic characteristics. However, different design fires may be used in the design process. The design of mitigation systems depends on the functionality required for each system and the probability of the fire events. For example, in tunnels where dangerous goods are permitted a high heat release rate may be selected, as self evacuation remains the priority. On the other hand, it may not be relevant to design the ventilation system beyond the capabilities of the fire fighter to approach and extinguish the fire.

Step 4: is the consideration of risk during which the evaluation of the safety level of the tunnel systems designed at Stage 3 are evaluated. If the design fire used for the design is less than the worst case fire, then it is recommended that the residual risk be evaluated.

Step 5: is the decision process of the design. It consists of accepting the design if the safety level evaluated in step 4 matches the safety level requirements defined in Step 2. If the safety level is not satisfied, the system has to be redesigned (Step 3). This might require improvement of the mitigation systems or an increase in the design fire size for which tunnel safety systems have to be designed.

Step 6: is not necessarily required, but can be used if optimisation of the design is appropriate for economic reasons, for example when the safety level of the tunnel system is higher than the safety
level requirement. The system is then redesigned (Step 3). It can consist of reducing the performance of the mitigation systems, or decreasing the design fire for which they have to be designed.

In a prescriptive approach, the authority, perhaps through existing guidelines, sets the design fire size and thus accepts the level of risk implied. In a performance-based approach, the designer selects a design fire size and must demonstrate that the risk of the system is below an acceptable level. When the designer proposes a design fire size it is important to apply a risk-based approach and also to consider the purpose of the safety design procedure. The purpose is to ensure adequate conditions with respect to smoke control during the time needed for evacuation, rescue and fire fighting. With respect to fire fighting, it is crucial to take into account the maximum heat radiation fire fighters are able to withstand in a fire-fighting situation. The Runehamar and other tests have shown that for fire sizes over 50-75 MW the heat radiation may be too high for the fire brigade to approach and extinguish the fire, or the fire may be insensitive to the actions of the fire service. Even relatively smaller fires, in the range of 20-30 MW, may exceed the levels at which the fire brigade is able to fight the fire. This needs to be considered in regard to the chosen design fire size.

If a heavy goods vehicle fire becomes fully developed it is possible that, even if fire-fighting operations are employed, this may have little impact in extinguishing the fire. However, any fire fighting water that is applied to the fire area will have a cooling effect on the fire plume.

Normally, fire-fighting operations would occur after the self-evacuation phase, but in the case of a rapidly developing fire, such as a tanker fire, intervention may not be possible at all. It is important to recognise this risk and appreciate that it does not invalidate the choice of a lower design fire.

It is clear that the Runehamar and other full scale fire tests have shown that the ventilation condition, the tunnel cross sectional area, and the height of the tunnel, influence the fire growth and the fire size, and these should be considered when the design fire characteristics are suggested for a specific tunnel.

Traditionally, requirements for structural and safety design were established around a safety definition, which was based on an empirical or intuitive approach. More recent efforts in defining safety are based on a risk based approach. Thus safety is defined in terms of appropriate liabilities, or tolerable failure probabilities.

2.3.4. Concluding Remarks

In a prescriptive approach, the design fire is set by the local authorities’ codes or standards, and there is no choice for the designer to make: the risks ascertained by the authority are implicitly accepted. In a performance-based approach, a process of design assessment will establish levels of risk that are acceptable. The starting point may be the prescriptive values adopted, modified in the light of mitigation measures and acceptable risk levels.

Between these two approaches, there are intermediate options that allow a degree of performance-based design on the basis of prescriptive guidance.
3. IMPLICATIONS ON THE DESIGN FIRE OF THE SMOKE-MANAGEMENT SYSTEMS

3.1. GENERAL

PIARC report “Fire and Smoke Control in Road Tunnels” [7] provides extensive details on smoke management and PIARC report “Road Tunnels: Operational Strategies for Emergency Ventilation” [16] discusses different ventilation methodologies and operational strategies. The purpose of this chapter is to highlight the main ventilation factors in the context of design fire sizes. The prime purpose of a smoke management system is to provide tenable conditions for self-rescue without exacerbating the growth of the fire. Moreover, it is to be applied in the best possible manner to support rescue and fire-fighting.

3.2. LONGITUDINAL SMOKE MANAGEMENT

Longitudinal ventilation systems induce a longitudinal flow along the axis of the tunnel, and this provides an efficient smoke-management system as long as the tunnel is occupied only on one side of the fire, thus assuming that traffic downstream can proceed out of the tunnel. Smoke is blown toward the unoccupied side, so that egress can be carried out in the upwind direction. This is achieved when the longitudinal ventilation is conducted at a velocity of at least the critical velocity. Too low a velocity would result in smoke propagation upstream of the fire (i.e. back-layering).

As shown in illustration 3, see for example [17], the critical velocity increases rapidly with the fire size up to about 50 MW and then only increases slightly with increased heat-release rate. Consequently, for many standard tunnel applications, it may only require the provision of additional jet fans and hence may be only a marginal increase in the capital costs required to provide for an increase in the longitudinal velocity and hence accommodate a larger fire size. Other impacts on ventilation of larger design fires were discussed in the PIARC report “Systems and Equipment for Fire and Smoke Control in Road Tunnels” [1].

Tests have shown that the fire-growth rate is proportional to the longitudinal air velocity (see appendix 2 and illustration A2.10) and that the maximum HRR also increases with longitudinal air speed. These effects need to be considered in the design and operation of such systems: see for example reference [16].
3.3. SMOKE EXTRACTION

Recent developments in semi-transverse smoke extraction aim at limiting the smoke spread on both sides of the fire. This enables egress away from the fire on either side. This method is essential in case of rescue from a fire in a tunnel with bi-directional traffic or traffic congestion. Some systems employ remotely controlled dampers that enable point extraction of smoke near to the fire. The construction costs for an extract system are higher than for longitudinal systems and since the required duct size increases with the heat-release rate, a larger design fire has an impact on the resulting investment costs.

The actual value for the extraction rate must consider the smoke production rate and the need for the aerodynamic management of smoke in the traffic space. Sufficient air needs to be provided in the direction of the extraction point (both upstream and downstream) to control the smoke flow and maximize the extraction efficiency. Traditionally, the dimensioning of the smoke extraction was about 150% of the smoke-production rate of the design fire, defined at a distance of 100 m from the fire (see reference [4]). This can be considered as the minimum smoke-extraction rate. Additionally, aerodynamic considerations for the management of the smoke in the traffic space apply. Taking the accuracy of the control of the longitudinal flow into account, this leads to a typical extraction rate of 2.5 to 4 times the tunnel cross section.

Ideally, the extraction system should cause air to flow in the traffic space, towards the fire on both sides, as shown in illustration 3.2, at a velocity proportional to the critical velocity modified by the fire heat content extracted. This confines the smoke region and increases the efficiency of extraction. Although increasing the fire size increases the extraction rate, in order to provide the amount of air required on both sides of the fire, the variation of critical velocity with fire size indicates that the requirement for extraction flow would not increase excessively for larger fire sizes. Note, however, where the extraction point is a long distance away from the smoke front, the fresh air velocity may need to be equal to the critical velocity.
The factors that affect the longitudinal velocity in the tunnel, such as buoyancy forces and the flow due to differences in ambient pressures at the portals, also influence smoke extraction efficiency, which deteriorates as the velocity increases. An increase in the design fire size makes this problem more severe, so it is essential to supplement the smoke extraction with a control of the longitudinal flow. Controlling the longitudinal velocity within a bandwidth of about ± 0.5 m/s is feasible but difficult.

Where the smoke-production rate exceeds the capacity of the smoke-extraction system, the action of the system still provides some improvement in the tenability conditions.
4. CONCLUSIONS

This report discusses the issues associated with the choice of design fires in road tunnels. The re-examination of this topic is prompted by the significant fires that have occurred in recent years and the subsequent tests that have been undertaken. Both the actual events and the tests have shown the possibility of fires that are larger than those generally found in codes and standards.

The implications of design fire size are profound on matters ranging from tunnel design, E&M design, sizing and operational strategies, refurbishment and recourse prioritization perspectives.

The purpose of this report is to give some direction to the choice of a design fire from a life-safety perspective. The report provides information on tests and the events that have brought the topic into question and also summarises the criteria for the design fire that are currently adopted in different countries. Structural response is dealt with on the basis of time-temperature curves and is not discussed in this report. However, it is interesting to note that the relationship between heat release rate, tunnel geometry, ventilation and gas temperatures arising from a fire have also been studied: see reference [29].

It is evident from the review of the practices currently applied that the choice of a design fire is not straightforward. Prescriptive values vary widely, from 30 to 300 MW, and depend on the type of traffic in the tunnel and in some cases the nature of the ventilation system employed. Because of this specific recommendations on the choice of design fire are not made in this report, but rather a basis of understanding of the major issues and information from actual and experimental fires is provided so that a reasonable choice can be made to suit the circumstances in a particular tunnel. In some circumstances, where a prescriptive value is adopted, it can be legitimately modified in accordance with the particular tunnel. Thus a prescriptive value for the design fire may be a starting point from which to consider whether the systems employed for safety in the tunnel can provide a basis for modifying the value. Where a prescriptive value cannot be challenged there may be no opportunity to determine its appropriateness.

A performance-based approach, where a defined level of risk is adopted and the design aims to achieve appropriate measures to meet the objectives, is good practice and used in many jurisdictions. However, even where a fire size is prescribed, modifying the design fire according to the particular features of the tunnel is not uncommon. For example, if a fixed fire suppression system is installed then it might be argued that the design HRR based on a prescriptive code may not be reached, and so a lower value taken for the design. The report outlines the main factors that are taken into account in this process.

Although the significant fire incidents that have occurred in recent years are relative rarities they do give some useful insights into the causes and consequences of fires in tunnels. It is clear that large fires, estimated up to about 100 MW can occur, e.g. Mt Blanc and Gotthard. Fires of smaller magnitude, e.g. the estimated 30 MW of the Viamala tunnel, can be problematical; this fire took ten hours to bring under control. Those where there has been a spread of the fire to adjacent vehicles, e.g. Nihonzaka and Mt. Blanc, appear to be very difficult to control, and take many hours or even days to bring under control.
It is interesting to note that the documented tanker fire at the Caldecott tunnel was dealt with quite promptly, within less than three hours, suggesting that the size and severity was not comparable to the solid fuel fires noted above. This raises the question as to whether a tanker fire, generally proposed at 300 MW size, is an appropriate design fire case. Drainage will obviously come into play in controlling the size of the liquid fuel source and hence the intensity of the fire. Solid fuel fires may therefore tend to be potentially more severe than liquid pool fires arising from a single tanker incident.

The performance of the ventilation systems reported in these actual events is variable, and in several cases is clearly not adequate. Smoke propagates over long distances in the tunnel, complicating egress and fire fighting. This is a ventilation design and operational issue, which is related to the growth and peak HRR.

The time of arrival of the fire services reported in these events was at least 15 minutes for all of the real fires noted. Based on the test results discussed in appendix 2, the fires undergo an incubation period when the HRR is fairly small, and then grow more rapidly until a peak value is reached. Tests indicate some reasonable consistency with regard to these times, the incubation times being between 3 and 8 minutes, and the growth time between 4 and 15 minutes. Thus, the time taken for the fire service to arrive at the tunnel and begin responding to the event seems to coincide quite closely with the time taken for the fire to reach its peak HRR, irrespective of the size of the fire. This suggests that the design fire should not be modified on the basis of the arrival of the fire service, and if a large fire size is adopted then ventilation systems should be sized such that the smoke spread can be limited and that the fire service can approach the fire to extinguish it. In this context the role of a fixed fire fighting system in reducing the design fire size is clear.

The reported events also reveal the difficulty of extinguishing the fire either due to the density of smoke or the intensity of radiation from the fire preventing the fire service approaching the fire source. It seems likely that once a fire reaches between 50 and 100 MW, then it becomes difficult to approach it.

Generally, prompt response combined with adequately sized ventilation systems prevents fires from escalating beyond the control of emergency services and allows for evacuation of the tunnel. The more serious fires have in common the spread of the fire to more than one vehicle, which affects the duration as well as the size of the fire. The risk of this is higher in a smaller diameter tunnel.

Evidently, specific recommendations for design fire sizes are not really possible since the circumstances of system design, traffic and tunnel geometry all have an influence. The type of traffic, such as the allowance of dangerous goods, is the most relevant driving factor. In the absence of dangerous goods, a modest fire size would be determined, e.g. on the basis of vehicle fire sizes presented in table 2. If dangerous goods are allowed, then the decision becomes more complex in the light of tests and experiences from real events. Fires in excess of 100MW are extremely rare and have proved difficult to extinguish. The probability of such events needs to be weighed against the initial and operating costs of the tunnel.

Currently an exact universal design fire cannot be specified, indeed to do so would be inconsistent with the known variability and probability of differing fire sizes in tunnels.
5. BIBLIOGRAPHY / REFERENCES


[7] PIARC TECHNICAL COMMITTEE ON ROAD TUNNELS “Fire and Smoke Control in Road Tunnels”, reference 05.05.BEN, PIARC, Paris, 1999


## GLOSSARY

<table>
<thead>
<tr>
<th>TERM</th>
<th>DEFINITION</th>
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<tr>
<td>extraction</td>
<td>Removal of air from the tunnel</td>
</tr>
<tr>
<td>longitudinal ventilation</td>
<td>Ventilation principle based on generating a longitudinal airflow in a tunnel, either to dilute pollutants or push smoke in one direction.</td>
</tr>
<tr>
<td>natural ventilation</td>
<td>Airflow created in a tunnel by natural conditions such as winds, atmospheric pressure differentials, temperature variations, etc.</td>
</tr>
<tr>
<td>semi-transverse ventilation</td>
<td>Ventilation system capable of either supplying fresh air or extracting vitiated air uniformly over part of the whole length of a tunnel.</td>
</tr>
<tr>
<td>stratification</td>
<td>Situation formed when hot combustion products form a layer of generally smoke-laden gases above a clear layer of cooler air.</td>
</tr>
<tr>
<td>transverse ventilation</td>
<td>Ventilation principle in which both the supply of fresh air and the extraction of vitiated air, smoke and hot gases can occur in the same section of a tunnel.</td>
</tr>
</tbody>
</table>
APPENDICES

As has been stated earlier, different fire characteristics are used for the design of the tunnel structure and for ventilation facilities. In the latter, the design fire has been traditionally based on the heat release rate or the smoke release rate versus time. This dependence upon time, as already noted, is very important for the evaluation of the conditions at the beginning of the fire, taking into account the evacuation phase.

Consequently, the recommendation of the PIARC report “Fire and Smoke Control in Road Tunnels” [7], previously described, have been broadly used in the guidelines of different countries. However, during recent years an important review of the national guidelines has been accomplished. Consequently, in the following paragraphs, a brief summary of the information, related to design fire characteristics is included. Further information can be found within the referenced documents.
1. PRACTICES ADOPTED IN DIFFERENT COUNTRIES

1.1. AUSTRALIA

Australia uses a performance-based approach for establishing the appropriate design response once the fire size is selected. The design response is broken up into two parts: the structural response (asset protection) and the response required to provide life safety for tunnel users. While no specific fire size is mandated for the ventilation system, generally a fire size of 50 MW is specified for road tunnels and 30 MW for bus tunnels. Given the design fire size, the designer is then required to perform egress modelling and assure safe egress in a tenable environment by the use of additional design elements which include the mandatory use of a deluge system.

The selection of the structural design fire varies from that required for the life safety (ventilation) response. The selection of the structural design fire can include the specification of a fire rating between various elements, and the determination of the probable design fire from a risk assessment where inundation or collapse may occur.

The determination of appropriate fire detection and response mechanisms undergoes an extensive consultation process with the Fire Brigade and other stakeholders to achieve an agreed outcome. This process is documented in the “International Fire Engineering Guidelines” (IFEG) and includes the development of a Fire Engineering Brief, a Fire Safety Assessment Report, the development of a trial design, and ensuring that the agreed solution is well documented for historical purposes. The final report must be continually updated by the asset owner and in particular if any design modifications are undertaken.

1.2. AUSTRIA

According to RVS 09.02.31, the specification of the ventilation system for tunnels of lengthwise gradients < 3% with two lanes and normal tunnel cross sections is carried out on the basis of a fire involving one heavy vehicle and two passenger cars which produces a smoke volume of 120 m³/s. The specification of ventilation systems for tunnels with combined passenger car and heavy vehicle traffic and for those with only passenger car traffic is to be carried out on the basis of 30 MW fires and 5MW fires respectively. In tunnels within the highest risk category the impact of a 50 MW fire has to be taken into account.

The impact of air pressure in the tunnel, due to temperature increases occurring under normal conditions, as well as in cases of fire, must be taken into account. The buoyancy effects caused by the fire are represented by a certain temperature increase calculated as a function of HRR, tunnel geometry, and distance from the fire. Efficiency losses of fans within the smoke regions have to be taken into account.

For longitudinal ventilation the fans must be designed in such a way that they can run in reverse and can provide an air flow speed of 2 m/s or an air volume flow of 120 m³/s in cases of fire under the set conditions defined in section 6.1 of RVS 09.02.31. The more critical of the characteristics just noted is decisive. Jet fans have to withstand temperatures of 250 °C over 90 min. In tunnels within the highest risk category the fan requirements are 400 °C over 120 m. In systems providing point smoke extraction, the capacity of the extraction fan must be at least 200 m³/s during a fire. Smoke extraction fans have to withstand 400 °C over 120 min.
In Transverse and Semi-transverse ventilation systems the ventilation system must be designed in such a way that in cases of fire in any part of the exhaust air duct minimally 120 m³/s must be extracted over a section of 150 m in length (reference values 20 °C and 1.013 bar). Exhaust gas fans as well as all equipment within the exhaust air duct has to withstand temperatures of 400 °C over 120 min.

1.3. CANADA

There is no specific method, or standard, in Canada for Design Fires in Road Tunnels. Recent projects are considering a case by case approach depending on the asset value and if failure may cause complete or partial tunnel loss (value and risk analysis). For equipment and subsystems of tunnels, NFPA 502 is considered and for structures, with no dangerous goods, about 30-50 MW.

1.4. FRANCE

The central technical reference is the Circular on Safety in Tunnels for the National Road Network, which was published in 2000. Its application to all road networks (national and local) has been made effective in practice by subsequent laws.

Ventilation systems must be dimensioned for a 30 MW fire (dimensioning is made in steady regime), considering the most unfavourable location of the fire. If hazardous materials are allowed in the tunnel, the design HRR is 200 MW for longitudinal ventilation. In the case of transverse ventilation, dimensioning the system for such a fire is regarded as too difficult and not as cost-effective as, for example, creating more emergency exits; the presence of dangerous materials is therefore not taken into account for the sizing of a transverse ventilation system. Lower values of HRR are used for reduced-height urban tunnels.

Jet fans must at least withstand a temperature of 200°C for 2 hours. However, it is now common practice to use jet fans which resist 400 °C for 2 hours since the dimensioning then requires fewer fans. For transverse ventilation, the standard is 200 °C for 2 hours but fans with a higher level of resistance are sometimes used when they are likely to be very close to a fire.

For the study of accident scenarios, the fire growth is assumed to be linear and the maximum HRR is reached after 10 minutes (5 minutes for the 200 MW petrol tanker fire). For tunnels where dangerous materials are prohibited, some scenarios are simulated with fires exceeding the design fires, with a HRR of 100 MW for example. The theoretical curves used in specific Hazard investigations for the study of fire scenarios are presented in the following illustrations:
1.5. GERMANY

In general the dimensioning of fire ventilation is based on a heavy goods vehicle fire HRR in accordance with table 1. The HRR is the extent of power reached or exceeded during the entire fire or only during a short time period of a few minutes. The minimum is 30 MW. In tunnels with a high volume of heavy goods vehicles, the possibility of one fire spreading over more vehicles and thereby creating a higher HRR needs to be taken into account.
The dimensioning above a HRR of 100 MW may result in ventilation system requirements that are no longer feasible technically or in terms of plant engineering. Therefore, risk analyses need to be performed in the individual cases, and if necessary special regulations need to be created, in order to achieve technically feasible and justifiable solutions in terms of cost.

Fans and dampers through which the smoke is extracted directly out of the traffic area, must be designed for operation at a minimum temperature of 400 °C for 90 minutes. Extraction fans connected to a suction channel with concrete walls are usually not exposed. With regard to the temperature resistance of the ventilation system, the following requirements apply to extraction fans to a heat exceeding 250 °C for a 90 minutes period (strong cooling effect of channel walls). Other constructions require a special examination of the temperatures.

Jet fans, including the electrical connections and feed cables in the traffic area, must operate at temperatures of 250 °C for 90 minutes. Short distances between (e.g. less than 150 m) the ventilator locations and the HRR > 30 MW may require higher temperature stability (max. 400 °C for 90 minutes)

The function of the ventilation system and automatic fire alarm system in the tunnel will be checked before a new tunnel goes into operation or after an extensive upgrade. To check the system, a fire is generated with a HRR of 5 MW (equivalent to 20 litres of gasoline on an area of 4 m2) combined with a longitudinal airflow of 6 m/s. The fire must be detected within one minute and then the ventilation system must begin to work.

Doors and gates in the emergency exits of road tunnels must be capable of withstanding fire for a period of 90 minutes. The fire resistance of the doors and gates is defined by the temperature-time curve (standardized) and additional provisions.

### TABLE A1.1. HRR MEASUREMENT

<table>
<thead>
<tr>
<th>Heavy goods vehicle x km/day and tube</th>
<th>HRR</th>
<th>Smoke volume at 300°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to 4.000</td>
<td>30 MW</td>
<td>80 m³/s</td>
</tr>
<tr>
<td>From 4.000 to 6.000</td>
<td>50 MW</td>
<td>120 m³/s</td>
</tr>
<tr>
<td>Above 6.000</td>
<td>Risk analysis and if applicable, increasing of HRR to 100 MW and smoke volume of 200 m³/s</td>
<td></td>
</tr>
</tbody>
</table>

Additional Technical Terms of Contract and Guidelines for Civil Engineering Works (ZTV-ING) Part 5: “Tunnelling” “Guidelines for Operation and Equipment of Road Tunnels” (RABT)

#### 1.6. ITALY

In the guidelines a risk analysis procedure is illustrated and suggested for the design of the tunnel, in order to verify that the minimum required safety level is reached. A fire size in the range 30-50 MW and a corresponding smoke production in the range 80-120 m³/s are suggested for a heavy goods vehicles; in the case of a tanker lorry the suggested range for the fire size is 100-200 MW and the proposed smoke production is 300 m³/s.

- DL 264 5th October 2006 on minimum safety requirements in the tunnels of the State Road Network belonging to Trans-European network (transposition to the Italian law of the European Directive 2004/54/CE).
- “Guidelines for safety design of road tunnels” from ANAS (formerly an acronym for Azienda
Nazionale Autonoma delle Strade), the Italian government-owned company deputed to the administration, the construction and maintenance of Italian road and motorways network under the control of Italian Ministry of Infrastructure and Transport.

- A QRA – one should read the standard to describe it fully.

### 1.7. NORWAY

Norwegian road tunnels always use longitudinal ventilation systems, the thrust of jet fans being designed to give a longitudinal air flow of minimum 3.5 m/s. The necessary air flow depends on the traffic volume, the tunnel length, the slope of the tunnel and the size of the design fire, the latter being based on the following criteria:

<table>
<thead>
<tr>
<th>Traffic Volume (vehicles/day)</th>
<th>Length (m)</th>
<th>Fire Size (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 4,000</td>
<td>&gt; 1000</td>
<td>20</td>
</tr>
<tr>
<td>4,000 – 8,000</td>
<td>500 – 1000</td>
<td>20</td>
</tr>
<tr>
<td>4,000 – 8,000</td>
<td>&gt; 1000</td>
<td>50</td>
</tr>
<tr>
<td>8,000 – 12,000</td>
<td>&lt; 1000</td>
<td>50</td>
</tr>
<tr>
<td>8,000 – 12,000</td>
<td>&gt; 1000</td>
<td>100</td>
</tr>
<tr>
<td>12,000 – 50,000</td>
<td>&lt; 1000</td>
<td>20</td>
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<td>12,000 – 50,000</td>
<td>&gt; 1000</td>
<td>50</td>
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<tr>
<td>&gt; 50,000</td>
<td>&lt; 1000</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>1000 – 2000</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>&gt; 2000</td>
<td>100</td>
</tr>
</tbody>
</table>

Only one-way traffic is allowed in tunnels with a traffic volume greater than 12,000 vehicles/day.

### 1.8. JAPAN

There is no specific regulation or standard in Japan for Design Fires in Road Tunnels. However, recently in some important tunnel projects, numerical simulations on smoke behaviour have been carried out on the basis of 30MW fires in order to verify that minimum required safety is reached.

### 1.9. PORTUGAL

The EU Tunnels Directive (2004/54/CE), transposed to the Portuguese law with the decree-law 75/2006, is the reference document for road tunnel safety in Portugal. While the EU Directive requirements are just applicable to tunnels of the European road network, the Portuguese law extended such requirements to the tunnels of the national road network also.

Usually the choice of the tunnel fire scenarios is based upon the PIARC recommendations; however, in some recent tunnels for general traffic including heavy good vehicles (no dangerous goods) the considered fire size is 100 MW, although this is not imposed by regulation.
1.10. SINGAPORE

Design fire sizes vary from 30 to 200 MW:

- Fire size depends on type of vehicle permitted and year of design/ completion;
- With FFFS for all new tunnels;
- Normally longitudinal ventilation system adopted;
- Hazmat Transport Vehicle Tracking System (HTVTS) with vehicle immobiliser to prevent hazardous goods vehicle from entering the tunnel.

1.11. SPAIN

The Spanish guidelines on minimum safety requirements in the tunnels of the State Road Network (transposition to the Spanish law of the European Directive) indicates that “Ventilation systems should be capable of exhaust the smoke for a minimum fire size of 30 MW and minimum air flow rate of 120 m3/s. (RD 635/2006)

1.12. SWITZERLAND

The Swiss Directive on the Ventilation of Road Tunnels formulates in chapter 7.2 the information and requirements on design fires. Even though a range for fires loads in MW is indicated in the directive (0 to 30 MW) the main requirements for the calculations is given as temperature and buoyancy distributions due to the fires. This approach was taken to ensure consistency in the design assumptions for all new tunnel ventilation design in Switzerland and to avoid varying assumptions and models by different designers.

Since the year 2000 all new tunnels as well as major refurbished tunnels in Switzerland have been adjusted to this design level. It is important to note that the indications of temperature strongly influence the necessary thrust of the jet fans in function of the tunnel slope.

On the Swiss highway network there are a number of bidirectional tunnels. In the Alps these tunnels have slopes up to 6.5%. Short (< 1 km) bidirectional tunnels of such slopes cannot be equipped with an adequate ventilation for the fire case [29].

In the guidelines, reference is made to the fire loads of the PIARC report “Fire and Smoke Control in Road Tunnels”, and the consideration that in the case of an HGV, higher fire loads can occur and that very high fire loads (tanker 200 MW) cannot be excluded.

The main requirement for the jet fan design is that the thrust be designed to be able to produce a longitudinal flow of 3 m/s in a unidirectional tunnel and of 2 m/s in a bidirectional tunnel in the case of fire. A more detailed calculation according to the critical velocity is not required. For extraction fan design the minimum required extraction capacity in m3/s at the fire location is 3.3 x AF for unidirectional tunnel with low congestion occurrence and 4 x AF for all other tunnels with AF = the tunnel cross-section. The duct leakage has to be added. These values are related to a fire with a HRR of 30 MW according to an analysis of the Memorial tunnel fire test data.

For the ventilation design an incident with a spill of dangerous (toxic) liquids or gases without any fire load (0 MW) has to be included. In an incident without an initial fire the ventilation
operation should be the same as with a fire at that location. The control system has to be able to adjust the ventilation response to varying buoyance forces during a fire.

The temperature measurements documented in the Memorial Tunnel Tests lead to the following buoyancy curve as a function of distance from the fire, for an air flow with the critical velocity at the fire location, and constant tunnel slope. For other cases (varying slope, heat leaving the tunnel, symmetric smoke spread) the curve has to be adjusted.

![Buoyancy Curve](image)

Illustration A1.2. - Local distribution of buoyancy due to a 30 MW fire at critical velocity in a tunnel of constant slope.

For the ventilation design a stationary incident has to be considered and the most unfavourable location is assumed to determine the ventilation capacity.

The calculation of starting phase of the fire has to include a linearly rising buoyancy force over 10 minutes. The relevant constant value for the pressure difference between the portals has to be included.

### 1.13. THE NETHERLANDS

The European Directive 2004-54-EC is implemented in the structure of Dutch laws and Building Codes. This has resulted in additional laws and codes on tunnel safety and an extension of the common Dutch Building Code (Bouwbesluit 2003).

The additional codes require both a QRA and a scenario analysis to be carried out when building a new tunnel or refurbishing a tunnel. This is meant to examine the internal safety. In these risk analyses several fires sizes have to be examined. The fire sizes are not defined in the additional codes but according to historical practice and taking into account international publications the fire sizes are assumed to be:
The effects of the fire sizes are implemented in the risk analysis by assumptions of the impact on life safety of temperature, radiation and amount of smoke, including concentrations of CO, and visibility depending the distance from the fire. In the risk analysis of fires caused by car break down and accidents, the following fire curves are assumed:

The type and capacity of ventilation is based on the fire size. In case of longitudinal ventilation the total thrust of jet fans should designed to give a longitudinal airflow of minimum 2.5 m/s for the larger fires 100 – 200 MW. For smaller fires the curve for backlayering speed as presented by PIARC is used. A fire size of 100MW is used for trucks, and if tankers are allowed then 200 MW is used as a design criterion for longitudinal ventilation.
It is accepted that in existing tunnels with a transverse system the smoke management capacity is not sufficient to fully handle the maximum fire sizes. The distance between escape doors should then be adjusted. Also additional detection and warning systems are applied to start up the escape process as soon as possible.

For structural behaviour the RWS-curve is used. This represents the temperatures for a 200 MW tanker fire. The same curve is used for truck fires, unless it is known that the fire magnitude reduces within about an hour.

1.14. UNITED KINGDOM

The reference for Design Fire in the UK is the Design Manual for Roads and Bridges, Design of Road Tunnels BD 78/99, which has the following table related to fire size:

<table>
<thead>
<tr>
<th>Vehicle Classification</th>
<th>Fire Load (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car</td>
<td>5</td>
</tr>
<tr>
<td>Van</td>
<td>15</td>
</tr>
<tr>
<td>Coach/Lorry</td>
<td>20</td>
</tr>
<tr>
<td>HGV, fully laden</td>
<td>30 – 100</td>
</tr>
</tbody>
</table>

However, the final choice of design fire load depends on the cost-benefit of using increased fire protection in comparison to increased reinstatement costs if a fire incident occurs.

For hazardous goods vehicles, the heat output of a pool fire is based on the liquid pool dimension which depends on the leakage rate from the tanker. The total heat output from the fire is calculated using a value of 43.7 MJ/kg for the heat of petrol combustion. However, it is assumed that, due to the reduced supply of air within a tunnel, the fire intensity will be limited to 100 MW. Nevertheless reference to design fires of 200 MW for petrol tanker and 300 MW for immersed tunnels in other countries is cited.

Although the guidance in the Design Manual for Roads and Bridges is still current, recent refurbishment projects have employed performance-based design using a design fire of 30 to 100 MW.

1.15. USA

The National Fire Protection Association (NFPA) publishes NFPA 502 Standard for Road Tunnels, Bridges, and Other Limited Access Highways. The standard specifies that the design fire size, defined as the heat-release rate produced by a vehicle or vehicles, shall be used to design the emergency ventilation system.

In the USA the tunnel designer in consultation with the tunnel owner are responsible to agree on the design fire size to be used. The selection of the design fire size shall consider; the types of vehicles that are expected to use the tunnel, rate of fire development, the number of vehicles that could be involved in the fire and the potential for the fire to spread from one vehicle to another.
Typical heat release rate are given in an Annex (for information only) as follows:

<table>
<thead>
<tr>
<th>Vehicles</th>
<th>Peak Fire Heat Release Rates (MW)</th>
<th>Time to peak HRR (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger car</td>
<td>5 – 10</td>
<td>0 – 30</td>
</tr>
<tr>
<td>Multiple passenger cars (2–4 vehicles)</td>
<td>10 – 20</td>
<td>13 – 55</td>
</tr>
<tr>
<td>Bus</td>
<td>20 – 30</td>
<td>7 – 10</td>
</tr>
<tr>
<td>Heavy goods truck</td>
<td>70 – 200*</td>
<td>10 – 18</td>
</tr>
<tr>
<td>Tanker</td>
<td>200 – 300 :</td>
<td>---</td>
</tr>
</tbody>
</table>

*Maximum registered for open truck.

Notes:
1. The designer should consider the rate of fire development (peak heat release rates may be reached within 10 minutes), the number of vehicles that could be involved in the fire, and the potential for the fire to spread from one vehicle to another.
2. Temperatures directly above the fire can be expected to be as high as 1000 °C to 1400 °C (1832 °F to 2552 °F).
3. The heat release rate can be greater than in the table if more than one vehicle is involved.
4. A design fire curve should be developed in order to satisfy each engineering objective in the design process (e.g. fire and life safety, structural protection, etc.).

Source: INGASON [30]
2. FIRE TESTS

2.1. BACKGROUND

Most of the information used for the definition of fire design characteristics comes from fire tests. For example, much of the information on smoke and heat generation included in the PIARC report of the Brussels Congress [4] was based in the results of the fire tests conducted in the Ofenegg tunnel, in Switzerland.

Later, most of the information used for the description of fire design characteristics within the PIARC report “Fire and Smoke Control in Road Tunnels” [7] was collected from the reports of the large scale fire tests conducted recently, which included the EUREKA EU 499 – FIRETUN Project in Europe, the Memorial Tunnel Tests in the United States.

2.2. QUANTIFICATION AND DETERMINATION OF FIRE LOADS IN TUNNELS

The essential characteristic that describes quantitatively the “fire size” is the Heat Release Rate (HRR), normally expressed, in the context of a tunnel, in MW. Although theoretical estimations of HRR have been used, e.g. the Mont Blanc tunnel fire investigation, recent discussions on fire size are associated with large-scale fire tests, where HRR has obtained through in-situ measurements.

In general, two kinds of techniques are available to directly measure HRR: open-burning HRR calorimeters and compartment fire tests. In the first case, some experiments have been completed with car size vehicles, as cited later. However, most of the values of HRR used in the literature have been obtained through large-scale tunnel fires, and the values obtained by the following methods:

• The designer should consider the rate of fire development (peak heat release rates may be reached within 10 minutes), the number of vehicles that could be involved in the fire, and the potential for the fire to spread from one vehicle to another
• Temperatures directly above the fire can be expected to be as high as 1000 °C to 1400 °C (1832 °F to 2552 °F)
• The heat release rate can be greater than in the table if more than one vehicle is involved
• A design fire curve should be developed in order to satisfy each engineering objective in the design process (e.g. fire and life safety, structural protection, etc.)

As in all kind of measurements, different uncertainties can be expected depending on the method used, so it is common to use more than one procedure to evaluate HRR during large scale campaigns.

2.3. RESULTS OF FIRE TESTS IN ROAD TUNNELS

2.3.1. Car fires

Much work has been done on car fire size. An exhaustive collection of HRR results for car size fires has been collected by Ingason and Lönnermark,[18]. Zhao and Kruppa [19], in a study of behaviour of a car park steel structure under fire action, presented an allocation of European cars
into five categories. These categories are based on the energy released during a fire based on the average mass and the energy released.

Based on these results, different attempts have been made, e.g. [20], to define heat release rate curves for car fires, expressed by analytical expressions. The authors cited report that the HRRs for single passenger car varies between 1.5 and 8 MW, with most being less than 5 MW. The HRR may rise to about 10 MW when two cars are involved. The time taken to reach peak HRR varies widely in the reported experiments, being between 10 and 55 minutes. Reports of other fire tests on vehicles can be found in references [21] to [25].

Hence, the results of these studies are generally in accord with prescriptive values normally assumed for the design fire size for passenger car fires.

2.3.2. Heavy Good Vehicles (real and simulated loads)

The number of large scale fire tests involving HGV in which measurements of HRR has been accomplished is not so numerous as for passenger cars. However, the most broadly referred are the following.

**Eureka 499-Project**
In the Eureka-project EU499 [8] full-scale tests were conducted in the disused Repparfjord Tunnel in Norway. The overall objective of the tests was to investigate parameters that affect the protection of people and preservation of property in the event of fires in underground transportation facilities.

The project consisted of 20 full-scale fire tests of road and rail transportation vehicles, wood cribs, and heptane pools. Extensive instrumentation was used to measure gas temperature and velocity profiles, tunnel surface, temperatures, heat fluxes, smoke obscuration, and gas composition at various distances in both directions from the location of the fire. Temperatures and mass loss of the burning object were also measured. Several approaches were used to determine the heat release rate of the burning object based on the available temperature, velocity, and gas composition data. *Table A2.1* summarises the main details.
TABLE A2.1. EUREKA TEST SUMMARY

<table>
<thead>
<tr>
<th>Tunnel Geometry</th>
<th>Fire Load</th>
<th>Test Parameters</th>
<th>Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.3 km</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slope:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1% N-S</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross-section:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area = 34 m² (±4 m²)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horse-shoe rock</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross-section with flattened ceiling and concrete floor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Isolation of walls:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tunnel ceiling and walls in the immediate vicinity of the fire load (260 m – 345 m) were lined with a steel-fibre reinforced light-weight shotcrete</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Materials:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>wood, plastics, heptane</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wood crib:</td>
<td>“WC”</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Private car:</td>
<td>“PC”</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Public bus:</td>
<td>“PB”</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heavy goods vehicle:</td>
<td>“HGV”</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heptane pool fire:</td>
<td>“HP”</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plastic vehicle:</td>
<td>“PV”</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lorry load (wood+tyres+plastic)</td>
<td>“MF”</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Humidity:</td>
<td>80-95%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blockage ratio:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WC: 2.4/5.5 = 0.44</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HP: 0.3/5.5 = 0.05</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC: 1.45/5.5 = 0.26</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PB: 3.2/5.5 = 0.58</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HGV: 4.25/5.5 = 0.77</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PV: 2.0/5.5 = 0.40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MF: 2.4/5.5 = 0.44</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arrangement:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fire load was arranged centrally with respect to the tunnel cross-section at 293 m from the north portal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ambient conditions:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prevailing wind in the N-S and S-N directions in winter and summer, respectively.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air velocity (m/s):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WC: 0.3-2.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HP: 0.6-2.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC: 0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PB: 0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HGV: 3.4 – 6.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PV: 0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MF: 0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FFFS: N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiation:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 pyrometers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air velocity:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>76 bi-directional probes and anemometers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smoke:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>34 Opacimeters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 optical density</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gases analysers:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24 CO/CO₂/O₂/SO₂/C₄H₁₀/NO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass loss:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 weighing platforms for WC and ML tests</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Observations:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13 videos cameras (stationary &amp; variable, infrared)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Illustration A2.1* shows the measured heat release rates versus time for tests conducted with wood cribs, a public bus, a plastic car, mixed fuel, heptane pool fire, and a heavy goods vehicle as the fuel sources.

For design purposes it may be useful to consider the fire behaviour in an idealized manner, representing the various stages of ignition, growth, steady state and decay. Such curves are also shown, for each type of fuel load, in *illustration A2.1*. The idealized curves for all tested fuel loads and the key data are shown in *illustration A2.2*.

In developing these idealized curves, some constraints or criteria were respected. The total energy released, growth rate, and decay rate of the idealized curves were approximately maintained the same as the experimental data.

The fire HRR varies considerably even within a single vehicle class. No recommendation is made, therefore, for a single idealized curve for design use. The concept is presented, however, as a possible characterization of the design fire, the actual parameters being adjusted on a case-by-case basis.
Illustration A2.1 - Measured total heat release (HRR) - 1/3

h_{f} / h_{T}: height of the fuel / height of the tunnel section
Plastic Vehicle  \( (h_f/h_T = 0.40) \)

Public Bus  \( (h_f/h_T = 0.58) \)

\( h_f \): height of the fuel / \( h_T \): height of the tunnel section

*Illustration A2.1 - Measured total heat release (HRR) - 2/3*
Simulated Lorry Load ($h_f/h_T = 0.44$)

Mixed Fuel: Woodcribs (72%), Tyres (12.5%), and Plastic (12.5%)

HGV ($h_f/h_T = 0.77$)

$T_{ambient} = 13^\circ$C, $V = 3.0$ m/s, $E = 87,400$ MJ

$h_f$: height of the fuel / $h_T$: height of the tunnel section

*Illustration A2.1 - Measured total heat release (HRR) - 3/3*
Illustration A2.2 - Idealized HRR-time curves

- $t_{inc}$ = duration of incubation phase
- $t_g$ = duration of growth phase
- $t_s$ = duration of steady-state phase
- $t_d$ = duration of decay phase
- $t_f$ = total duration time of fire
Referring to *illustration A2.2*, the defined timescales of the idealized curves illustrate:

- $t_{\text{inc}}$: time from ignition until the fire is producing flame (smouldering region)
- $t_{g}$: time from end of incubation to maximum heat release (fire growth region)
- $t_{s}$: duration time of the steady-state region
- $t_{d}$: time from the start of the decay of the HRR to the end of it (decay region)
- $t_{T}$: duration time of the fire from ignition

It can be seen that the time for the fires to grow are between 7 and 12 minutes, relatively short durations in the context of evacuation and response. The duration of the fires varies considerably. The HGV fire has the shortest duration and was the most intense fire. However, it should be noted that the fire size was influenced by ventilation, the 140 MW being associated with a ventilation air velocity of 6 m/s. The influence of air velocity on fire size is discussed further below.

**BENELUX tunnel tests**

The Benelux tests [9] were performed in tube D of the 2nd Benelux tunnel near Rotterdam, Netherlands. The cross-section is approximately rectangular, with a width of 9.8 m and a height of 5.1 m. The ceiling was originally protected by an insulating material; extra insulation was added over a length of 75 m around the fire during the tests, on the ceiling, sidewalls and floor. A sand bed was also used to protect the floor and absorb spilt fuel.

For these tests, the HGV loads were simulated by means of a construction with a synthetic canvas and a stack of loading pallets underneath to achieve a rate of heat release of approximately 20 MW in conformity with that of a small HGV (4.5 m x 2.4 m x 2.5 m).

The cargo area, also referred to as ‘aluminium HGV hood’, consisted of a steel sheet floor with a self-sustaining hood made up of aluminium sheets. The side and front walls of the hood consisted of nine flanged sheets that were assembled by means of a bolt connection. The cargo area was loaded with 4 stacks each having 9 wooden Euro-pallets (in total 36 pieces) and a car tyre on top of each stack. The load was ignited by lighting two small bowls of petrol that were placed in the middle of the cargo floor between the wooden stacks.

An additional test (number 14) comprised two rows each having four wooden stacks placed on the weighing platform. Each stack consisted of nine wooden Euro-pallets. In total 72 pallets were burned in order to realise a maximum rate of heat release of approximately 40 MW. In order to have extra smoke developing, 6 car tyres were added. Schematics of the test setups are given in *illustration A2.3*. 
TABLE A2.2. SUMMARY OF BENELUX TESTS

<table>
<thead>
<tr>
<th>Test #</th>
<th>Fire load</th>
<th>Intended HRR (MW)</th>
<th>Intended air velocity (m/s)</th>
<th>Ventilation</th>
<th>Sprinkler</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pool</td>
<td>5</td>
<td>0 – 1</td>
<td>Off</td>
<td></td>
</tr>
<tr>
<td>2a</td>
<td>Pool</td>
<td>5</td>
<td>0 then 6</td>
<td>Switched on with a delay</td>
<td></td>
</tr>
<tr>
<td>2b</td>
<td>Pool</td>
<td>5</td>
<td>0 to 6</td>
<td>Progressive build-up</td>
<td></td>
</tr>
<tr>
<td>3a</td>
<td>Pool</td>
<td>5</td>
<td>0 – 1</td>
<td>Off</td>
<td></td>
</tr>
<tr>
<td>3b</td>
<td>Pool</td>
<td>20</td>
<td>0 then 6</td>
<td>Switched on with a delay</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Pool</td>
<td>20</td>
<td>0 to 6</td>
<td>Progressive build-up</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Passenger car</td>
<td>5</td>
<td>0 – 1</td>
<td>Off</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Passenger car</td>
<td>5</td>
<td>0 – 1</td>
<td>Off</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Passenger car</td>
<td>5</td>
<td>6</td>
<td>On</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Canvas hood, 36 pallets, 4 tyres</td>
<td>20</td>
<td>0 – 1</td>
<td>Off</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Canvas hood, 36 pallets, 4 tyres</td>
<td>20</td>
<td>6</td>
<td>On</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Canvas hood, 36 pallets, 4 tyres</td>
<td>20</td>
<td>6</td>
<td>On</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Van with 18 pallets</td>
<td>10 – 15</td>
<td>1</td>
<td>On</td>
<td>Delayed activation</td>
</tr>
<tr>
<td>12</td>
<td>Aluminium hood, 36 pallets, 4 tyres</td>
<td>20</td>
<td>3</td>
<td>On</td>
<td>Immediate activation</td>
</tr>
<tr>
<td>13</td>
<td>Aluminium hood, 36 pallets, 4 tyres</td>
<td>20</td>
<td>0 – 1</td>
<td>Off</td>
<td>Delayed activation</td>
</tr>
<tr>
<td>14</td>
<td>72 pallets, 6 tyres</td>
<td>35</td>
<td>0 – 1</td>
<td>Off</td>
<td>Delayed activation</td>
</tr>
</tbody>
</table>

**Illustration A2.4** compares the fire tests with potentially higher loads and without fire suppression influencing the HRR, specifically tests 9, 10, 11 and 14.

Tests 9 and 10 both have 36-pallet stacks under a canvas, with a longitudinal airflow of about 6 m/s. The results compare well with each. The growth rate is a bit higher in test 9, and so is the peak HRR; the ventilation system was working at full capacity during the growing phase, whereas it was only at 50% in the first minutes of test 10. Both tests show an incubation time of about 4 minutes.
Test 14 involved a pallet stack about twice as large as in 9 and 10, with almost no longitudinal air flow. A sprinkler system was tested but according to the report, it was only activated after 22 minutes in the fire region, at a time when the fire was almost out. A sprinkler system was actually operated earlier further downstream of the fire, over a tanker that served as fire target. The idea was to investigate the cooling efficiency of the sprinkler system on the tanker while keeping the fire HRR high. The behaviour of this fire is very similar to the previous ones. The incubation time is a bit longer (5-6 minutes), perhaps due to the weak ventilation; the growth rate is similar in the linear phase (about 7 MW/min). The decay is a little faster. From this comparison, the repeatability of pallet stack fires seems good, and the qualitative behaviour is consistent regardless of the ventilation conditions. Strong ventilation reduces the incubation time and maybe accelerates growth.

Test 11, a van loaded with 18 pallets and a weak longitudinal air flow (1 m/s), with late activation of the sprinkler system. This test is quite difficult to interpret. In contrast with the other tests described, the van is set on fire using a small petrol bowl placed on the driver’s seat. However, the HRR is 2 MW from the very beginning of the test, which is probably a measurement error. If we regard this HRR as zero, the incubation time is quite long (6-7 minutes) and the growth is slow. The activation of the sprinkler system after 13 minutes probably prevents the HRR from reaching a peak higher than 7 MW, a value that seems moderate regarding the load.

Runehamar tests
The Runehamar large-scale fire tests were conducted in 2003 in an abandoned tunnel in Norway. The 1600 m tunnel has a cross section at the fire site of about 9 meters wide and 6 meters high. The area was reduced to about 50 m2 due to the installation of a steel structure that supported the fire protection boards.

In total four tests were performed with a fire in a semi-trailer set-up. In three tests mixtures of different chosen cellulose and plastic materials were used, and in one test a “real” commodity consisting of furniture and fixtures was used. In all tests the mass ratio was approximately 80% cellulose and 20% plastic. A polyester tarpaulin covered the cargo.
Illustration A2.5 shows the test configurations. Table A2.3 provides the main details of the test results and illustration A2.6 shows the variation of HRR with time for the tests.

Illustration A2.5 - Illustration of runehamar test setup
TABLE A2.3. RUNEHAMAR TEST DATA

<table>
<thead>
<tr>
<th>FIRE LOAD</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Test 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Materials</strong></td>
<td>Wood pallets and plastic pallets (11010 kg)</td>
<td>Wood pallets and mattresses (Polyurethane) 6853 kg</td>
<td>Furniture and fixtures + rubber tires (7530 + 800 kg)</td>
<td>Plastic cups (Polystyrene) in cardboard boxes on wood pallets (2849 kg)</td>
</tr>
<tr>
<td><strong>Arrangement</strong></td>
<td>A trailer load with total 11.1 ton wood (82%) and plastic pallets (18%). 360 wood pallets measuring 1200 800 150mm, 20 wood pallets measuring 1200 1000 150mm and 74 PE plastic pallets measuring 1200 800 150mm—122m² polyester tarpaulin.</td>
<td>A trailer load with total 6.8 ton wood pallets (82%) and PUR mattresses (18%). 216 wood pallets and 240 PUR mattresses measuring 1200 800 150mm—122m² polyester tarpaulin.</td>
<td>A trailer with 8.5 ton furniture, fixtures and rubber tyres. Furniture and fixtures (tightly packed plastic and wood cabinet doors, upholstered PUR arm rests, upholstered sofas, stuffed animals, potted plant (plastic), toy house of wood, plastic toys). Ten large rubber tyres—122m² polyester tarpaulin.</td>
<td>A trailer mock-up with 2.85 ton corrugated paper cartons filled with plastic cups (19%). 600 corrugated paper cartons with interiors (600mm 400mm 500mm; L W H) and 15% of total mass of unexpanded polystyrene (PS) cups (18,000 cups) and 40 wood pallets (1200 1000 150mm)—10m² polyester tarpaulin.</td>
</tr>
<tr>
<td>FIRE LOAD PLATEAU (GJ)</td>
<td>244</td>
<td>135</td>
<td>179</td>
<td>62</td>
</tr>
<tr>
<td>Growing time (Time from ignition to peak HRR (min))</td>
<td>18.5</td>
<td>14.1</td>
<td>10</td>
<td>7.4</td>
</tr>
<tr>
<td>Maximum HRR value (MW)</td>
<td>201.9</td>
<td>156.6</td>
<td>118.6</td>
<td>66.4</td>
</tr>
<tr>
<td>Peak Temperature (°C)</td>
<td>1365</td>
<td>1282</td>
<td>1281</td>
<td>1305</td>
</tr>
</tbody>
</table>

Referring to illustration A2.6, it can be seen that the incubation time is about 4-6 minutes and the growth time, from developed fire to peak HRR, ranges from 4 to 10 min. The growth rate varies from 15 to 30 MW/min. Ventilation effects were also noted in these tests. In tests 1 and 2 a pulsation of the fire was observed which “created a pulsating flow situation at the measuring station, where the measurements showed that the maximum velocity was pulsating in the range of 3 to 4 m/s down to a minimum in the range of 1 to 1.5 m/s” [11].

It is interesting to compare the test configurations of the Benelux and Runehamar tests. The arrangements for Benelux tests 8 and 10 are qualitatively similar to that of Runehamar test 1 with the following quantitative differences:

- Runehamar T1 involved 380 wood pallets and 20 plastic pallets; the fire load was therefore about 11 times larger than in the Benelux tests.
- The Runehamar tunnel cross-section was significantly smaller (dimensions between the protection boards: width 7.1 m, maximum height 5 m)
Memorial tunnel fire ventilation test program

Other large-scale fire tests have been conducted to evaluate the fire and smoke behaviour in tunnels using pool fires. In most of them, measurements showed a clear correlation between the pool surface and maximum HRR. Nevertheless, due to the immediate development of the flashover phase, no interesting findings can be stated on this topic. One of the most complete large-scale fire test campaigns involving pool fires was the Memorial Tunnel.

The Memorial Tunnel Fire Ventilation Test Program (MTFVTP) [13] consisted of a series of full-scale fire tests conducted in an abandoned road tunnel. Various tunnel ventilation systems and configurations of such systems were operated to evaluate their respective smoke and temperature management capabilities. These tests generated a significant database relevant to the design and operation of road tunnel ventilation systems under fire emergency conditions.

The Memorial Tunnel is located near Charleston, West Virginia. This is a two-lane, 2800-foot long, mountain tunnel having a 3.2% grade. In preparation for the MTFVTP, the tunnel was modified and instrumented to allow operation and evaluation with the following ventilation system configurations:

- Full Transverse Ventilation
- Partial Transverse Ventilation
- Partial Transverse Ventilation with Single Point Extraction
- Partial Transverse Ventilation with Oversized Exhaust Ports Point Supply and Point
- Exhaust Operation Natural Ventilation
- Longitudinal Ventilation with Jet Fans

Illustration A2.6 - Runehamar test results [12]
The tunnel was equipped with instrumentation and recording equipment for data acquisition. Sensors measuring air velocity, temperature, carbon monoxide (CO), and carbon dioxide (CO2) were installed at various tunnel sections. Data from these sensors were recorded. Smoke generation and movement and the resulting effect on visibility was assessed using seven remote-controlled television cameras with associated recording equipment.

Ventilation system effectiveness in managing smoke and temperature movement was tested for the following fire sizes: 10, 20, 50, and 100 megawatts (MW). The heat release of a 20 MW fire is approximately equivalent to a bus or truck fire, and a 100 MW fire is equivalent to a flammable fuel spill feeding a pool approximately 44.6 m² (480 sq ft) in area.

In addition to varying the fire size, systematic variations were made in airflow quantity, longitudinal air velocity near the fire, and fan response time for each ventilation system. Tests were also conducted to assess the impact of longitudinal air velocities on the effectiveness of a foam suppression system.

In the MTFVTP, various smoke management strategies and combinations of strategies were employed, including extraction, transport, control direction of movement, and dilution to achieve the goals of offsetting buoyancy and external atmospheric conditions and to prevent backlayering. A total of 98 tests were conducted.

The basic findings to date are summarized below:

• The ASHRAE criteria of 0.155 m³/s per line-meter (100 cubic feet minute per lane-foot) of tunnel for emergency road tunnel ventilation has been used as a minimum design basis for many years. However, there had been no validation of this value. The tests showed that longitudinal airflow near a fire affects the required extraction rate for temperature and smoke management. Hence, specifying a ventilation rate for temperature and smoke management, solely on its extraction capabilities, is an insufficient design criteria.

• Longitudinal ventilation using jet fans was shown to be capable of managing smoke and heat resulting from heat releases up to 100 MW. The required longitudinal air velocity to prevent backlayering in the Memorial Tunnel was approximately 600 feet per minute (3 m/s) for a 100 MW fire. Since the longitudinal velocity generated by jet fans will manage temperature and smoke only on one side of the fire, to the detriment of smoke and temperature conditions on the opposite side, such systems should be applied only in road tunnels with uni-directional traffic flow.

• Jet fans positioned downstream of, and close to, the fire were subjected to temperatures high enough to cause failure. Accordingly, this condition needs to be considered in the system design and selection of emergency operational modes.

• Full transverse ventilation systems can be installed in single-zone or multi-zone configurations and can be operated in a balanced or unbalanced mode. Single-zone, balanced (equal flow rates for supply and exhaust air) full transverse systems indicated very limited smoke and temperature management capability. Ventilation-rates of 0.155 m³/s per line-meter (100 cfm/lf) exhaust capacity did not manage conditions resulting from heat release rates of 20 MW and greater, unless the system was operated in an unbalanced mode (reduced supply airflow). Single-zone full transverse systems operated in the unbalanced mode had improved temperature management capability. However, even 0.155 m³/s per line-meter (100 cfm/lf) exhaust capacity provided only limited temperature and smoke management for a 20 MW
heat release rate. Multiple zone full transverse systems have the inherent capability to manage smoke and temperature by creating longitudinal airflow.

- Partial transverse ventilation systems can be installed in single-zone or multi-zone configurations and can be operated in supply or exhaust mode. Single-zone partial transverse systems capable of only supplying air (no possible reversal of fans to exhaust air) were relatively ineffective in smoke or temperature management. Single-zone partial transverse systems which can be operated in the exhaust mode provided a degree of smoke and temperature management.

- Longitudinal airflow is a significant factor in the management of smoke and heat generated in a fire. Ventilation systems which effectively combine extraction and longitudinal airflow can significantly limit the spread of smoke and heat. Multiple-zone ventilation systems allow control over the direction and magnitude of longitudinal airflow, and can effectively manage smoke and temperatures in the tunnel. Two-zone partial transverse ventilation with 0.155 m$^3$/s per line-meter (100 cfm/lf) effectively managed 20 MW heat release rates.

- Single point extraction (SPE) is a ventilation system configuration capable of extracting large volumes of smoke from a specific location through large, controlled openings in a ceiling exhaust duct, thus preventing extensive migration of smoke. These openings range from 9.3 to 28 m$^2$ (100 sq ft to 300 sq ft) in size and are generally spaced on 91.5 m (300 ft) distributed along the tunnel. The SPE transverse type system effectively managed smoke and temperature conditions for a 20 MW fire with ventilation rates lower than 0.155 m$^3$/s per line-meter (100 cfm/lf). SPE systems are applicable to bi-directional traffic flow, with a degree of dependency, however, on the location and spacing of the SPE openings. Smoke and heat being drawn from the fire to the SPE opening could pass over or possibly around stalled traffic and vehicle occupants.

- Oversized exhaust ports (OEP) are a modification to transverse type systems which provides smoke extraction capability in the immediate location of a fire. The concept consists of 2.8 m$^2$ (30 sq ft) oversized exhaust ports spaced approximately 9 m (30 ft) and designed to fully open when subjected to the heat of a fire. Significant improvements in temperature and smoke conditions were obtained using OEPs relative to the basic transverse ventilation system using conventional size exhaust ports. The OEP enhancement is also applicable to tunnels with bi-directional traffic.

- Natural ventilation resulted in extensive spread of heat and smoke upgrade of the fire. However, the effects of natural buoyancy are dependent on the fire size and the physical characteristics of the tunnel.

- Fan response time, the interval between the onset of a fire and ventilation system activation, should be minimized since hot smoke layers can spread quickly, e.g., up to 490 to 580 m (1600 to 1900 ft) in the initial two minutes of a fire.

- The maximum temperature experienced at the inlet to the central fans (closest location to the fire approximately 213 m (700 ft) was 163 °C (325 °F) for a 100 MW fire, 124 °C (255 °F) for a 50 MW fire, and 107 °C (225 °F) for a 20 MW fire.

- The restriction to visibility caused by smoke occurs more quickly than does a temperature high enough to be debilitating. Carbon monoxide (CO) levels near the roadway never exceeded the guidelines established for the Test Program.

- The effectiveness of the foam suppression system was not diminished by operation in strong longitudinal airflow. In the MTFVTP, the system was operated and tested in conditions with 4 m/s (800 fpm) longitudinal air velocity.

- Adequate quantities of oxygen to support combustion were available from the tunnel air. The possible increase in fire intensity resulting from the initiation of ventilation did not outweigh the benefits.
Table A2.4 presents a summary of the actual measurements for the different tests examined.

<table>
<thead>
<tr>
<th>Table A2.4. SUMMARY OF TEST MEASUREMENTS</th>
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<tbody>
<tr>
<td>Test Program</td>
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</tr>
<tr>
<td>Eureka</td>
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<td>Benelux</td>
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<td>Runehamar</td>
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RWS fire suppression tests – Runehamar 2008

In January 2008 RWS conducted full scale fire test [14] on the water based fire suppression system designed for use in the A74 Roermond Tunnels in the Netherlands. The tests were carried out in the same location, and under similar conditions to, the earlier full-scale fire tests carried out at Runehamar by the Swedish Fire Research establishment. The objectives were to demonstrate the ability of a water mist fire suppression system to reduce significantly the heat output from a solid fire, and the ability of the system to extinguish a large flammable liquid fire.

The test layout is shown in illustration A2.7 and comprised 3 sections of 25 m in length, spray nozzles every 2 meters a flow 3.000 l/min pressure 50 bar and AFFF mixing units.
The test program considered solid and liquid fuel fires in the range anticipated range of 50 to 200 MW, as follows:

<table>
<thead>
<tr>
<th>TABLE A2.5. RWS FIRE SUPPRESSION TESTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 MW Solid (with AFFF)</td>
</tr>
<tr>
<td>200 MW Liquid (with AFFF)</td>
</tr>
<tr>
<td>200 MW Liquid (without AFFF)</td>
</tr>
<tr>
<td>200 MW Liquid (with bioversal)</td>
</tr>
<tr>
<td>200 MW Solid (without AFFF)</td>
</tr>
</tbody>
</table>

The flammable solid fires were similar to the 2003 full-scale fire tests, representing loaded trucks with wooden and plastic pallets. The flammable liquid fires utilised a 100 m² diesel pool. Ventilation air speeds were up to 5 m/s.

Temperature measurements are shown in *Illustration A2.8*, showing that one minute after activation of the watermist the solid fire temperatures are reduced to less than 50 °C 20 m upstream and less than 280 °C 5 m down-stream. The liquid fire is extinguished.
Tenability tests were also undertaken to determine conditions 20 and 300 m down stream of the fire, the parameters measured were temperature, CO concentration and visibility. *Illustration A 2.9* show the results at 300 m. It is clear that the conditions are untenable prior to the activation of the suppression system, but are restored afterwards.
Illustration A2.9 - RWS suppression tests – tenability
2.4. DISCUSSION

The tests presented provide a useful database with regard to the form of the fire curve, considering the incubation period of the fire, the subsequent growth and peak value of HRR, and the decay time. The tests also show some specific correlation between some of the characteristics apparent in a tunnel and the aforementioned fire characteristics, such as the correlation between the fire load (combustible energy) and the peak heat release rate, and the impact of the air velocity in the tunnel and the fire growth and peak HRR. This effect was observed in the Runehamar test and, probably, on the EUREKA 499 Fire tests. This is important to consider, especially for narrow tunnels.

Fire growth and peak HRR, for open fires, show a substantial increase in conditions of higher air velocity. This is also in line with what would be expected, since it is well known that air forced over a fire increases the burning rate. The reason is twofold: more oxygen is transported to the fuel, increasing the combustion rate, and the deflection of the flame increases fire spread and consequently the fire growth rate. However fires in enclosed vehicles, where the air velocity is not able to contact the fire centre, do not behave in the same way as for open fires.

The fire tests in the Benelux tunnel indicated a fire growth rate twice as fast with an air velocity of 4-6 m/s compared with the fire growth rate without ventilation. The same test showed about 1.5 times the peak HRR rate at an air velocity of 4-6 m/s than without ventilation.

The increase in fire growth when increasing the air velocity can be estimated to be about 3.5 – 5.5 times higher if the air velocity is increased from zero up to 4-6 m/s. In the Benelux Test 9, the increase in fire growth rate was about 5.5 and in test 10 about 3.5. A study comparing results from full scale and small-scale tests verifies that the impact of air velocity on the fire growth almost follows a linear correlation, illustration A2.10, reference [26].

The impact of air velocity on the peak HRR is also demonstrated in the EUREKA HGV fire test with varying ventilation condition, 6m/s, 0m/s and 3m/s. The heat release rate was reduced from 120 MW at a forced air velocity of 6 m/s to nearly 42 MW without forced ventilation, i.e. a factor of three. When the fan was restarted with an air velocity of about 3 m/s, the heat release rate increased rapidly up to about 128 MW.
Since the ventilation operating conditions influence the growth rate and HRR, it follows that the tunnel section characteristics, such as ceiling height and cross sectional area, must also influence the fire development. Therefore, the impact of these characteristics on the fire growth and fire
size should be considered in the assessment of test results. In the Runehamar Test 1 the rock tunnel cross section area was about 50 square meters. At the location of the fire an additional inner tunnel was set up to function as protection of the rock tunnel. That inner tunnel cross-section area was about 32 square meters. In that section, stacks of wood and plastic pallets, simulating a loaded truck, were placed.

The distribution of the fire load is also likely to influence the test results. The Runehamar test (T1) exceeded higher heat release rates than the EUREKA HGV’s 100-120 MW, but it is important to consider that the test setup with wood and plastic pallets was extraordinarily well ventilated due to the free air flow through the open pallets and accordingly gave an ideal combustion situation. The Runehamar test (T3) with upholstered furniture, fixtures, plastic and wood cabin doors and rubber tyres showed that fire development in an early phase was faster but did not reach the high HRR as test (T1) although the fire load was almost the same. The most significant difference between these two tests was the shape of the combustible material and the exposed surface area accessible for oxygen and burning. A more compact set up of fire load leads to less surface area per kg of combustible material and accordingly a lower HRR. The HRR measured in test (T3) correspond better with the EUREKA HGV test.
3. EXPERIENCES FROM REAL FIRES

3.1. NIHONZAKA TUNNEL, JAPAN (11 JULY 1979)

The Nihonzaka tunnel consists of two 2 km-long tubes with unidirectional traffic. There were no restrictions on hazardous materials travelling through the tunnel, although this changed as a result of the fire. The fire was started by a rear-end collision involving 4 trucks and 2 cars. The accident caused tanks on the vehicles to leak, and this fuel subsequently ignited.

Among the burnt-out vehicles there were two road tankers carrying neoprene and accompanying solvent. The load on another lorry involved in the accident consisted of 10 drums of ether. These also leaked as a result of the accident and the ether began to burn intensely. Other materials which burnt were artificial resin and plastics.

The deluge sprinklers located in the tunnel were set off automatically by fire alarm systems. After about 10 minutes the fire appeared to have been extinguished. However, about 15 minutes later the fire flared up again. This produced thick black smoke. Thereafter the fire grew to a length of more than 1100 meters. Although there was a message at the portal of the tunnel that there had been an accident, vehicles continued to drive into the tunnel. A tailback of 231 vehicles formed in front of the seat of the fire.

The Nihonzaka tunnel is monitored from two control centres (Shizuoka and Kawasaki). The fire was first noticed by the Kawasaki control room. Mistakenly, from here the fire service responsible for the Shizuoka district was alarmed initially, although it was further away. A unit of the fire service which was much closer was only informed 40 minutes after the fire broke out.

It took 2 days to bring the fire under control and a week to finally extinguish it. During the fire the semi-transverse ventilation system of the tunnel worked in the exhaust mode at full power. However this was not sufficient to extract enough smoke and hot burning gases for the fire service units, who were equipped only with limited respiratory protection, to effectively fight the fire.

7 people died in the fire and 2 were injured. Of the 230 vehicles in the tunnel, 173 were destroyed by the fire. The tunnel lining and the additional 4.5 mm-thick reinforcement of the tunnel walls were damaged for a length of about 1,100 meters. The greatest damage occurred in an area of about 500 metres on either side of the seat of the fire. The road surface melted in places up to a depth of 2-3 cm on average, with the maximum depth being 7 cm. Electric cables and pipes in a cable duct in the road surface concrete continued to function normally.

3.2. CALDECOTT TUNNEL, OAKLAND, CALIFORNIA (7 APRIL 1982)

The fire occurred when an inebriated driver lost control of his car and collided several times with the wall of the tunnel. Behind a right-hand curve in the tunnel he stopped in the left-hand lane in order to inspect the damage he had caused. Two or three cars then passed the stationary vehicle without there being an accident. However, an empty bus then pulled out to overtake a full petrol tanker without noticing the stationary car in the left-hand lane. When the towing vehicle of the petrol tanker was level with the stationary car all three vehicles collided. The bus driver was thrown out of the bus by the force of the collision. The bus itself carried on without the driver and smashed into a concrete pillar outside the tunnel.
This alerted the personnel operating the tunnel to the accident inside the tunnel.

The tanker was carrying a total of 33,300 litres of petrol, of which 20,400 litres were in the trailer, which was torn open by the collision. The petrol leaked out and ignited.

As there were no traffic lights at the entrance to the tunnel, vehicles continued to drive into the tunnel even after the fire had broken out. Some of these drove into the area affected by the fire, with the result that in total 2 trucks and 4 cars burnt out.

The tunnel personnel initially tried to find out what was going on in the tunnel. However it took about 7 minutes until the fire brigade was notified. The first fire service units reached the western portal of the tunnel about 11 minutes after the vehicles collided. Fire units did not reach the eastern portal until 19 minutes. The ventilation in the tunnel switched itself off at this time. From then on, the course the fire took was influenced by the natural ventilation. Within three minutes of the collision the tunnel filled with over 150 °C hot smoke between the eastern portal and the burning tanker.

As the escape routes to the neighbouring tubes were not particularly well marked they were not noticed by the people in the tunnel. They remained with their cars and were enclosed by the smoke. Some of the vehicles which drove into the tunnel after the fire had started reversed back out of the tunnel. As the natural air current drove the burning gases to the eastern portal, it was possible for the fire fighters on the opposite side of the fire to get within 25 meters of the source. At this time, however, they did not make any effort to extinguish the fire.

When they wanted to operate a valve in order to keep the water and petrol mixture in the tunnel drainage system away from a local lake, they discovered that this valve was corroded and could not be moved.

When about 75 minutes after the collision the first efforts were made to extinguish the fire, the water pressure dropped and the extinguishing water supply in the tunnel failed.

This may have been attributable to the damaged fire-fighting water connections in the vicinity of the burning tanker, as some fire fighters noticed that water was leaking out of the damaged connections. The residual fire was finally extinguished with foam extinguishing agents and extinguishing powder. After about 2¼ hours (after the time of the collision) the fire was finally under control.

3.3. PFÄNDER TUNNEL, AUSTRIA (10 APRIL 1995)

This fire was located 4.3 km from the northern portal and 2.4 km from the southern portal. The accident was caused by a driver, travelling in a southerly direction, who fell asleep. He crossed over to the oncoming traffic lane and crashed into an articulated vehicle laden with bread. This lorry began to skid, and then also crossed over to the wrong side of the road, slid along the tunnel wall for 130 meters and then finally crashed into an oncoming minibus with caravan carrying three people. The minibus caught fire immediately and then set the articulated lorry and a following car on fire.
In the tunnel control room the computer-controlled fire programme was started immediately and the alarm was passed on to the local municipal police force and the rescue services. While the alarms were being given, an explosive flare-up was observed on the monitors in the tunnel control centre. The scene of the accident was filled with smoke within seconds and it was no longer possible to follow the course of the fire on the screens in the control centre.

The volunteer fire service personnel entered the tunnel from both portals 12 minutes after the alarm without having any exact information on the situation at the seat of the fire. Some minutes later four people fleeing in the direction of the southern cavern of the tunnel were rescued (the car driver causing the accident, the driver of the articulated lorry involved in the accident and two lorry drivers who had driven into the danger area from the southern side). These people and the rescue teams were caught up in the smoke that was drifting in a southerly direction.

From the scene of the accident the tunnel was completely filled with smoke in a northerly direction for about 270 meters and in a southerly direction for about 800 meters. In spite of the excessive amount of smoke, and the detonations that could be heard in the tunnel, four fire fighters attempted to reach the scene of the fire with a special fire engine equipped for tunnel use. The driver of the fire engine was only able to find his way in the tunnel by skirting the edge of the pavement with his tires in order not to lose his bearings.

In order to be able to finally begin extinguishing the fire, it was initially necessary in the smoke-filled tunnel for the fire fighters to identify by touch a fire extinguishing bay from where they could open a water valve located in front of a hydrant. The extinguishing work was also greatly hindered by the heat at the scene of the fire. Nevertheless, the fire was under control about 1 hour after the fire brigades had been alarmed.

Coordination of the fire-fighting measures was also greatly hindered by the fact that the two-way radio system in the tunnel stopped working.

The tunnel ceiling at the scene of the fire showed spalling and cracks. Even the supporting consoles of the false ceiling on the internal vault were weakened by the heat of the fire. This structural damage stretched over a length of approx. 24 meters. Additionally, the tunnel was completely blackened by soot over a length of 35 meters north of the scene of the accident, and 70 meters in a southerly direction.

The operating equipment, such as the tunnel lighting, the aerial cables for the tunnel radio and the supply lines in a cable duct on the tunnel ceiling, was damaged over a length of 360 meters. In order that the tunnel could be put back into temporary operation, the false ceiling was initially supported with thick wooden poles and planks. In addition, narrow-meshed steel net was fixed in place on the ceiling in the damaged part of the tunnel. The tunnel was reopened after 2 days.

3.4. GOTTHARD TUNNEL, SWITZERLAND (31 OCTOBER 1997)

A car transporter, laden with 8 new cars, caught fire in the tunnel. After noticing the fire, the driver stopped about 1 km before the exit portal and called for help via the nearest emergency telephone. The automatic fire alarm system of the tunnel registered the fire about 1 minute after the emergency call made by the lorry driver. When the fire broke out there were 60 vehicles, including 20 trucks, in the tunnel.
Approximately half of these vehicles were driving in the direction of the fire and therefore had to be stopped. From measurement data of the tunnel surveillance system and information provided by the emergency services, it was possible after the fire to estimate the maximum energy release rate of the fire at about 22 MW.

The fire alarm was received by the tunnel control centre at 7:21 am. After 1 minute all emergency systems were activated, some automatically and some by hand. Four minutes after the alarm the tunnel fire service entered the tunnel from the southern portal, the portal located nearest to the fire. The tunnel fire service responsible for the northern portal drove into the tunnel 9 minutes after the alarm was raised. First aid workers were already in the tunnel 3 minutes after the emergency call, dealing mainly with the vehicles that had formed a tailback. They instructed the car drivers to turn around and drive out of the tunnel.

Only a few of the lorry drivers went to the emergency rooms located in the tunnel without first being requested to do so. Most of the drivers did not want to leave their vehicles in spite of the immediate danger presented by the smoke.

At the scene of the fire the emergency services were placed in danger by concrete spalling, and it was difficult to estimate the remaining strength of the damaged false ceiling. This was exacerbated by the fact that the false ceiling was scarcely visible owing to the dense smoke. The rescue was made easier by the relatively slow development of the fire and the slow rate at which the smoke spread. Approximately 1 hour after the start of the fire it was under control, before being completely extinguished after a further 30 minutes.

The spalling of the false ceiling stretched over an area of 90 m² to 100 m². The spalling reached down as far as the reinforcing steel. The vertical deformation of the false ceiling was up to 10 cm. Subsequent laboratory analyses showed that the strength of the ceiling sections had dropped, owing to the effects of the high temperatures of the fire and the water used to extinguish the fire, to about 50% of the values for new ceiling sections.

The damage to the tunnel equipment was also extensive. Through the effects of the smoke, the temperature being about 700 °C, and the direct effects of the fire, video cameras, aerial cables, communication cables, lighting equipment, traffic signs and an emergency telephone were damaged. The false ceiling and its reinforcement outside the direct location of the fire were heated up to around 500 °C by the smoke from the fire.

The repair work began immediately after the fire had been extinguished and was carried out at the same time as the tunnel was being cleared (removal of the wrecked vehicle, turning around and driving out the lorries jammed in the tunnel). Such measures were taken immediately with the intention of reopening the tunnel as quickly as possible and were completed 13 hours after the fire started. The immediate measures included removal of the damaged electrical installations over a length of 100 meters and the installation of emergency lighting, clearing of the tunnel walls of loose material and supporting of the damaged false ceiling, and clearing of the damaged road surface and installation of a temporary one.

Repairs were able to be undertaken quickly due to the local storage of temporary supports for the false ceiling, and training of the tunnel personnel in the execution of immediate measures. Ceiling sections were replaced or repaired with sprayed concrete. These measures comprised a
ridge area of 120 m² and a length of 24 meters. Furthermore, the concrete sections of the side walls had to be replaced over a length of 136 meters by new sections.

3.5. MONT BLANC TUNNEL, FRANCE/ITALY (24 MARCH 1999)

The Mont Blanc tunnel is 11.6 km long, with a cross-section of approximately 46 m². The tunnel section is formed like a vault with the highest point 6 m above the road surface. The width is 8.5 m. The tunnel operators had some experience of fires, there having been a total of 17 truck fires since it was opened in 1965. Most of these fires were extinguished with fire extinguishers located on board the trucks or in the tunnel. In at least 5 of the fires the fire brigade was called into action. In these fires it was possible for the fire service to reach the scene of the fire without difficulty and extinguish the burning vehicle. 4 of the 5 fires in which the fire brigade had to take action involved trucks with an overheated engine. Such overheating may be attributable to the height differences which have to be overcome in order to reach the tunnel. None of the 17 fires spread to other vehicles. Although experience had therefore been gained of vehicle fires in the Mont Blanc tunnel, the lorry fire on March 24, 1999, got out of control.

The fire started in an articulated lorry that was transporting about 9 tonnes of margarine and 12 tonnes of flour. Besides the load, other flammable materials on the lorry were approx. 550 litres of diesel fuel and the highly inflammable foam material of the heat insulation of the refrigerator semi-trailer. This semi-trailer stopped 6.5 km from the French entrance. A second semi-trailer truck stopped 12 m behind the first one and a third truck 6 m behind the second one, and so on. A total of 14 HGVs was stopped behind the first truck. The longitudinal ventilation velocity at the place where the truck stopped was estimated to be 1 to 1.5 m/s. The ventilation system consisted of transverse ventilation with air supply at a lower level and extraction or supply at higher levels, depending on the operational situation. Based on the amount of oxygen available at different stages of the fire it is estimated that the HRR in the vicinity of the first truck could be somewhere between 75 MW and 110 MW. These values presuppose that at most half of the oxygen in the longitudinal airflow (50-70 m³/s) was consumed at the section where the first truck was located.

The fire started under the driver’s cab and spread to the entire articulated lorry after it had been stopped. During the course of the fire the margarine melted and was transformed into extremely flammable oil. Moreover, the liquid margarine very probably flowed on to the road surface, thereby causing the power of the fire to increase considerably, owing to the enlarged surface. The fire spread from the first vehicle to the others behind.

The first fire alarm was received at about 10:55 am. The traffic lights at the entrances to the tunnel were switched to red. On the Italian side the barrier in front of the tunnel was also closed.

The lorry driver failed in his attempt to extinguish the initial phases of the fire. As early as 2 to 4 minutes after the fire alarm was raised, 1,200 meters of the tunnel was filled with so much smoke that fire engines belonging to the tunnel operator, which had entered the tunnel, had to stop. The French and Italian fire services reached the tunnel almost simultaneously at approx. 11:10 am. A quarter of an hour after the fire had broken out, a pump water tender from Chamonix, located in the tunnel, was enclosed in smoke at a distance of approx. 2,700 meters from the burning lorry (11:10 am). A pump water tender that had entered the tunnel at 11:36 am was trapped by the smoke at a distance of 4,800 meters from the scene of the fire.
The ventilation system of the tunnel was turned to maximum air input in order to supply the people located near the fire with fresh air. However, this also fanned the fire and pushed hot burning gases through the tunnel. This measure did not therefore help the situation, but rather placed the people in the tunnel in additional danger. On the French side the fire flashed over distances of up to 300 meters, spreading to other vehicles. The smoke spread on the Italian side to a lesser extent than in the direction of France.

At about 11:05 am a police motorcyclist from the Italian side was able to get within 10 meters of the burning articulated lorry.

Between 11:20 and 11:30 am the Italian fire fighters were able to get within 300 meters of the lorry.

The extinguishing work on the Italian side was helped by the use of foam fire extinguishers. However, the extinguishing and rescue work were hampered by:

- Almost zero visibility
- Extreme heat
- Difficult use of the self-contained respiratory protection equipment in overheated surroundings
- Incompatibility of the respiratory protection equipment used by the tunnel operator and that of the fire brigade
- Insufficient water pressure in the French half of the tunnel
- Extinguishing water pumps did not work
- Communication problems inside the tunnel, as some of the communication equipment was very quickly destroyed by the fire
- Incompatibility of the hose connections for the various emergency services.

The damage to the tunnel vault stretched over a length of more than 900 meters. The road surface and the slabs under the road surface were damaged over a somewhat shorter distance. Additionally, the tunnel equipment was damaged or made unusable over a long distance as a result of the temperatures that were reached or the secretions caused by the fire.

### 3.6. TAUERN TUNNEL, AUSTRIA (29 MAY 1999)

The Tauern tunnel is 6400 m long, 9.5 m wide and 5 m high. At the time of the event road works had been set up about 800 meters before the northern portal. A lorry laden with paints, behind which there were 4 cars, stopped in the tunnel at the red light in front of these road works, about 750m from the north portal.

A following articulated lorry failed to stop and in the resulting accident pushed 2 cars under the lorry laden with paints and 2 cars against the wall of the tunnel. The vehicles caught fire immediately. Then the fire spread to the vehicles that had now tailed back in the tunnel. In total 16 lorries and 24 cars caught fire.

The ventilation system in the Tauern tunnel consisted at that time of a full transverse ventilation with 4 ventilation sections. The maximum volume of fresh air, according to the ventilation calculation, was approximately 190 m$^3$/s/km and the maximum volume of exhaust air was approximately 114 m$^3$/s/km. Exhaust air openings were situated every 6 m in the tunnel ceiling.
When the fire started the fire alarm activated the ventilation system in the north fourth section where the accident occurred. The exhaust system extracted 230 m$^3$/s upwards into the exhaust-air duct. Initially, the smoke lay essentially along the ceiling with a smoke-free zone created near the road. This layering was maintained for at least 10 to 15 minutes. Although the smoke was still being successfully extracted, the heat and smoke generated outgrew the design capability of the system so it was no longer possible to keep the carriageway free of smoke, and the smoke began to flow towards the northern portal.

The tunnel fire brigade, which entered the tunnel only a few minutes after the alarm had been given, had to withdraw again immediately, as they encountered thick smoke and very high temperatures. Furthermore, there were also explosions in the tunnel. Not until around 8 hours after the start of the fire were investigation teams able to enter the tunnel. Parts of the intermediate ceiling had to be stabilised before accessing the fire site. Even after 12 hours a fire was still burning over a length of 50 to 60 metres. It was not possible to fully extinguish the fire until 17 hours after the ignition. After the fire it was stated that 16 HGVs and 24 cars were consumed in the fire. The damage of the tunnel was mainly in the intermediate ceiling, the inner concrete of the tunnel walls over a length of 350 m, the concrete carriageway surfacing and the niches over a length of 900 m.

3.7 ST GOTTHARD FIRE ROAD TUNNEL, SWITZERLAND
(24th OCTOBER 2001)

The worst incident in the Gotthard Road tunnel was caused by an articulated truck driven by a drunk driver. Gotthard road tunnel is operated with bidirectional traffic two lanes. As the articulated truck shifted to the wrong traffic lane, a head-on collision with another articulated truck occurred. Subsequent to the collision, large amounts of diesel spilled to the road surface. This ignited within 2 min and already after 3 min, both vehicles were on fire. One of the articulated trucks was loaded with tires and the fire therefore produced heavy smoke.

The collision occurred about 1.2 km from the south portal. Prior to the accident, the longitudinal flow at this section was low. 3 min and 20 sec after the accident, the automatic alarm activated the safety systems including traffic control, illumination, tunnel ventilation and egress-tunnel ventilation. Within minutes and as a result of the large distance to the north portal and the fact that the predominant traffic direction was towards north, a longitudinal velocity of up to 4.5 m/s direction north emerged. The smoke flow towards north caused to engage the exhaust fans in the northern ventilation sections of the fire. After 20 min, the operator took over the control of the tunnel ventilation. As the fire brigade only had access to the fire from the south, the direction of the flow was never reversed. South of the accident, there were no damages. Smoke at reducing density with distance was detected up to 3 km north of the accident.

Smoke spread caused 11 fatalities. These were all located in the area from 300 m to 600 m north of the accident. At 230 m north of the accident, 7 trucks completely burned out. Moreover, 6 trucks as well as 10 passenger cars and delivery vans were damaged by the heat. Over a length of 230 m, the false ceiling and over a length of 750 m, the electrical installations were destroyed. The maximum heat-release rate is estimated to be at least 100 MW. The fire was not under control until 10 h after the onset of the fire. However, due to the spread out of the fire, certain smaller fires were not extinguished until the following day.
The refurbishment works amounted to CHF 15 mio, and the tunnel was re-opened to traffic on the 22nd of December 2011.

### 3.8 VIAMALA FIRE SWITZERLAND (16th September 2006)

The Viamala tunnel is 765m long and is operated in bidirectional traffic on in total two lanes. It is located on the alternative transit route of the Alps to the Gotthard route. The tunnel has a slope from north to south of 5.3 % and is equipped with longitudinal ventilation using jet fans. At the time of the accident, the only escape routes were the two tunnel portals.

The investigation revealed that a 90 year old driver of a passenger car did not hold his lane after having entered the tunnel through the north portal. Consequently, two passenger cars collided with a bus. At a distance of 150m from the lower situated portal (north), a fire ignited and developed quickly so that the bus and a passenger car burned out completely.

The first alarm was raised by telephone to the operation centre. The reporting, however, was imprecise, due to the fact that this route contains several short tunnels. The automatic response of the safety systems, the red light at the portals, the illumination and the ventilation with four jet fans was activated by the linear heat detector. At a later stage, the tunnel ventilation was switched off, as this could not impede the smoke flowing towards the upper portal.

21 persons from the tourist bus escaped using the lower situated portal. They had to egress though the windows of the bus, as the doors were damaged by the crash. Fortunately, the passengers were a group of young athletes. The tunnel users south of the accident had to egress using the higher situated south portal. Some managed this by making a U-turn and driving out, other escaped by foot. Amongst the nine fatalities, there was a family with two young children, who did not leave the car.

The fire brigade arrived on site already after 10 min. The tunnel was filled with smoke to the upper portal within 3 ½ minutes. The heat from the fire caused a flow of about 8m/s, which means that the heat-release rate could be estimated to about 30 MW. After eight days, the tunnel was re-opened to traffic. The damage repair works amounted to about CHF 2 mio.

### 3.9 BURNLEY TUNNEL FIRE (23 MARCH 2007)

On 23 March 2007 at 09:52:30 am in a steep (>6%) downhill section of Melbourne Australia’s 3 lanes, 3.4km Burnley Tunnel, a truck made an unscheduled stop. Over the next two minutes 103 vehicles passed the stopped truck without incident. Two minutes later, by 09:54:24 seconds several vehicles, including 4 HGVs and 7 light vehicles had crashed, 3 people were dead and fire and a series of explosions were initiated.

The incidents were detected by automated incident detection systems, and responded to by expert, trained and accredited tunnel operators who manually optimised computer suggested response sequences – manually commanding the most appropriate ventilation, deluge and evacuation sequences.

By 09:56:00 am (two minutes after ignition) emergency ventilation, including point extraction and a fixed fire suppression system had been activated, and an effective emergency evacuation
of several hundred tunnel users had commenced. Fire growth and spread were contained, smoke migration up the 6% grade (in the direction of emergency egress) was controlled, emergency services were able to approach the incident from both sides of the incident and extinguish the fires. Tunnel damage was minimal, and tolled operations could have recommenced within hours.