VENTILATION DURING ROAD TUNNEL EMERGENCIES

VERSION : FINAL

by R C Hall (Mott MacDonald)

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Client: SSR (CE Division), HA
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<th>Approvals</th>
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Executive summary

This report describes research undertaken by Mott MacDonald and TRL Limited. The main purpose of the project has been to review the requirements and advice on ventilation during road tunnel emergencies, contained in the standard BD 78/99 ‘Design of Road Tunnels’ and the draft standard TD 43 ‘Limited facility grade separation’ (set out in Volume 2 of Hillier et al, 1999), and recommend how this should be amended and updated if appropriate in the light of current knowledge and best practice.

The study has involved a review of published literature, consultation of other organisations involved in this field, evaluation of key technical issues, and preparation of recommendations. All factors that are relevant for the design and operation of tunnel ventilation systems have been considered.

It is concluded that whilst BD 78/99 continues to provide good guidance in general, there are a number of areas in which improvements should be made. Recommendations have therefore been made as follows:

a) A set of standardised vehicle fire scenarios and a framework for risk-based design have been proposed. A key objective is to ensure better consistency between tunnel designs and with current international best practice. The proposed framework is capable of supporting key decisions such as the choice of design scenario for a particular tunnel and the selection and justification of the ventilation configuration.

b) Improved design guidance is given on minimising smoke spread between bores and defining ventilation systems with extract capability. New guidance is proposed on ventilation analysis, covering the choice of ventilation model and modelling strategies, the expertise required by the user, and the interpretation and reporting of results.

c) Improved guidance is also given for operations and emergency response. This covers the roles and responsibilities of the tunnel operator and the fire brigade, and the selection of ventilation responses. A key aspect is the need for pre-defined ventilation plans, which can be used without delay by the tunnel operator.

For low headroom tunnels, covered by the draft standard TD 43, attention is drawn to the potential for rapid deterioration of conditions in the event of a fire, even when only light vehicles are involved. Even relatively short tunnels may need mechanical ventilation and/or enhanced life safety measures.

Further work is recommended as follows:

a) There is a need for consistency between the guidance followed by fire brigades, tunnel operators and designers. This could be achieved through a working party comprising representatives drawn from tunnel operators, designers and the National Operations Committee of the Chief Fire Officers Association.

b) There appears to be relatively little information on visibility and toxicity levels for large vehicle fires under natural ventilation conditions. Opportunities should be investigated to participate in future tunnel fire test programmes with a view to obtaining such information, which would help to improve confidence in modelling predictions of visibility in particular.

c) There is a need for statistical information about HGV fires, to help estimate the risk of severe fires in road tunnels. For example, it would be useful to know how often the load is involved in the fire and the proportion of incidents in which the load is completely destroyed.
1 Introduction

1.1 Objectives

This report describes research undertaken by TRL Limited and Mott MacDonald under the Highways Agency Framework Contract 3/359, ‘Provision of R&D advice and facilities for the design and management of highway structures’. The technical tasks were undertaken by Mott MacDonald with support from TRL Limited.

The main purpose of the project has been to review the requirements and advice on ventilation during road tunnel emergencies, contained in the standard BD 78/99 ‘Design of Road Tunnels’ and the draft standard TD 43 ‘Limited facility grade separation’ (set out in Volume 2 of Hillier et al., 1999), and recommend how this should be amended and updated if appropriate in the light of current knowledge and best practice. All factors that are relevant for the design and operation of tunnel ventilation systems have been considered under this contract.

The factors include the tunnel geometry and layout, the traffic characteristics and the nature of the external wind environment. Regarding emergencies, the nature of the possible incident scenarios and the limits of tolerability for tunnel occupants under hazardous conditions are clearly important, together with the operating control strategy.

The particular objectives of this work are to provide:

a) comprehensive advice on the planning, design, control and operation of road tunnel ventilation systems in emergency situations;

b) revisions to BD 78/99 in the light of experience of normal and incident operations, technological advances and international perspectives;

c) a framework for the ventilation design of new and existing tunnels;

d) advice for the operation of existing systems;

e) revisions to draft TD 43 for low headroom tunnels;

f) recommendations for further research to resolve outstanding areas of uncertainty.

1.2 General approach

The approach has involved the following main tasks: (a) review of published literature; (b) consultation of other organisations involved in this field; (c) evaluation of the information assembled; and (d) preparation of recommendations.

A wide range of sources have been examined during the literature review including:

- papers published in Tunnel Management International and other journals and magazines;
- proceedings of conference series on ‘Safety in Road and Rail Tunnels’ and ‘Tunnel Fires’ (ITC series), ‘Aerodynamics and Ventilation of Vehicle Tunnels’ (BHRG series), plus one-off conferences such as those on ‘Tunnel Safety and Ventilation’ (Graz, 2002), ‘Catastrophic Tunnel Fires’ (Borås, 2003) and ‘Safe & Reliable Tunnels’ (Prague, 2004);
- guidance published by PIARC (the World Road Association);
- national regulations, standards and guidance (including such from Australia, Austria, France, Japan, Netherlands, Switzerland, USA);
- information published by the ‘Fires in Tunnels’ (FiT) European thematic network (Van Dessel et al, 2004), plus other internet sources.
During the course of the literature review, a questionnaire was prepared to obtain feedback on a range of points from tunnel operators, emergency services and organisations involved in ventilation design. These points covered ventilation design standards, design practice, tunnel operations and emergency response. The full questionnaire is included in Appendix A of this report. The questionnaire was then either issued to be completed by the recipients or used as a framework for meetings or telephone conversations. For some tunnels, relevant up-to-date information on current practice was already available to Mott MacDonald as a result of ongoing or recent projects. In these cases, it was considered unnecessary to approach the organisations.

1.3 Layout of the report
The findings of the literature and consultation exercise are discussed together on a point by point basis in Section 2, at the end of which a summary is presented of the main areas identified for attention during the evaluation phase. Section 3 describes work carried out in the evaluation phase. The recommended revisions to the standards are considered in Section 4. Finally, Section 5 summarises the key conclusions of the study.
2 Review of current practice and technical developments

2.1 Ventilation design scenarios

2.1.1 Introduction

A wide range of incidents can occur in any tunnel. Rather than attempting to analyse every possible eventuality, only the critical ones are analysed for design purposes. Design requirements invariably focus on fires, but other incidents could occur in which tunnel ventilation would have an important influence. Possible non-fire incidents include vapour cloud explosions and toxic gas releases. In recent years, there has also been increased concern over possible terrorist incidents, including the release of chemical or biological agents.

2.1.2 Vehicle fires

BD 78/99 gives guidance on the minimum fire sizes to be used when designing the ventilation system, as reproduced in Table 2.1. This is based on the ventilation controlling the smoke spread to allow evacuation from the incident via the emergency escape doors. In the absence of escape routes in older tunnels, the potential need for a higher ventilation design fire size is noted. For reduced headroom tunnels, draft TD 43 (Hillier et al., 1999) specifies a ventilation design fire size of 5 MW if only cars are to be permitted, or 17.5 MW if small goods vehicles are permitted.

Table 2.1 Minimum design fire sizes for longitudinal ventilation (BD 78/99)

<table>
<thead>
<tr>
<th>Road tunnel Length/Type</th>
<th>Equivalent Ventilation Design Fire Size (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Motorway</td>
</tr>
<tr>
<td>Length &gt; 2000m</td>
<td>50</td>
</tr>
<tr>
<td>Length &lt; 2000m</td>
<td>50</td>
</tr>
</tbody>
</table>

The requirements for French tunnels, defined in the Inter-Ministry Circular No. 2000-63 (2000), are presented in terms of fire sizes, smoke generation rates and minimum velocities for longitudinal airflows. These requirements are summarised in Table 2.2. The prescribed smoke generation rates and minimum longitudinal airflows allow a ventilation system to be sized directly in most cases without the need to carry out any further analysis. The fire sizes are provided for information only.

Table 2.2 Ventilation requirements for French tunnels

<table>
<thead>
<tr>
<th>Type of tunnel</th>
<th>Characteristic vehicle(s)</th>
<th>Fire size (MW)</th>
<th>Smoke generation rate (m³/s)</th>
<th>Minimum airflow velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Headroom &lt; 2m</td>
<td>2 or 3 light vehicles</td>
<td>8</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>2m &lt; Headroom &lt; 3.5m</td>
<td>1 van</td>
<td>15</td>
<td>50</td>
<td>2.5</td>
</tr>
<tr>
<td>Headroom &gt; 3.5m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Without Dangerous Goods</td>
<td>Heavy truck</td>
<td>30</td>
<td>80</td>
<td>3</td>
</tr>
<tr>
<td>With Dangerous Goods</td>
<td>Hydrocarbon tanker</td>
<td>200</td>
<td>&gt;300</td>
<td>4</td>
</tr>
</tbody>
</table>
The French requirements are supported by more detailed guidance on the standard scenarios (CETU, 2003a). The guidance defines the vehicles involved in each scenario, the associated fire load (in MJ), the time taken for the fire to reach its peak ($T_{\text{growth}}$), the duration of the peak ($T_{\text{max}}$) and the time taken for decay ($T_{\text{decay}}$), as summarised in Table 2.3. The intention is that these standard curves should be used when performing ventilation analyses. Figure 2.1 illustrates the standard curves for the 8, 15 and 30 MW scenarios. Note that there are two 30 MW scenarios, representing empty and loaded HGVs.

**Table 2.3 Fire scenarios defined in French ventilation guidance (CETU, 2003a)**

<table>
<thead>
<tr>
<th>Fire size (MW)</th>
<th>$T_{\text{growth}}$ (mins)</th>
<th>$T_{\text{max}}$ (mins)</th>
<th>$T_{\text{decay}}$ (mins)</th>
<th>Fire load (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>5</td>
<td>25</td>
<td>20</td>
<td>18,000</td>
</tr>
<tr>
<td>15</td>
<td>5</td>
<td>60</td>
<td>15</td>
<td>63,000</td>
</tr>
<tr>
<td>30</td>
<td>5</td>
<td>0</td>
<td>45</td>
<td>50,000</td>
</tr>
<tr>
<td>30</td>
<td>10</td>
<td>50</td>
<td>30</td>
<td>125,000</td>
</tr>
<tr>
<td>100</td>
<td>10</td>
<td>60</td>
<td>20</td>
<td>450,000</td>
</tr>
<tr>
<td>200</td>
<td>10</td>
<td>60</td>
<td>30</td>
<td>960,000</td>
</tr>
</tbody>
</table>

**Figure 2.1 Fire scenarios defined in French ventilation guidance (after CETU, 2003a)**

In the Austrian tunnel ventilation standard RVS 9.261 (1997), rather than specifying fire sizes, the design requirements are specified in terms of ventilation extraction rates and a minimum longitudinal velocity. They are summarised in Table 2.4.

**Table 2.4 Ventilation requirements for Austrian tunnels (RVS 9.261, 1997)**

<table>
<thead>
<tr>
<th>Type of ventilation system</th>
<th>Longitudinal air velocity</th>
<th>Minimum extraction rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal uni-directional traffic</td>
<td>$1 \text{ m/s} &lt; v &lt; 1.5 \text{ m/s}$ in the traffic direction</td>
<td>$80 \text{ m}^3/\text{s}$</td>
</tr>
<tr>
<td>Longitudinal bi-directional traffic</td>
<td>$1 \text{ m/s} &lt; v &lt; 1.5 \text{ m/s}$ in the main traffic direction</td>
<td>$200 \text{ m}^3/\text{s}$ for a single point extraction</td>
</tr>
<tr>
<td>Semi-transverse</td>
<td>-</td>
<td>$80 \text{ m}^3/\text{s}$</td>
</tr>
<tr>
<td>Transverse</td>
<td>-</td>
<td>$80 \text{ m}^3/\text{s}$</td>
</tr>
</tbody>
</table>
The US fire standard for road tunnels, NFPA 502 (2004), indicates that the selection of design fire size must take into account the types of vehicles that are expected to use the tunnel, and provides guidance on representative fires. This is shown in Table 2.5. The values are drawn from PIARC data. For longitudinally ventilated tunnels, the fire size can be used to calculate the critical velocity using the approach described by Kennedy (1996), as described in section 2.5.1 of this report.

### Table 2.5 Ventilation requirements for US tunnels (NFPA 502, 2004)

<table>
<thead>
<tr>
<th>Cause of fire</th>
<th>Equivalent size of gasoline pool (m²)</th>
<th>Fire size (MW)</th>
<th>Smoke generation rate (m³/s)</th>
<th>Maximum temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger car</td>
<td>2</td>
<td>5</td>
<td>20</td>
<td>400</td>
</tr>
<tr>
<td>Bus / truck</td>
<td>8</td>
<td>20</td>
<td>60</td>
<td>700</td>
</tr>
<tr>
<td>Gasoline / tanker</td>
<td>30-100</td>
<td>100</td>
<td>100-200</td>
<td>1000</td>
</tr>
</tbody>
</table>

The UNECE (United Nations Economic Commission for Europe) group of experts, which addressed safety in road tunnels following the Mont Blanc and Tauern fires, proposed in 2001 that “a fire power of 30 MW should be taken as the basis for dimensioning the ventilation systems in tunnels”. This recommendation represented a compromise which reflected the large number of tunnels that could be affected.

2.1.2.1 Other fire information

BD 78/99 also gives guidance on typical vehicle fire sizes for design of structural fire protection. This data is reproduced in Table 2.6.

### Table 2.6 Fire sizes for design of structural fire protection (BD 78/99)

<table>
<thead>
<tr>
<th>Vehicle Classification</th>
<th>Fire size (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>

The TRL report on ‘Fire detection and suppression systems in road tunnels’ (Crabb et al., 2001) provides a suggested list of fire sizes for assessing the requirements of fire detection and suppression systems. This is shown in Table 2.7. The values are derived from several sources including tests carried out for the Channel Tunnel project, the Eureka 499 Firetun fire tests in Norway, and design information from the Stockholm Ring Road Tunnel and the Oresund Tunnel.
Table 2.7 Vehicle fire sizes relevant for assessing the requirements for fire detection and suppression systems (Crabb et al, 2001)

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Peak fire size (MW)</th>
<th>Time to reach peak fire size (minutes)</th>
<th>Fire duration (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car</td>
<td>7.5</td>
<td>13</td>
<td>60</td>
</tr>
<tr>
<td>Bus</td>
<td>20</td>
<td>10</td>
<td>90</td>
</tr>
<tr>
<td>Lorry</td>
<td>120</td>
<td>10</td>
<td>90</td>
</tr>
<tr>
<td>Hazardous load</td>
<td>150</td>
<td>1</td>
<td>60</td>
</tr>
</tbody>
</table>

Ingason and Lönnermark (2003) summarised the findings from four full-scale fire tests in the Runehamar Tunnel involving HGV trailer mock-ups with longitudinal ventilation. Peak heat release rates in the range of 71 to 203 MW were measured for loads comprising cellulose and plastic materials (three of the tests) and furniture and fixtures (one test). The time to reach the peak size was found to be in the range of 8 to 18.5 minutes from ignition. The maximum smoke temperatures above the fire varied between 1250 and 1365°C.

The results of vehicle fire tests and actual tunnel fire incidents are summarised by Ingason (2003) and Ingason and Lönnermark (2004). It was noted that the fire sizes observed in major tunnel incidents are consistently larger than the design fire sizes typically used for tunnel design purposes.

2.1.2.2 Discussion

BD 78/99 and the various Highways Agency research reports provide a lot of information but this is not provided in one place. A risk-based approach is suggested but there are no clear guidelines on what this means. In actual design projects, this has been interpreted in qualitative and therefore subjective terms, leading to a lack of consistency in approach across the UK.

The French regulations provides the most complete set of details for ventilation design, covering the full range of tunnel heights, configurations and traffic flows. Notably, it gives special attention to potentially very large fires involving hydrocarbon tankers.

BD 78/99 gives fire sizes rather than required controlling airflow velocities and flow rates. The opposite is true in other European countries. The main benefit of focusing on fire size is the ability to optimise ventilation systems for specific tunnels and avoid unnecessary over-design. The extra fan capacity required to achieve even quite small increases in longitudinal airflow velocity can be significant.

It is assumed that the ventilation design fire sizes in BD 78/99 (see Table 2.1) represent the total fire sizes rather than the convective fire sizes. This needs to be stated clearly in BD 78 to avoid confusion. The values do not fit well with recent data on severe HGV fires. It would be beneficial to provide a revised set of fire data covering the range of circumstances found in the UK. Consideration should be given to severe HGV and tanker fires.

Consideration should also be given to providing a specific methodology for determining the design scenarios on the basis of risk. In principle, this could identify when severe HGV fire and dangerous goods incidents should be taken into account for ventilation design. If a Quantitative Risk Assessment (QRA) approach was taken, then the design could be based on incidents with return periods within N times the design life. However the adoption of a detailed QRA approach might be difficult. Generic event trees might offer a possible approach. An approach along the lines of the Austrian safety analysis process (see section 2.2.1) might also be worth considering.
2.1.3 Non-fire emergencies

Vapour cloud explosions and toxic gas releases can occur in tunnels as a result of accidents involving the transport of dangerous goods. Such scenarios are not considered for the purposes of ventilation design, although they would typically be considered in risk assessments and in terms of operational procedures. These issues are more important for certain tunnels in the UK due to local industrial factors. For example, road tankers each carrying approximately 20 tonnes of chlorine or bromine travel several times each day through the A55 Conwy, Penmaenbach and Pen-y-Clip tunnels between chemical plants at Ellesmere Port and Amlwch on Anglesey. Riley et al (1999) reported that a 1994 study for HSE identified five major road routes nationally for chlorine transport and three routes for ammonia transport.

The effects of tunnel ventilation on the spread of a hazardous gas cloud were considered by Considine et al (1989) using modified versions of atmospheric gas dispersion models. Hall (2001) carried out research involving both Computational Fluid Dynamics (CFD) modelling of dense (heavier-than-air) gas releases in a road tunnel and the development of a simplified dense layer model. A key difference between the behaviour of buoyant and dense gases in a road tunnel is that the dense gases would form a layer at road level, where they would be subject to the blocking and enhanced mixing effects around vehicles. The CFD modelling showed that large releases could have a significant effect on tunnel airflows, and in some situations, conditions might not return to normal until 20-30 minutes after the release. Ventilation extracts at soffit level not surprisingly appeared to be inefficient for removal of dense gas in layers at road level. The following implications were suggested:

- The optimum protocol used to control smoke in the event of a fire will not necessarily be appropriate for a dense gas release. Several UK tunnels are located under rivers or estuaries and thus have a mid-tunnel low point. Whilst smoke will tend to rise naturally to the portals, dense gas could become trapped in the middle of the tunnel.
- Another issue is the blocking effect both of vehicles and of a dense gas cloud itself on the ventilation airflow. The results suggested that in some situations the tunnel ventilation may take several minutes to clear dense gas from the tunnel. Considering life safety in the tunnel, the need for rapid detection and emergency response is clear.

The possibility of large releases of dense toxic gases such as chlorine raises the difficult question of whether to operate the ventilation system and risk casualties amongst the local population or switch off the fans and risk casualties amongst road users.

The OECD/PIARC Quantitative Risk Assessment (QRA) Model for dangerous goods transport through road tunnels (Cassini et al, 2001; OECD, 2001) provides a means of evaluating the overall risks for the local population as well as for road users. Comparisons can be made between a route with a tunnel and an alternative open route. The QRA Model considers 13 different scenarios that are intended to be representative of the broad groupings of substances transported by road. The scenarios include:

- Heavy goods vehicle (HGV) fires with no dangerous goods (20 and 100 MW);
- Boiling Liquid Expanding Vapour Explosion (BLEVE), vapour cloud explosion (VCE), and torch fire of Liquid Petroleum Gas (LPG) in bulk or in cylinders;
- Pool fire and VCE of motor spirit in bulk;
- Release of chlorine and ammonia gas;
- BLEVE of carbon dioxide in bulk;
- Release of acrolein (toxic liquid) in bulk or in cylinders.

Ventilation can have a significant influence on most of these scenarios. For example, tunnel airflows could increase evaporation from a pool of flammable liquid, blow toxic gases or flammable vapour in a particular direction, and dilute gas concentrations. The QRA Model incorporates simple routines to predict the consequences of these scenarios, the numbers of fatalities and injuries which could occur
and the resulting levels of societal and individual risk. These outputs can be used to decide whether to consider a particular scenario in detail for the purposes of ventilation design and operation.

2.1.3.1 Discussion

The conclusion must be that the risks of non-fire incidents should be assessed to decide whether such incidents should be taken into account for design and operation. The use of the OECD-PIARC QRA Model for dangerous goods transport should be considered.

2.2 Choice of ventilation configuration

2.2.1 Natural ventilation

The first fundamental question which the ventilation designer must address is whether a mechanical ventilation system is required. To answer this question, consideration has to be given to how smoke will behave in the tunnel environment, recognising that natural ventilation does not allow smoke to be controlled during an incident.

Before a fire develops significantly, the overall airflow movements in the tunnel will depend on traffic-induced airflows and external wind conditions. When traffic stops, the traffic-induced effects, such as the ‘piston effect’ in a uni-directional traffic tunnel, will decay. Smoke may spread initially to both sides of the fire as a stratified layer, but will generally become fully mixed over the tunnel cross-section within a few minutes at a short distance in the order of 200-300m from the fire. This is illustrated in Figure 2.2 (CETU, 2003b). Strong adverse winds at the portal may limit or block the natural venting of smoke to atmosphere, and if smoke is still stratified as it approaches the portal, could cause the stratification to break down rapidly. The tunnel gradient may also have a strong influence on the smoke behaviour. Buoyancy effects will reduce smoke spread down a slope and increase smoke spread up a slope. This is addressed in section 2.3.2.

BD 78/99 specifies that a mechanical ventilation system would generally not be required for a tunnel of up to 300m in length, since evacuation distances will be acceptably short, i.e. portals and/or exits will be no more than 150m apart if the tunnel complies with BD 78/99. Between 300m and 400m, a mechanical ventilation system may be required for smoke control if traffic is relatively heavy or the gradient is steep. Mechanical ventilation will be required for all tunnels longer than 400m. Basically, the BD 78/99 limit for natural ventilation is 300m, but in some cases this may be extended to 400m.

The requirements of the French Inter-Ministry Circular (2000) are summarised in Table 2.8. The allowable tunnel lengths exceed the distances over which stratified smoke conditions would be expected to occur during the initial stages of a fire incident. The French circular defines ‘urban’ tunnels as those located in cities or towns with more than 20,000 inhabitants and satisfying one of the following conditions: traffic greater than 1000 vehicles per lane per hour during peak periods, frequent congestion or junctions within the tunnel. Tunnels that do not meet these conditions are classed as ‘non-urban’ tunnels. Light traffic is defined as less than 2000 vehicles per day and 400 vehicles at peak times. HGVs are counted as five vehicles for the purpose of this assessment. Thus
the allowable lengths have been derived on the basis of risk and assume the risks are lower in ‘non-urban’ tunnels.

### Table 2.8 Maximum allowable lengths of naturally ventilated tunnels in France

<table>
<thead>
<tr>
<th>Tunnel characteristics</th>
<th>Maximum allowable length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban tunnel (uni- or bi-directional traffic)</td>
<td>300m</td>
</tr>
<tr>
<td>Non-urban tunnel with significant traffic (uni- or bi-directional)</td>
<td>500m</td>
</tr>
<tr>
<td>Non-urban tunnel with light traffic (including bi-directional)</td>
<td>1000m</td>
</tr>
</tbody>
</table>

The Austrian standard RVS 9.261 provides an iterative safety analysis process to determine whether a particular ventilation strategy is acceptable. This is illustrated below in Figure 2.3. The ‘danger potential’ takes account of whether the traffic is uni- or bi-directional, the presence of merging lanes or junctions in or immediately before the tunnel, and the number of dangerous goods vehicles using the tunnel each day. The standard of safety is defined by a ‘safety coefficient’ that takes account of the following:

- the tunnel cross-section area
- spacing of smoke vents and extraction rate
- spacing between emergency exits
- distance which emergency vehicles have to travel from base to reach the tunnel
- presence of a permanently manned control centre
- automatic detection of traffic congestion
- automatic detection of dangerous goods vehicles and escorting of such vehicles
- automatic fire alarm and equipment to detect a smouldering fire
- effective radio communications.

![Figure 2.3 Decision process for Austrian tunnels](image)

**Figure 2.3 Decision process for Austrian tunnels**
The US fire standard NFPA 502 indicates that a mechanical ventilation system is not required in tunnels of up to 240m in length. For tunnels longer than 240m, tunnel ventilation is not required “where it can be shown by an engineering analysis using the design parameters for a particular tunnel (e.g., length, cross-section, grade, prevailing wind, traffic direction, type of cargoes, design fire size, etc.) that the level of safety provided by a ventilation system can be equalled or exceeded by enhancing the means or egress”. The engineering analysis must be approved by the authority having jurisdiction.

The European directive 2004/54/EC on minimum safety requirements for tunnels in the trans-European road network specifies that a mechanical ventilation system is required in all tunnels longer than 1000m with a traffic volume higher than 2000 vehicles per lane (per day).

2.2.1 Discussion

The maximum length and time over which a stratified layer might persist is in the order of 200m to 300m for a few minutes, after which smoke would be expected to mix down towards road level. The upper limit of 400m in BD 78/99 seems rather optimistic.

The question of whether a mechanical ventilation system is required has to be addressed for every road tunnel. It is recommended that further work is carried out to develop a risk-based methodology, perhaps involving analysis in a similar way to that required by the US standard, to ensure that this is dealt with in a sound and consistent manner. This should take account of relevant factors including the cross-section and gradient of the tunnel.

2.2.2 Longitudinal ventilation

Having confirmed that mechanical ventilation is required, the second fundamental question which the ventilation designer must address is whether longitudinal ventilation is acceptable. Longitudinal ventilation is the simplest and generally least expensive strategy, for shorter tunnels at least. However it may not be satisfactory in certain cases, particularly tunnels with permanent bi-directional traffic.

There are three basic methods of providing longitudinal ventilation:

- Jet fans mounted along the crown of the tunnel.
- Injectors, directing jets of fresh air into the tunnel.
- Push-pull arrangements of axial type fans in chambers.

BD 78/99 describes longitudinal ventilation and its suitability for dealing with tunnel incidents in some detail. If a fire incident occurs during normal traffic operations with uni-directional traffic, the ventilation system is used to blow smoke in the normal direction of traffic movement. This ensures smoke-free air upstream of the fire site providing protected routes for the evacuation of vehicle occupants and the intervention of the emergency services. The velocity of the longitudinal airflow required to prevent the upstream spread of smoke, or backlayering, is called the ‘critical velocity’. In a road tunnel, the critical velocity is measured in the cold airflow upstream of the fire and in an unoccupied section of the tunnel. The determination of this critical velocity is discussed in section 2.5.1.

BD 78/99 draws attention to the need for the careful consideration of smoke control and emergency service response in the event of a fire in a bi-directional traffic tunnel, since smoke may be forced over vehicles approaching the fire in the non-incident lane. The worst scenario is when a fire occurs closest to the supply (normal entrance) portal or shaft, in which case the smoke could potentially spread over the longest queue of traffic. Reversing the airflow of the fans would take time (notionally 20 minutes) leading to smoke logging of the whole tunnel. A possible response is to leave the ventilation system switched off. The stratification of the hot smoke (for a limited time and distance from the seat of the fire) allows people, within the relatively clear and cooler air below, to escape safely from the tunnel. However, turbulence and cooling will cause such smoke layers to descend at
some distance from the fire. It is advised in BD 78/99 that “unless the fans are started quickly, and at a moderate flow rate, the smoke may billow in all directions”.

In the French Inter-Ministry Circular, specific limits are imposed on longitudinal ventilation as summarised in Table 2.9. In each case, longitudinal ventilation is accepted for longer tunnels on the condition that massive extraction systems are installed at intervals corresponding to the limits shown in Table 2.9. The one exception to this is a non-urban, bi-directional tunnel with heavy traffic, where longitudinal ventilation is not acceptable for tunnels longer than 1000m. For tunnels with uni-directional traffic without congestion, the ventilation system must be started as soon as possible under conditions which will make it possible to achieve at least 3 m/s in the direction of traffic movement. If there are vehicles on both sides of a fire, initial efforts must be made to restrict the longitudinal airflow as much as possible in order to maintain the smoke stratification and to permit users to be evacuated. Subsequently, it may be appropriate to increase the rate of ventilation in order to control the smoke and allow firefighters to approach the fire safely.

Table 2.9 Maximum allowable lengths of longitudinally ventilated tunnels in France

<table>
<thead>
<tr>
<th>Tunnel characteristics</th>
<th>Maximum allowable length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban tunnel, bi-directional traffic</td>
<td>Prohibited</td>
</tr>
<tr>
<td>Urban tunnel, uni-directional traffic</td>
<td>500m, or 800m with appropriate operation and equipment</td>
</tr>
<tr>
<td>Non-urban tunnel, bi-directional traffic, heavy flows</td>
<td>1000m with compensatory measures</td>
</tr>
<tr>
<td>Non-urban tunnel, bi-directional traffic, light flows</td>
<td>1000m, or 1500m with compensatory measures</td>
</tr>
<tr>
<td>Non-urban tunnel, uni-directional traffic</td>
<td>5000m</td>
</tr>
</tbody>
</table>

For Austrian tunnels, the limits on longitudinal ventilation are treated in the same way as the limits on natural ventilation, using the iterative safety analysis process. RVS 9.261 also specifies that, in the event of a fire, the longitudinal air velocity should be reduced to between 1.0 to 1.5 m/s for uni-directional as well as bi-directional tunnels.

The US standard NFPA 502 specifies that in tunnels with bi-directional traffic where there may be people on both sides of the fire, smoke stratification should not be disturbed, the longitudinal air velocity must be kept at low magnitudes, and smoke extraction through ceiling openings or high openings on the tunnel wall(s) should be considered. An important point is made about the need to avoid disruption of the smoke layer by not operating jet fans that are located near the fire site. Rather, fans that are farthest away from the site should be operated first.

The European Directive 2004/54/EC states that “in tunnels with bi-directional and/or congested unidirectional traffic, longitudinal ventilation shall be allowed only if a risk analysis … shows it is acceptable and/or specific measures are taken, such as appropriate traffic management, shorter emergency exit distances, smoke exhausts at intervals”.

2.2.2.1 Discussion

It may be appropriate to limit the length of longitudinally ventilated tunnels in some circumstances. Currently, in the absence of any firm guidelines, this is dealt with in a subjective way for UK tunnels. It is recommended that further work is carried out to develop a risk-based methodology to ensure a sound and consistent response to this issue.
2.2.3 Ventilation systems with extraction capability

Ventilation systems with extraction capability include fully transverse and semi-transverse systems (with dual pollution and smoke control functions) as well as dedicated smoke extraction systems (via shafts or ceiling ducts). Most existing semi-transverse systems supply fresh air along the tunnel length at kerb level, forcing the polluted air to be discharged through the portals or through shafts to atmosphere. For smoke control purposes, the ventilation system must be reversible with the supply/exhaust ports at high level. A transverse ventilation system supplies fresh air and extracts polluted air along the length of the tunnel. For smoke control purposes, the exhaust ports should be located at high level.

BD 78/99 does not recommend the use of a semi-transverse supply ventilation system for smoke extraction because this would require time for the supply fans to be reversed and could lead to smoke de-stratification problems. Furthermore, little smoke would be extracted for a fire located mid-way between ventilation shafts. Care would also need to be taken to avoid damaging equipment or parts of the structure within the ventilation ducts. BD 78/99 outlines the advantages and disadvantages of transverse ventilation systems and recommends upward extraction, i.e. air supplied at low level and extracted at high level, as the most effective layout for smoke control in an emergency. No minimum ventilation flow rates are prescribed in BD 78/99 for either type of system.

The French Inter-Ministry Circular (2000) provides more specific guidance on smoke extraction. Key aspects include:

- Design based on a 30 MW HGV fire producing 80 m$^3$/s of smoke;
- Ventilation sections of limited length, up to 400m in urban tunnels and 600m in non-urban tunnels;
- Spacing of ceiling smoke vents at 50m intervals in urban tunnels and 100m intervals in non-urban tunnels;
- Careful control both of fresh air supply and longitudinal airflows below 1.5 m/s to help avoid de-stratification of the smoke layer;
- Extraction flow to be increased in comparison with the flow of smoke produced by the fire in order to take into account the inevitable entrainment of fresh air by the extraction system;
- Where the air flow can be regarded as being under control, an increase of one third in the smoke flow produced by a fire is to be adopted for roof-mounted smoke vents (e.g. for a fire which produces 80 m$^3$/s of smoke, this results in a minimum extraction flow of approximately 110 m$^3$/s);
- Where the longitudinal air flow cannot be regarded as under control, some compensation is to be provided by increasing the extraction flow by an amount equal to one and a half times the tunnel cross-section (e.g. for a 30 MW fire in a tunnel with cross-section of 60 m$^2$, the extraction flow is to be at least 80 + 1.5 \times 60 = 170$ m$^3$/s). This takes into account both the entrainment of fresh air and the compensation intended to allow for insufficient control of the longitudinal air flow.
- Mean velocity through smoke ducts to be limited to 15 m/s.

The French circular also describes the use of ‘massive extraction systems’ to extend the lengths of longitudinally ventilated tunnels. These systems have to be dimensioned so that they can remove all the airflow arising from the direction of the fire, including the smoke produced, and the air drawn in from the other direction at a minimum speed of 1 m/s. Monitoring of the longitudinal airflow is considered to be of special importance. Insufficient longitudinal airflow will result in smoke backlayering, while excessive airflow will result in smoke being carried beyond the extract openings.

In the Austrian standard RVS 9.261, the key requirements for smoke control using transverse and semi-transverse ventilation systems are:
• Semi-transverse ventilation systems must be reversible in the event of fire and capable of extracting a minimum of 80 m³/s of air (at ambient temperature) from the most adverse point of the tunnel. The ventilation in the fire zone must be switched to extraction mode immediately in the event of a fire, and the adjacent ventilation sections operated to give maximum fresh air supply.

• For smoke control using transverse ventilation systems, the ventilation system must be capable of extracting a minimum of 80 m³/s of air in the event of fire (at ambient temperature) from the most adverse point of the tunnel. The fresh air supply must be reduced to a third at most, and the extraction outlets fully opened above the fire and fully closed in all other sections.

The US standard NFPA 502 specifies the following objectives for transverse or reversible semi-transverse systems, for tunnels with unidirectional traffic where motorists are likely to be located upstream of the fire site. Firstly, the exhaust rate in the ventilation zone that contains the fire should be maximised and the amount of outside air that is introduced by a transverse system should be minimised. Secondly, a longitudinal airflow in the direction of traffic flow should be created by operating the upstream ventilation zone(s) in maximum supply and the downstream ventilation zone(s) in maximum exhaust.

Annex G of NFPA 502 summarises key findings of the Memorial Tunnel Fire Ventilation Test Program (MTFVTP). Transverse ventilation was tested using an extraction rate of 100 cfm/lane-ft (0.155 m³/s per lane-metre). This extraction rate is commonly used to design transverse ventilation systems for US tunnels (ASHRAE, 2003). Tests were also carried out for the ‘single point extraction’ concept, which can be viewed as an enhanced transverse system with large openings to the extraction duct that can be operated during a fire emergency to extract a large volume of smoke as close to the fire source as possible. The Memorial Tunnel fire tests demonstrated the effectiveness of this concept. The results also indicated that the specification of a minimum exhaust capacity per lane-metre is insufficient on its own. The size and location of extract openings are also essential elements that have to be addressed to ensure effective smoke control.

The European Directive 2004/54/EC states that transverse or semi-transverse ventilation systems capable of exhausting smoke are to be used in tunnels where a mechanical ventilation system is necessary and longitudinal ventilation is not allowed. Furthermore, for bi-directional traffic tunnels longer than 3000m, with a control centre and a traffic volume higher than 2000 vehicles per lane (per day), the following minimum measures are specified:

• Air and smoke extraction dampers are to be installed which can be operated separately or in groups.

• The longitudinal air velocity is to be monitored constantly and the steering process of the ventilation system (dampers, fans etc.) adjusted accordingly.

The draft PIARC guidance on Systems and Equipment for Fire and Smoke Control in Road Tunnels (2004) focuses on the importance of maintaining stratification. The following guidance is being considered:

“The main condition for stratification development appears to be the limitation of longitudinal velocity. Longitudinal velocity tends to:

• increase the turbulence and mixing effects between smoke layers;

• increase the thermal exchange between the individual smoke layers and between the smoke and the walls.

With transverse ventilation systems, the problem of longitudinal velocity control is difficult to solve since the longitudinal velocity varies as a function of location along the tunnel. Ventilation system operation is therefore dependent on the fire location.
The most common recommendation for controlling longitudinal velocity with a transverse system is to balance the injection and extraction rates. There are several problems associated with this solution:

- It is not recommended that fresh air be blown into the smoke area. Some recommendations propose to limit the length of the tunnel section that receives the fresh air.
- It is recognized that fresh air injection can present a risk to smoke stratification, especially if the jet passes through the smoke layer. Therefore, fresh air vents should not be located along the top of the walls. Furthermore, some studies performed for the Mont Blanc Tunnel renovation have shown that even if the injection is performed at the bottom of the walls, the risk of smoke de-stratification remains. To minimize this risk, fresh air injection velocities should be kept as low as possible.
- Severe changes in longitudinal velocity can occur if the natural ventilation flow varies during the fire.
- Manual operation is complex because the relationship between the ventilation system operation and the resulting longitudinal velocity is not direct. Moreover, natural ventilation introduces an additional complexity.

2.2.3.1 Discussion

The advice given in BD 78 on transverse and semi-transverse systems should be updated, with specific requirements given for the design and operation of the tunnel ventilation system during an incident along the lines of the French and draft PIARC guidance.

2.2.4 Mobile ventilation units

Mobile ventilation units could be useful for firefighting in some situations. The concept involves creating a positive pressure at one end of the tunnel, thus generating a longitudinal airflow through the tunnel and allowing the fire brigade to operate in the smoke-free conditions upstream of the fire. The fans can be used at one portal to supplement a longitudinal ventilation system or to increase or reverse natural airflows, depending on the circumstances. Mobile fans could also be used at both portals to boost the extraction performance of a fixed ventilation system based on transverse or extraction principles.

Bader and Coffman (2002) presented details of testing in a 1550m long tunnel in Switzerland using a 1.25m diameter mobile fan with 37.5 m$^3$/s output. With the fan positioned in front of the portal, a longitudinal airflow of 2.1 to 2.3 m/s was achieved along the length of the tunnel after 6 minutes. Heissl and Hotbauer (2002) presented the results of similar tests carried out in a number of Austrian and Italian road tunnel, as summarised in Table 2.10. Two mobile fans were used to generate the longitudinal airflows of about 3 m/s in the 1650m long Runehamar tunnel during the recent fire test programme (Lönnermark and Ingason, 2003). The fans had a diameter of 1.52m, and produced a thrust of 2500 N and 52.7 m$^3$/s output.
Table 2.10 Examples of practical testing of mobile fans (Heissl and Hotbauer, 2002)

<table>
<thead>
<tr>
<th>Fan thrust (N)</th>
<th>Tunnel length (m)</th>
<th>Natural airflow (m/s)</th>
<th>Direction of forced ventilation</th>
<th>Airflow achieved (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2500</td>
<td>1000</td>
<td>0.5</td>
<td>against natural flow</td>
<td>4</td>
</tr>
<tr>
<td>5000</td>
<td>9400</td>
<td>0</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>1000</td>
<td>1700</td>
<td>1.0</td>
<td>against natural flow</td>
<td>1.5</td>
</tr>
<tr>
<td>2500</td>
<td>750</td>
<td>0.5</td>
<td>with natural flow</td>
<td>3.75</td>
</tr>
<tr>
<td>2500</td>
<td>3000</td>
<td>0.5</td>
<td>with natural flow</td>
<td>3</td>
</tr>
</tbody>
</table>

2.2.4.1 Discussion

Mobile ventilation units are not intended to replace fixed ventilation systems, but may be useful when a tunnel does not have a fixed ventilation system or when part or all of the fixed ventilation system is not available. Nevertheless, justification could be problem for such specialised equipment, especially if there are only one or two short non-ventilated tunnels in the area covered by a given fire brigade. The provision of fire brigade resources is generally based on an assessment of the levels of risks across all types of risk and geographical areas, and there could well be higher priorities.

Maintenance of equipment is an important factor. Fire brigades would not have personnel with the appropriate expertise and specialist contractors would probably have to be employed to carry out routine maintenance. However, the authority responsible for the tunnel could be made responsible for their provision and maintenance.

How the equipment would be used is also important. Presumably, the mobile fan would be operated by a specialist unit, along the lines of the response units for chemical incidents. The implications for training also need to be considered carefully because of the limited time available for training of fire brigade personnel. In some areas at least, training for tunnel fires is covered only indirectly as part of training for underground incidents in general.

An alternative approach to using mobile fans might be to provide one or more small jet fans at the portals of short tunnels for emergency use only, controlled from the fire brigade panels. Whilst effective smoke control might not be achievable, it might provide a useful degree of air movement to assist firefighting and to purge the tunnel of smoke after the fire has been brought under control.

2.3 Behaviour of smoke and hazardous gases

2.3.1 Ventilation effects on fire development

The concern over the use of excessive ventilating airflows relates to the possibility of faster fire growth and increased heat release rates. From a numerical analysis using a Bayesian model, Carvel, Beard and Jowitt (1999) suggested that the maximum heat release rate might increase by a factor of five and the fire growth rate by a factor of twelve at an airflow velocity of 3 m/s compared to still air ambient conditions. This effect was investigated as part of the Benelux Tunnel fire tests in the Netherlands (Rijkswaterstaat, 2002). It was found that there was no increase in maximum heat release rate or fire growth rate for cars. For HGV loads, the size of a fire increased by 20-50% and the growth rate by 2 to 3 times. The view was also stated in the test report that the variation of fire development behaviour due to vehicle characteristics was at least as great as the variation caused by increased ventilation.
The evidence from the Benelux tunnel fire tests suggests that the differences in maximum fire size and fire growth rate between the critical velocity (to prevent smoke spreading upstream of the fire) in the region of 2.5 m/s for a 30 MW fire and a typical design velocity of 3-4 m/s will be relatively small. The differences will probably be less significant than the variability due to other aspects such as vehicle and load characteristics.

Carvel, Beard and Jowitt (2004) have revised their Bayesian model in the light of more recent fire test data, concluding that an HGV fire subject to a longitudinal airflow of 3 m/s would be expected to have a heat release rate during its growth phase about four times larger than under natural ventilation conditions, and a peak heat release rate about three times larger.

2.3.1.1 Discussion

It appears that the problem was exaggerated due to the lack of data. Subsequent full-scale fire tests have not supported the scale of the predictions. In contrast, some parties believe that strong airflows actually help to cool and dilute the combustion products and therefore mitigate the hazards and do not make conditions worse.

Another aspect that tends to be overlooked is that, in the case of longitudinal ventilation being used during unidirectional traffic operations, the key objective is simply to prevent smoke spreading upstream of the fire. Provided smoke-free conditions for escape can be achieved, the rate of fire growth is unlikely to be critical for life safety. Of course, if strong airflows cause a fire to grow larger than the design fire size, then backlayering would be expected and this could potentially have life safety implications. The design fire size should be reviewed.

It would be difficult to investigate this issue by analysis alone, since computational models of fire spread in realistic situations are not yet available. More comprehensive fire test data would be helpful.

2.3.2 Gradient effects on smoke or gas movement

As the fire develops, tunnel gradient and the effects of smoke buoyancy may strongly influence the airflow direction. This could lead to smoke spreading in one direction under the influence of the ‘stack effect’ rather than spreading in both directions. Where the tunnel gradient varies along its length, the local gradient in the vicinity of the fire may dictate the ultimate (‘steady-state’) airflow direction throughout the whole tunnel.

The effects of smoke buoyancy in a sloping tunnel are illustrated by Test 501 of the Memorial Tunnel Fire Ventilation Test Program (Bechtel/Parsons Brinkerhoff, 1995). This test involved a 20 MW fire under natural ventilation conditions. The tunnel was 853m long with a gradient of 3.2%. After 2 minutes, the smoke had spread in both directions away from the fire due to the momentum of the smoke layers. By 5 minutes, i.e. only 3 minutes later, the smoke distribution had changed dramatically. Under the influence of the ‘stack effect’, all smoke was moving in the uphill direction and mixed over the whole cross-section of the tunnel.

BD 78/99 describes the phenomenon but gives no specific limit on allowable tunnel gradient. The French tunnel ventilation guidance (CETU, 2003b) describes the effects of different airflow velocities on smoke behaviour as illustrated in Figure 2.4.
The European Directive 2004/54/EC specifies a limit on gradient of 5% unless no other tunnelling solution is possible. Furthermore, in tunnels with a gradient steeper than 3%, “additional and/or reinforced measures” have to be provided to enhance safety on the basis of a risk analysis.

2.3.2.1 Discussion

Tunnel gradients can have a major effect on smoke or gas movement under natural ventilation. This could be important under bi-directional traffic conditions, since the common operational response of switching off the ventilation would not guarantee reduced airflows. Experience from the A38 Saltash tunnel supports the observation that bi-directional traffic operations in tunnels with steep gradients can be difficult for the ventilation system to manage. It may be useful to define a maximum gradient for which bi-directional or congested traffic operations should be permitted for the future.

2.3.3 Smoke or gas ingress to access and egress points

BD 78/99 includes a requirement for ventilation to maintain a supply of fresh air to the escape route and positive pressure or other provisions to prevent smoke ingress. No quantitative criteria are given.

For buildings, BS 5588 Part 5 (1991) specifies measures to protect intervention access points such as firefighting stairs from smoke ingress. The requirements include an over-pressure of 50 Pa with doors closed and an average airflow velocity of 2 m/s through a single open door leaf. BS 5588 Part 4 (1998) deals more generally with smoke control in buildings using pressure differentials. Its contents suggest that in the context of a twin bore tunnel with cross passages, while the non-incident bore should perhaps be pressurised to 50 Pa, a lower level would be acceptable for cross passages that are used only for access and as temporary refuges.

The French tunnel regulations refer to the pressurisation of escape routes to prevent smoke ingress, with an upper limit of 80 Pa with doors closed to ensure that doors can still be opened easily. In addition, an airflow velocity of at least 0.5 m/s is required through an open double-leaf door.

The European Directive 2004/54/EC specifies that “appropriate means, such as doors or overpressure, shall prevent the propagation of smoke or gases from one tube to the other”.

An alternative performance-based approach is to calculate a specific critical velocity for a cross passage located downstream of the fire, using the method described by Tarada (2000). This method is an adaptation of the calculation method used for tunnels as described by Kennedy (1996). A longitudinal airflow along the incident bore will cool the smoke, thus reducing the critical velocity in
the cross passage. The worst case corresponds to no longitudinal airflow along the incident bore. To illustrate this, Table 2.11 gives the predicted critical velocities to prevent ingress of smoke from a 30 MW fire through a door opening of 2.1m high by 1.0m wide, for a range of tunnel airflow velocities.

### Table 2.11 Critical velocities for cross passages

<table>
<thead>
<tr>
<th>Tunnel airflow velocity (m/s)</th>
<th>Critical velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>2.09</td>
</tr>
<tr>
<td>1.0</td>
<td>1.59</td>
</tr>
<tr>
<td>1.5</td>
<td>1.45</td>
</tr>
<tr>
<td>2.0</td>
<td>1.34</td>
</tr>
<tr>
<td>2.5</td>
<td>1.25</td>
</tr>
<tr>
<td>3.0</td>
<td>1.17</td>
</tr>
</tbody>
</table>

2.3.3.1 Discussion

For the protection of firefighting access points, reference to an airflow velocity of approximately 2 m/s through a single open door leaf would provide consistency with what is currently required for buildings in the UK. It is interesting to compare this with the French requirement for road tunnels for an airflow velocity of 0.5 m/s through an open single-leaf door. Both values of 0.5 and 2 m/s are arbitrary. The actual airflow velocity required to prevent smoke ingress will vary according to a number of factors, including fire size and geometry.

There is a question about how many escape doors in a tunnel should be considered open at the same time. For the intervention phase, it would be appropriate to consider only a limited number of doors simultaneously in use by the fire brigade. A maximum of 2 open doorsets on each side of the fire is probably realistic, that is a total of 4 open doorsets.

It is unclear to what extent the evacuation phase should be taken into account for ventilation design. Certainly there is no issue in the case of a longitudinally ventilated tunnel with traffic upstream of the fire since, in the normal course of events, there should be no persons downstream of the fire. During congested conditions or in a bi-directional traffic tunnel, smoke ingress could occur. However, doors would be open only when people are moving through cross passage. With escape doors at 100m intervals, there might be about 90-100 persons using each doorset. On this basis, the doors would need to be open only for 2-3 minutes. A lower level of protection, or none at all, may therefore be acceptable on the grounds that the relatively small amount of smoke ingress that could occur during this period would not pose a life safety threat.

It is recommended that BD 78 be revised. Consideration should be given to the proposal that this aspect of the ventilation design in future be based on firefighting access only. The degree of pressurisation required to achieve approximately 2 m/s through 4 open doors would clearly yield lower airflows if several more doors were open during the evacuation phase. Modelling could be performed to assess the levels of smoke ingress likely and confirm the acceptability of this proposal.

2.3.4 Re-circulation of smoke or gas at portals

At the portals of a twin-bore tunnel, the proximity of the two bores may result in smoke discharged from one bore being drawn into the adjacent bore, particularly under adverse wind conditions. The level of re-circulation depends on a number of factors including the relative magnitudes of the smoke...
discharge velocity, the velocity and direction of the wind, the portal geometry and the nature of the local topography.

To minimise the re-ingestion of emissions between bores, BD 78/99 suggests a central dividing wall extending at sufficient height for some distance (up to 40m) beyond the portal or staggering the portals longitudinally by some 50m. The TRL report on tunnel ventilation (Clark et al., 2001) provides similar general guidance but no additional quantitative information to help designers.

The French Inter-Ministry Circular (2000) provides similar recommendations to consider a central dividing wall and staggering the portals. It also advises that operational procedures may need to be designed to avoid any risk of drawing smoke from one tube into the other.

2.3.4.1 Discussion

An effective mitigation measure is to control the airflow direction in the non-incident bore to match airflow direction in the incident bore. This avoids the problem completely during the incident operations.

If the non-incident bore is being pressurised to prevent smoke ingress through cross connections, then careful consideration should be given to controlling the ventilation of the non-incident bore so as to achieve both pressurisation and the required longitudinal airflows. This approach has been adopted for the Heathrow Airside Road Tunnel and Dublin Port Access Tunnel.

2.4 Installation issues for ventilation systems

2.4.1 Loss of fan efficiency due to reduced density of hot smoke

BD 78/99 refers to the effect of reduced fan efficiency with less dense hot smoke, but there is no specific requirement that this should be taken into account when calculating ventilation performance. The French Inter-Ministry Circular refers to the need to take this effect into account and recommends increasing the thrust by 30% for tunnels shorter than 500m and by 50% in other circumstances. No information appears to be given on this topic in the Austrian or US standards.

Mott MacDonald and other designers have developed models which take account of this effect, and have used these models in the design of tunnel ventilation systems for several years.

2.4.1.1 Discussion

This issue is well understood by designers and further research is considered to be unnecessary. However, some strengthening of the wording in BD 78 is recommended.

2.4.2 Fire resistance of ventilation equipment

Tunnel ventilation equipment must be capable of tolerating the high temperatures generated during fire incidents, in order to ensure the safety of people during evacuation and the safety of firefighters during the intervention phase.

BD 78/99 specifies that the ventilation equipment must be capable of operating continuously in smoke at a temperature of 250°C for 2 hours. Information is also provided on distances over which jet fans should be assumed to be destroyed by the fire. This is reproduced in Table 2.12. BD 78/99 also specifies that heavy items such as fans, subject to temperatures of 450°C, should not fall down during the firefighting phase.
Table 2.12 Distances over which jet fans should be assumed to be destroyed by fire (BD 78/99)

<table>
<thead>
<tr>
<th>Fire size (MW)</th>
<th>Distance upstream of fire (m)</th>
<th>Distance downstream of fire (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>40</td>
</tr>
<tr>
<td>50</td>
<td>20</td>
<td>80</td>
</tr>
<tr>
<td>100</td>
<td>30</td>
<td>120</td>
</tr>
</tbody>
</table>

The French Inter-Ministry Circular (2000) specifies that jet fans must be capable of operating continuously in smoke-laden air at a temperature of 200°C for 2 hours. For transverse ventilation systems, a distinction must be made on the basis of whether the fans are or are not likely to be subjected to very high temperatures. In the general case, extraction fans located at the end of a duct must be capable of operating at a temperature of 200°C for 120 minutes. However, under certain circumstances, it may be necessary for fans to be capable of withstanding 400°C for 120 minutes. Rather than providing information on the distances over which jet fans may be considered as destroyed, the French guidance provides smoke temperatures at various distances (CETU, 2003b). This is reproduced in Table 2.13. The circular also refers to the need to ensure that equipment does not fall down when exposed to a temperature of 450°C for 120 minutes.

Table 2.13 Smoke temperatures near the ceiling, with airflow close to critical velocity (CETU, 2003b)

<table>
<thead>
<tr>
<th>Downstream distance</th>
<th>10m</th>
<th>100m</th>
<th>200m</th>
<th>400m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light vehicle</td>
<td>250°C</td>
<td>80°C</td>
<td>40°C</td>
<td>30°C</td>
</tr>
<tr>
<td>Heavy vehicle</td>
<td>700°C</td>
<td>250°C</td>
<td>120°C</td>
<td>60°C</td>
</tr>
<tr>
<td>Tanker</td>
<td>&gt;1000°C</td>
<td>400°C</td>
<td>200°C</td>
<td>100°C</td>
</tr>
</tbody>
</table>

The Austrian standard RVS 9.261 was revised in the light of the Mont Blanc, Tauern and Gotthard tunnel fires. In particular, the high temperature rating of the fans (and associated air handling equipment) was increased from 250°C to 400°C for an operating time of 60 minutes. Pucher and Öttl (2002) presented test details for new 450 kW electric motors intended for the exhaust ventilation of the Platbutch Tunnel in Austria. The test arrangements consisted of a test chamber with the motor and a coupled generator for simulating the axial and radial loads acting on the motor. The effect of the load decreasing due to the lower air density in a fire was represented. The test demonstrated that the motor could be operated under load for 60 minutes without problems; continuation of the testing demonstrated that the motor could be operated under load in an air temperature of 400°C for approximately 165 minutes without serious problems.

The US standard NFPA 502 specifies a temperature rating for tunnel ventilation fans, attenuators and dampers of 250°C for 60 minutes.

The European Directive 2004/54/EC simply states “The level of fire resistance of all tunnel equipment shall take into account the technological possibilities and aim at maintaining the necessary safety functions in the event of a fire”.

TRL Limited 20 PPR140
2.4.2.1 Discussion

Table 2.12, reproduced from BD 78/99, describing the distances over which jet fans may be considered to be destroyed, should be updated to reflect any agreed revisions to the recommended ventilation design fire sizes.

2.4.3 Provision of standby fan capacity

Fans can become disabled in the case of a fire, when they are exposed to very high temperatures, but fans may also be unavailable while awaiting repair or routine maintenance. A level of redundancy is common practice in road and rail tunnels to ensure that the fan system can operate at the design rating under all foreseeable circumstances.

For tunnels equipped with jet fans, BD 78/99 states that 2 fans or 10% of the fans, whichever is greater, must be considered out of service. In addition, fans within the distances from the seat of the fire indicated by Table 2.12 must be assumed to be destroyed.

For fan installations in shafts, BD 78/99 states that standby fans must be provided in an arrangement that allows automatic switching from one fan to another. In terms of standby capacity, the guidance appears to be inconsistent, suggesting both that where “more than one fan serves a particular duty, only one standby unit is required” and “non-jet fans (large axial or centrifugal fans) should normally have 100% standby capacity”.

One of the requirements established by the US Federal Highway Administration is that, in a single ventilation zone, a ventilation rate equal to approximately 85% of the total ventilation capacity is required when one fan is out of operation (Bendelius, 1996). The US standard NFPA 502 also recommends a level of redundancy to allow for fans becoming disabled by the effects of a fire, but gives no precise requirements.

2.4.3.1 Discussion

Standby fan capacity should be considered in conjunction with power supply issues. There have been a number of instances during recent years where power outages have affected tunnels and underground systems. It is recommended that these aspects be addressed in terms of risk rather than specific levels of redundancy.

2.4.4 Effects of adverse portal winds

The effect of wind blowing towards the portal may require the air handling capacity of the ventilation equipment to be increased in order to overcome the adverse pressure gradient. There are several factors that need to be taken into account including the orientation of the portal with respect to the prevailing wind direction, the local topography, the proximity and size of surrounding buildings and structures, and the portal geometry, including the effect of the dividing wall (if present) to prevent recirculation.

BD 78/99 raises this issue but does not provide any specific criteria for the purposes of ventilation design. The typical approach currently used for design in the UK is to take the local wind rose, select the relevant sector(s) directed towards each portal and estimate the wind speed which is exceeded, say, only 5% of the time.

The French Inter-Ministry Circular (2000) actually defines the limiting atmospheric conditions which have to be taken into account. For tunnels without dangerous goods traffic, this limit corresponds to atmospheric conditions which are exceeded only 5% of the time (18.25 days per year). For tunnels through which dangerous goods traffic is permitted, the regulations specify that the mean longitudinal airflow velocity of 4 m/s must be achieved under adverse conditions which are exceeded only 10% of the time (36.5 days per year). In addition, a longitudinal airflow velocity of 3 m/s must be achieved in the presence of adverse atmospheric conditions which are exceeded only 5% of the time.
For Austrian tunnels, RVS 9.261 specifies that the limiting adverse wind speeds to be taken into account for design are those that are “achieved on at least 30 days per year for at least 30 minutes”.

### 2.4.4.1 Discussion

The adoption for design purposes of adverse wind conditions such as those outlined above, takes account of the risk of the ventilation system being incapable of achieving the design airflow velocity. However, this does not reflect the overall risks. It may be excessively onerous to consider an HGV fire coinciding with relatively rare strong wind conditions. For example, the combined probability of a major HGV fire with a return period of 100 years and an adverse wind speed exceeded 5% of the time, is given by $0.01 \times 0.05 = 0.0005$ /yr, giving a return period of 2000 years. Is it appropriate to consider such a rare combination of events? This could be addressed as part of a generic risk-based methodology for evaluating ventilation systems.

### 2.4.5 Noise levels due to fan operation

A tunnel ventilation system can produce high noise levels which interfere with communications in a tunnel and cause nuisance outside. Effective communications are particularly important during an emergency. Messages provided to the public using a radio re-broadcast or public address (PA) system need to be audible to ensure that people respond quickly when required. Likewise, when the emergency services arrive, they need to be able to use their radios without difficulty.

BD 78/99 specifies a maximum level of NR85 in the tunnel at a plane 1.5m above the road surface. Some guidance is given on what measures should be considered to control noise levels, such as additional sound absorbent material in the casing of jet fans and inlet or outlet silencers. Advice is given on the need to determine a balance between the use of quieter fans and the possible increase in their size and number to compensate for any increased pressure loss caused by a silencer.

In comparison, the French guidance on tunnel ventilation (CETU, 2003b) includes a limit on sound pressure level, for fans, of 80 to 83 dB(A) at 5m and 45° off the fan axis. There is no direct conversion between NR and dB(A), but to allow comparison with other noise levels the simplification $L_p [dB(A)] = L_p [NR] + 5$ can be used. On this basis, NR85 corresponds to about 90 dB(A).

From available records, the following noise levels were measured in various tunnels:

- Butetown (Cardiff)  82.6 dB(A)
- M25 Bell Common  83.0 dB(A) in north bore; 88 dB(A) in south bore
- M25 Holmesdale  86 dB(A)

In responses to the questionnaire (included in Appendix A), a number of tunnel operators reported noise problems when all fans are running. For example, at the Medway Tunnel, the noise levels were considered to be ‘severe’ and the effectiveness of communications ‘extremely poor’ as a result.

It would clearly be important to conduct communications exercises in any tunnel where the noise level was felt to be a problem when all fans are running.

### 2.4.6 Ventilation system commissioning tests

For commissioning purposes, tests need to be carried out to confirm that the ventilation equipment operates in accordance with the specification. No guidance is provided in BD 78/99 on how this should be carried out. Other design standards refer to carrying out ventilation analyses not just for emergency scenarios involving fires, but also for ‘cold’ scenarios that can be reproduced during commissioning tests to confirm that the performance of the ventilation system.
It is recommended that guidance on commissioning tests is added to BD 78 to ensure that such tests are carried out in a systematic manner to confirm that the installed ventilation fans and control system operate as intended.

2.5 Techniques for ventilation analysis and design

2.5.1 Calculation of critical velocity for longitudinal smoke control

The critical velocity for longitudinal smoke control is the magnitude of the longitudinal airflow velocity at which smoke is prevented from spreading upstream of the fire. When the airflow velocity is less than the critical velocity, the buoyancy-driven forces exerted by the hot smoke layer can overcome the opposing forces of the approaching longitudinal airflow, allowing the smoke layer to spread upstream of the fire. This is commonly called ‘backlayering’.

The most widespread method of calculating critical velocity, $V_{crit}$, is that described by Kennedy (1996) and stated in NFPA 502:

$$
V_{crit} = k_1 k_g \left( \frac{g H Q_c}{\rho c_p A T_f} \right)^{1/3}
$$

$$
T_f = \left( \frac{Q_c}{\rho c_p A V_{crit}} \right) + T
$$

In these relationships, $H$ and $A$ are the tunnel height (m) and cross-sectional area (m$^2$); $k_1$ is a constant; $k_g$ is a slope factor; $Q_c$ is the convective heat release rate (W); $T_f$ is the average temperature (K) at the fire location; and $\rho$, $T$ and $c_p$ are the density (kg/m$^3$), temperature (K) and specific heat (J/kgK) respectively of ambient air.

This method has a number of important limitations:

- It is essentially a one-dimensional analysis based on the perfect gas law, and assumes steady state behaviour, negligible smoke mass generation and no heat transfer to the walls.
- The fire is assumed to be ‘wide’ compared to the tunnel geometry, such that ventilating air cannot pass around the seat of the fire and therefore all ventilating air acts to cool the fire.
- Fully mixed behaviour is assumed. This will not be the case for smaller fires and this method will therefore under-predict the critical velocity for these smaller fires.
- The method over-predicts the critical velocity for large fires, as shown by comparison with test measurements from the Memorial Tunnel Fire Ventilation Test Programme (Bechtel/Parsons Brinkerhoff, 1995).
- The correction factor $k_g$ for the effect of blowing hot smoke downhill is based on limited model-scale experiments studies.

Tetzner et al (1999) described applying a correction factor $\beta$, with a value between 0 and 1, to the cross-sectional area (i.e. $\beta A$ instead of $A$) to take account of the incomplete mixing at the fire. The value of $\beta$ was chosen to give ‘improved’ agreement compared to the standard formulae for a small set of experiments. It appears that the relationship between $\beta$ and individual parameters such as cross-sectional area and aspect ratio (ratio of tunnel width to height) was not explored. The general applicability of the approach is uncertain.

The above method provides a link between heat release rate and critical velocity. However, from an examination of experiments and Computational Fluid Dynamics (CFD) analyses (see 2.5.4), Atkinson et al (1996) concluded that there is actually no significant link between critical velocity and heat release rate for large fires. Their alternative method, described in Appendix B of this report, was used in the analysis of data from the Benelux Tunnel fire tests (Rijkswaterstaat, 2002) and the Runehamar
tests (Lemaire, 2003). In the Runehamar tunnel fire tests, peak heat release rates in the range of 71 to 203 MW were measured. The tunnel is 1600m long, with a slope varying between 1 and 3%. It measured 7.2m wide by 5.2m high at the test section and was longitudinally ventilated. It was found that smoke backlayering was prevented by an airflow velocity of about 2.5 m/s. In comparison, the Kennedy method predicts critical velocities rising to 3 m/s for the largest fire, while the method of Atkinson et al predicts a critical velocity of about 2.5 m/s for a heat release rate greater than about 10 MW.

CFD modelling provides a more sophisticated method to determine the critical velocity, capable of taking into account the detailed geometry, presence and orientation of vehicles and the fire location with respect to the cross-section. This avoids the fundamental assumptions and reliance on empirically-derived constants, but the accuracy of the results depends on the modelling strategy.

2.5.1.1 Discussion

The standard method of calculating critical velocity appears to over-predict critical velocities for large fires. In some cases, this could result in the ventilation capacity being over-estimated. Guidance should be provided in BD 78.

Considering the design implications of critical velocities, it is clear from the above equations that the critical velocity will vary with fire location along a tunnel according to the local cross-section and gradient. This is illustrated in Figure 2.5 for a 2 km tunnel with two separate bores (‘Northbound’ and ‘Southbound’), a cross-sectional area of 65 m² and a design fire size of 30 MW. A conservative approach would be to size the ventilation system according to the ‘worst case’ combination of traffic, gradient and adverse portal wind. Alternatively, there may be scope to optimise the design by considering the overall risk of the ventilation system not achieving longitudinal smoke control. This may be appropriate if the adverse gradient affects only a small part of the overall tunnel length. It is recommended that a risk-based methodology is developed to allow such an assessment.
2.5.2 One-dimensional ventilation models

The principle of one-dimensional (1-D) tunnel ventilation models is the representation of a tunnel by a network of tunnel sections with uniform local fluid properties, and the solution of 1-D fluid flow, heat transfer and species transport equations across this network. The 1-D simplification provides a major benefit in terms of the speed with which a model can be set up and calculations carried out. Potentially, a large number of calculations could be carried out over a period of a few weeks, which permits different options to be investigated within the typical timescales available during design projects.

The use of such models for ventilation design is widespread. Examples include HOTFLOW (Mott MacDonald, UK), CAMATT (CETU, France), EXPRESS’AIR (Hydratec, France), SES (Parsons Brinkerhoff, USA) and SPRINT (HBI Haerter, Switzerland). The models have all been validated to some extent against full-scale fire test data.

The capabilities of the HOTFLOW program are typical. The program allows the user to model all the main features of the ventilation system including fans and their characteristics, fan shafts, ducts and dampers, together with the effects of traffic. The program predicts the transient movement of smoke in tunnels, shafts and ducts, taking into account the buoyancy effects of hot smoke, the degraded performance of fans when handling air and smoke at elevated temperatures (and reduced density), and the effects of heat transfer to the tunnel walls. External meteorological conditions are also taken into account. The program is routinely used for road and rail tunnel design, to determine the required capacities of the ventilation fans for dealing with tunnel incidents.

These models can be used effectively to investigate how actual incidents developed. Bradbury (2003) describes the use of the EXPRESS’AIR model for the investigations of smoke movement during the Mont Blanc Tunnel fire. The model was used to simulate the configuration and adjustments used during the fire. The results of this simulation were compared with empirical data on the smoke...
movement provided by opacimeters. The tool was then used to answer ‘what if?’ questions regarding alternative ventilation strategies.

1-D models also form the basis of tunnel ventilation simulators which can be used for operator training. For example, the simulator for the Mersey Kingsway Tunnel is based on the HOTFLOW program (see Figure 2.6).

2.5.2.1 Discussion

1-D models are well suited for designing tunnel ventilation systems and allow the designers to predict pressure distributions, airflows, temperatures and smoke propagation with reasonable accuracy. Complex systems can be modelled and modified in a straightforward manner, and parametric studies can be undertaken efficiently to find the best design solutions. Their main limitation is the inability to simulate the complex 3-D fluid flow and heat transfer phenomena involved in vehicle fires, including smoke stratification and backlayering. In addition, as with all computer models, their accuracy depends on the detailed modelling strategy used and the expertise of the modeller. It is therefore recommended that BD 78 is updated to include guidance on the selection and use of 1-D models for ventilation analysis.

2.5.3 Two-dimensional smoke models

‘Simple’ models have been developed with two or more layers in order to distinguish between the hot buoyant smoke layer and the cooler conditions below. The following examples illustrate some of the different approaches taken and the simplifying assumptions used.

The FASIT model of fire growth and smoke movement in tunnels is described by Charters et al (1994). This is a multi-zone, three-layer model based on the conservation of mass and energy, and empirical models for smoke movement and heat transfer. The layers can be described as hot, mixing and cool. The layers are mixed on the basis of a Richardson number (dimensionless ratio of buoyancy and inertia) criterion combined with an empirical entrainment coefficient for buoyancy-driven flows. Validation was carried out using a range of experimental results including those from the Ofenegg Tunnel fire tests.

Altinakar et al (1997) describe the development of a multi-compartment, two-layer zone model called TUFISI (Tunnel Fire Simulation). This was derived from the CFAST model (Peacock et al, 1993), which was developed by the Building and Fire Laboratory of the US National Institute of Standards and Technology (NIST) and can be downloaded free of charge from the NIST website. This original model was modified to allow mixing between the upper and lower layers using an empirical mixing coefficient based on the local Richardson number. Other modifications were implemented to take account of frictional pressure losses along a tunnel. The TUFISI model was validated using measurements from the Ofenegg Tunnel tests and from natural and longitudinal ventilation tests conducted as part of the Memorial Tunnel Fire Ventilation Test Programme (MTFVT).

In the European-funded research project OSIS (‘Outils de Simulation d’Incendie en Souterrain’, that is ‘Tools for Simulation of Underground Fires’), a two layer model was integrated into the FEUTEC tunnel fire model (TEC Ingénierie, 2000), which forms part of the 1-D tunnel ventilation program VENTITEC. The two layer model assumes that stratification depends on two parameters, which are the critical velocity and a critical temperature. If the local smoke temperature is less than the critical temperature then mixing of smoke and fresh air begins. Total mixing is assumed to occur after a distance of 5 hydraulic diameters. Validation was carried out using data from the Zwenberg and Repparfjord tunnel fire tests, and also from tests carried out in the Paris metro.

The OECD-PIARC QRA Model (Cassini et al, 2001) incorporates a simple model for stratified smoke layers. The initial velocity and depth of the smoke layer above the fire are calculated according to the approach of Heselden (1976). The movement of the smoke front along the tunnel is derived from a steady-state variation of smoke velocity and temperature along a level and naturally ventilated tunnel, as used in the FPETOOL software of the US National Institute of Standards and Technology (NIST)
In the QRA Model, when the depth of the layer grows descends to within 2m of the tunnel floor, the smoke is assumed to be fully mixed over the height of the tunnel. The smoke layer results are simply added to the ambient flows. For a smoke layer moving upstream of the fire against a longitudinal airflow, the smoke front is stopped when the velocity of the smoke layer is less than or equal to the velocity of the approaching airflow. Downstream of the fire, the smoke layer cools and grows until it becomes fully mixed. Validation was carried out using data from the Memorial Tunnel and Repparfjord fire tests.

The CRISP model is a Monte-Carlo simulation of entire fire scenarios developed by the Building Research Establishment (BRE). As part of the ongoing UPTUN research project (Nelisse, 2003), CRISP has been applied to a tunnel evacuation scenario under natural ventilation conditions. The fire and smoke spread are simulated by a two-layer zone model.

2.5.3.1 Discussion

There appear to be relatively few simple models for predicting stratified smoke conditions compared to 1-D tunnel ventilation models. The above examples demonstrate that these models tend to incorporate significant simplifications and limitations. Their applicability to scenarios involving steep gradients, large cross-sections and the effects of vehicles and jet fans is uncertain.

2.5.4 Computational Fluid Dynamics modelling

Computational Fluid Dynamics (CFD) modelling involves the solution of the fundamental equations of fluid flow (called the Navier-Stokes equations), heat transfer and species transport using three-dimensional models capable of representing complex geometries. CFD applications for tunnel ventilation and smoke control have been widely reported at conferences and in publications over the last few years. Most papers have focused on the capabilities and validity of the CFD modelling. Some papers have demonstrated how CFD has been used in actual tunnel ventilation design or safety studies.

Realistic modelling of smoke movement along a tunnel involves modelling the turbulent fluid flows as well as the effects of the fire itself and the heat transfer between the fire, smoke, tunnel structure and objects within the tunnel. Turbulence modelling has a fundamental influence on CFD modelling in general. Most commercially available CFD programs use techniques involving the solution of the so-called Reynolds-averaged Navier-Stokes (RANS) equations. This approach does not aim to resolve the turbulent motions but to provide the time-averaged characteristic quantities of the flow. Therefore the grid needs only to be fine enough to capture the important time-averaged features of the flow. A turbulence model is used to take account of the effect of turbulence on the flow. More recently, CFD modellers have started to use ‘Large Eddy Simulation’ (LES) techniques. This involves solving the Navier-Stokes equations for all but the smallest turbulent motions. This strictly requires far more grid cells than the RANS approach, since the length scales can vary from less than a millimetre to a several metres. The finest eddies are either ignored or modelled using a sub-grid scale model.

Starting with the ‘standard’ approach, useful progress from research and development studies was being reported at about the same time that BD 78/99 was published. Three examples follow, each of which included validation against data from the Memorial Tunnel Fire Ventilation Test Program (MTFVT).

Firstly, Gunton et al (1999) described the use of the commercially-available STAR-CD software in the European OSIS project. The fires were modelled using a combustion model, the so-called ‘eddy break-up’ model. For turbulence modelling, an algebraic stress model was implemented, to take account of the effects of strongly stable stratification on turbulence. Different radiation modelling techniques were investigated including the use of a soot model to describe the effects of local soot and gas concentrations and temperatures on radiation. A number of validation cases were examined. One case involved a kerosene tray fire in a 366m long tunnel, using data from tests conducted by the
Health & Safety Laboratory in their Buxton Dust Explosions Gallery. A second validation case involved the hot fume testing in the Paris metro, with a 1.1 MW heater. CFD comparisons were made between measured and predicted temperatures. A further validation case involved Test 501 from the MTFVTP featuring transient smoke spread from a 20 MW fire under natural ventilation conditions.

The second example concerns the CFD model SOLVENT, which was developed as part of the MTFVTP. Levy *et al* (1999) described the modelling of transverse ventilation systems using SOLVENT, which incorporates a flow network model for representing the supply and exhaust flows through the ventilation ducts. Validation was carried out using the measurements from Test 215B, a 20 MW fire test, from the MTFVTP. Karki *et al* (2000) subsequently described the modelling of longitudinal ventilation using jet fans. Validation is reported to have been carried out for 10, 20, 50 and 100 MW fire tests from the MTFVTP. Comparisons between measurements and predictions are presented for Tests 606A and 615B, which were 10 and 100 MW tests respectively.

In the third example, Miles and Kumar (1999) describe the validation of the CFD fire model TUNFIRE against Tests 607, 610 and 615B from the MTFVTP. These tests involved longitudinal ventilation and pool fires of 20, 50 and 100 MW respectively. Notably, comparisons were presented between predictions obtained using different computational grids, highlighting that agreement with experimental results depends on the modelling strategy used and experience and expertise of the modeller.

Practical applications in design and safety studies have since been widely reported.

### 2.5.4.1 Ongoing developments

The ‘Fire Dynamics Simulator’ (FDS) software has attracted widespread attention because the software can be downloaded free of charge from the website of the US National Institute of Standards and Technology. The software uses Large Eddy Simulation (LES) techniques rather than the ‘standard’ turbulence modelling approach. McGrattan and Hamins (2002) described the use of the model to estimate the thermal environment of the Howard Street Tunnel in Baltimore, Maryland, following the derailment of a freight train and the burning of spilled tripropylene and the contents of surrounding rail wagons. For these purposes, FDS was validated against temperature data from the MTFVTP.

Cochard (2003) describes another validation exercise for FDS against Test 321A of the MTFVTP. For this test, a ‘point supply’ ventilation arrangement was used with a single supply opening of 300 ft². The fire size was 40 MW. In order to halve the calculation time, the tunnel was considered to be symmetric about the vertical centreline. The smallest cells were approximately 20 x 20 x 20 cm, located around the fuel tray. The tunnel geometry was represented using 480,000 computational cells. Using a Pentium 4 computer with 512 MB of RAM, simulation of the first 5 minutes of the test took about 40 hours. Comparisons with measured values were found to generally good. Cochard concluded that FDS can provide “information equal to commercially available CFD codes”.

Ongoing CFD developments include modelling the effects of water sprays on fires in road tunnels. For example, Miles *et al* (2003) describe recent work on modelling sprinklers using the JASMINE program, in combination with the sprinkler particle-tracking model SPARTA. Using a statistically weighted sample of initial drop sizes and trajectories, a sprinkler particle-tracking model computes the paths of the droplet particles from a set of sprinkler heads through the gas phase. The transfer of mass, momentum and heat between the gas phase and the particles are computed at each time step, allowing the cooling of the combustion gases and the generation of water vapour to be predicted. The predictions were compared to experimental data. It was reported that the cooling of the smoke layer was captured “reasonably well”.

The coupling of CFD and evacuation models is another area of development. Lecointre and Pons (2003) describe an implementation of such an approach. The physical conditions predicted by the CFD model, including temperature, smoke toxicity and visibility, were used by the evacuation model...
TunnelEvac to predict the number of casualties and the evacuation time. Several scenarios were studied, for different traffic conditions and emergency response characteristics.

Another important area of activity is the evaluation of the reliability of CFD modelling for practical design and safety applications. For example, Gobeau et al (2002) provided general guidance on CFD modelling of smoke movement in complex enclosed spaces, aimed principally at HSE inspectors to aid them in their assessment of safety submissions incorporating CFD. More recently, Gobeau and Zhou (2004) evaluated the use of CFD for a number of practical applications including an underground railway station. One important recommendation was that a set of CFD simulations should always be undertaken to highlight the potential sensitivity of the results. The results from a one-off case could be misleading.

2.5.4.2 Discussion

It is clear that CFD modelling is already being widely used for tunnel design and safety studies. This use is likely to increase in the future as computing power allows problems to be analysed with greater realism and in shorter timescales.

Currently, it is not possible to make any firm statements about the quantitative accuracy attainable with CFD programs, because the results are very dependent on the detailed modelling strategy used and the experience and expertise of the modeller. In general, however, the results confirm that good qualitative agreement is achievable.

In reviewing the issues surrounding CFD modelling, it is important to consider four key topics, namely the capability, validity and practicability of the tools and techniques and the expertise of the modeller. The capability of any CFD model concerns the presence of appropriate sub-models for representing a particular aspect of the problem. For example, without a combustion model, the modeller has to make additional assumptions about aspects such as the fire shape, and this may lead to less realistic results. Validity concerns the degree to which a model can predict what would happen in a real fire incident. Practicability concerns the efficiency with which a modelling study can be performed and the impact of project constraints on the modelling. For example, if results are needed within one week rather than one month, this might put pressure on a CFD modeller to use a simpler model and coarser computational mesh, which might yield less accurate results. Overall, the expertise of the modeller is extremely important in view of the many decisions which have to be made in setting up and running a CFD model. The accuracy of the CFD predictions will depend on all of these factors.

The modeller has to make potentially critical decisions about the nature and extent of the computational mesh and the fluid flow and heat transfer boundary conditions. In practice, the real problem will always be simplified because of the constraints of project timescales and available computing power, and sometimes because the modeller judges that a certain feature will have little influence on the important predictions. Common simplifications include representing vehicles as simple boxes aligned with the traffic lanes, omitting tunnel equipment such as traffic signs, luminaries and their support structures, and representing fires as simple volume sources of heat rather than attempting to model the actual combustion processes.

It is interesting to note that, in France, the use of CFD is discouraged unless a complete description of the modelling strategy and results are provided, including consideration of possible errors. Concerning software, CETU currently favour the use of the ‘k-ε’ turbulence modelling and advise against the use of the free FDS software. Work is ongoing at CETU to investigate the accuracy of the results provided by FDS.

Another aspect that needs to be considered is how tenability is evaluated from CFD results. It is apparent that the criteria used to judge survivability vary quite widely between studies. Standardisation would be sensible. This could be achieved by requiring modellers to follow, for example, the methodologies set out in the international standard ISO/TS 13571 (2002), which presents guidelines for the estimation of time available for escape, and in the Published Document PD 7974:
Part 6 on human factors (British Standards, 2004), which supports the standard BS 7974 on the application of fire safety engineering principles.

In view of all of the above issues, it is judged that there is a real need to update BD 78 to provide guidance for all parties who may be involved in commissioning, performing, interpreting or reviewing CFD modelling.

2.5.5 Risk analysis

BD 78/99 does not provide a framework for risk-based design of tunnel ventilation systems. A simple methodology is described for the purpose of Preliminary Hazard Analysis, but this is qualitative rather than quantitative in nature. This simple methodology can be used as a screening tool in order to identify which scenarios should be taken into account. A similar methodology is described in the French guidance document on tunnel safety (CETU, 2003a).

Quantitative risk analysis (QRA) has been used for tunnel design in the Netherlands for several years. Standards for ‘external risk’ have been applied since 1996. ‘External risk’ is defined as the risk for people who reside and work in the vicinity of the transport link or facility, as opposed to the ‘internal risk’ which concerns those actually using the facility. One example concerning the Roermond Tunnel is described by Rigter et al (1999). The analysis considered fires and dangerous goods incidents. The implications of longitudinal smoke control were taken into account. From the analysis, it was concluded that the length of the tunnel should be limited to between 750 and 1000m if dangerous goods transport was to be accepted.

The OECD/PIARC QRA Model for dangerous goods transport, as described in section 2.1.3, can be used to examine some tunnel ventilation design questions. The model considers ‘non-hazardous’ HGV fires as well as dangerous goods loads.

The Austrian design guideline for ventilation systems RVS 9.261 includes a safety analysis procedure as described in section 2.2.1. It is understood that work is ongoing to update this using a QRA approach. Generic event tree analysis has been used, covering breakdowns, accidents and fires, and estimates made of the casualties and damage using data collected from tunnel accidents in Austria. The intention is apparently to provide a simplified evaluation methodology in RVS 9.261. For hazardous goods scenarios, it is intended that the OECD/PIARC QRA Model is used.

It is relevant to note that QRA has been used extensively for railway systems, including tunnels and underground stations, for many years.

2.5.5.1 Discussion

From consideration of the ventilation design issues, it has been recommended that a risk-based methodology be provided in BD 78 to give a clear and consistent basis for making key ventilation decisions. There are a number of possible approaches:

a) describe risk methods and provide guidance on their use;

b) adapt the existing qualitative method in BD 78/99 based on Risk Priority Number (RPN);

c) define a QRA methodology, with guidance on selection of inputs;

d) derive a simplified evaluation methodology.

It is recommended that a QRA methodology is provided in BD 78. This is preferred because it provides greater flexibility and transparency. It would also be consistent with the approach taken by the OECD/PIARC QRA Model, which is based on generic event tree analysis. With a simplified evaluation methodology, the original basis would be less clear and it could prove more difficult to ensure consistency with risk analyses carried out for other aspects of design.
2.6 Operational issues

2.6.1 Introduction
The key operational issues for emergency ventilation are how the ventilation system is controlled and what ventilation mode is actually selected. The first aspect concerns the roles of the tunnel operator and the fire brigade, and the extent to which the ventilation system is controlled automatically. The second aspect concerns the ventilation response options which are available for a given incident.

Information on current operational practices and concerns was obtained for all of the following UK tunnels: Clyde, Dartford, East India Dock, Hatfield, Holmesdale, Limehouse Link, Meir, Mersey Queensway and Kingsway, Queensway (Birmingham), Roundhill, Saltash and Southwick. Additional information has been drawn from the minutes of meetings of the UK Tunnel Operators’ Forum, notably those held at Hatfield (November 2002), Watford (April 2003), Liverpool (October 2003), Crowthorne (April 2004). This was complemented by information obtained from a variety of sources on current practices overseas.

Published information and feedback from tunnel operators and emergency services are presented in sections 2.6.2 to 2.6.6. The implications are discussed in section 2.6.7.

2.6.2 Tunnel safety management
The importance of the operator’s role during an incident was clearly highlighted by the major fire in 1999 in the Mont Blanc Tunnel, which at that time was operated by separate French and Italian control centres. The joint report of the French and Italian technical investigations (Duffé et al., 1999) gave several recommendations including the following relating to operational control:

- A single subsidiary (of the two controlling companies) should be created to operate the tunnel and to carry out all necessary works;
- A single control centre should be established, with a fully computerised control system to give all necessary information to the operator and to put decisions into action automatically, using pre-determined procedures;
- New safety procedures should be devised following a risk analysis. The personnel should be trained regularly and exercises organised at least every year.

This was certainly not the first time that such points had been made following a tunnel fire incident. For example, a lack of training and coherence of procedures between emergency services and the tunnel operator was noted in the investigation following a bus fire in the Ekeberg tunnel in Norway (Norwegian Public Roads Administration, 1996). During the incident, the ventilation system was operated such that smoke was blown towards firefighters tackling the incident. Improved training and regular emergency exercises were recommended as a result.

An operator’s viewpoint of tunnel management was presented by Allen (2003), manager of the Sydney Harbour Tunnel in Australia. Recommendations included operator involvement during tunnel design and construction, sharing of best practice among tunnel operators to ensure that tunnels are operated in the safest and most efficient manner is also encouraged, and continuous training through regular exercises where all emergency services are involved. Another important point concerns the nature of operating procedures and the potential influence on staff alertness. It is suggested that too much repetition in procedures can result in lower levels of alertness. A tunnel operator should be adequately trained and alert to deal with circumstances that require normal procedural actions but he must also be flexible and be able to deal with unexpected events.

Tunnel safety management is a key aspect of the European Directive 2004/54/EC. One of the requirements is the appointment of a Safety Officer. The Safety Officer, who may be a member of the tunnel staff or the emergency services, will perform the following tasks:
• “ensure coordination with emergency services and take part in the preparation of operational schemes;
• take part in the planning, implementation and evaluation of emergency operations;
• take part in the definition of safety schemes and the specification of structure, equipment and operation in respect of both new tunnels and modifications to existing tunnels;
• verify that operational staff and emergency services are trained, and take part in the organisation of exercises held at regular intervals;
• give advice on the commissioning of the structure, equipment and operation of tunnels;
• verify that the tunnel structure and equipment are maintained and repaired;
• take part in the evaluation of any significant incident or accident”.

It is interesting to note that BD 78/99 already requires the appointment of a Safety Officer, responsible for all aspects of tunnel safety, with “authority to obtain implementation of Safety Recommendations either directly, or immediately through the Tunnel Manager”. It elaborates:

“The Safety Officer shall be responsible for co-ordinating all aspects of handling emergency situations and traffic incidents including the effects and exposure limits of known pollutants and the effect of fire on materials which are likely to be transported through the tunnel. The Safety Officer shall have responsibilities for monitoring all arrangements for abnormal working of the tunnel and the performance of equipment to be used under emergency conditions.”

2.6.3 Ventilation control

BD 78/99 Appendix D gives general guidelines regarding the role of the tunnel operator for major incidents. Key aspects are that ventilation fans should be stopped and switched to manual control, the fire location should be assessed and fans switched to appropriate operating mode; and if there are vehicles on both sides of the incident, then fans should remain switched off until it is verified that no persons remain downstream of the indicated direction of smoke clearance. The standard advises that changes to fan operation should only be made with the agreement of the fire officer in charge of the incident.

Feedback from UK tunnel operators indicates that the ventilation response to a fire varies between tunnels. In some cases, the fans are switched to manual control and immediately operated in the direction of traffic movement. In other tunnels, the fans are switched off and the operator waits for instructions from the fire brigade. In the event of a dangerous goods incident, the standard response is to switch off the fans and await instructions. It is usual for the fire brigade to take command when they arrive at the incident. Once this has happened, the operator would provide support as requested.

In comparison to the UK practices, the French tunnel ventilation guidance (CETU, 2003b) advises that the method of controlling a tunnel ventilation system varies from manual to completely automatic and is usually dependent on the level of supervision at the tunnel. For example, tunnels that use the ventilation system only for smoke extraction may have a control panel near the portal that can be used by firefighters. It is advised that during the first few minutes of an incident, a pre-programmed response is required for any ventilation system. After the first few minutes, a manual response should be activated. This manual response should be activated in the control room. If there is no control room, a smoke control panel should be installed at the portal of the tunnel for use by firefighters.

The Austrian standard RVS 9.261 states that although the operation would usually be automatic, switching to manual operation mode must be possible at all stages of operation. Tunnel-specific procedures have to be developed for tunnels with mechanical ventilation systems in co-operation with the local fire officer. In the event of fire, these procedures would commence automatically until the arrival of the fire brigade. The fire brigade would then decide if and how the ventilation system would continue to operate. The operator must have the capability to adjust the system to reflect the circumstances.
2.6.4 Fire brigade perspective

The fire brigade perspective on tunnel ventilation was discussed with ACO Peter Hazeldine (Assistant Chief Fire Officer, Hertfordshire Fire & Rescue Service), who sits on the National Operations Committee of the Chief Fire Officers Association, with responsibility for tunnels (as well as certain other topics). This committee focuses on operational response and procedures only. Discussions were also held with fire officers from London Fire Brigade, which covers 12 tunnels ranging from the Limehouse Link (1553m) and Rotherhithe (1483m) to short naturally ventilated tunnels such as Hangar Lane (240m) and Green Man (170m).

Currently, there are about twenty fire brigades across the UK with tunnels in their areas and therefore a direct interest in tunnel fire safety. Tunnel-specific operational procedures are formulated by the local fire officers. These procedures should be reviewed once a year. For incidents in tunnels, all fire brigades currently follow Technical Bulletin 1/1993, issued by the HM Fire Services Inspectorate. This guidance covers topics such as pre-planning for operational incidents, risk management, access for fire appliances and personnel, water supplies, ventilation, communications, training and on-site exercises. Work has commenced on updating this guidance but there is apparently no date set for completion.

Training is carried out through practical exercises. These are particularly important for fire officers, since they may not have any other opportunities for planning and familiarisation. Time constraints on the availability of fire crews can be an issue, particularly for part-time personnel. Training has to cover a broad range of activities. For most fire brigades, tunnels would normally be dealt with as part of training for incidents in underground spaces, which include basements, car parks and shelters. The frequency and nature of training exercises varies between fire brigades. At some tunnels, regular visits are carried out to familiarise the fire crews with the tunnel arrangements. These visits are carried out when a bore is closed for maintenance. The closure period may be extended to allow for this activity.

The feedback from fire officers concerning the control of ventilation systems is that this should be handled by the tunnel operator unless the process is very simple, such as a single button to blow one way and another button to blow in the opposite direction. It is also very important to note that fire brigade procedures and training do not cover the issue of what to do with the ventilation system in the event of an incident occurring during bi-directional or congested traffic conditions. This calls into question the common practice of relying on fire officers to make ventilation decisions when they arrive at an incident.

2.6.5 Control of longitudinal ventilation during bi-directional or congested operations

BD 78/99 recommends that in the event of a fire, an assessment should immediately be made of the size and location of the fire, and the fans operated in the mode best suited to the particular conditions. While there may be a simple response in some cases, such as a longitudinally ventilated bore with vehicles only on the upstream side of the incident, the best response may not be obvious in other cases. For longitudinally ventilated tunnels with bi-directional or congested traffic, there is a number of possible ventilation responses:

- Switch off all fans - this would allow the smoke to spread naturally under the influence of traffic, wind and the fire itself. Smoke may spread initially to both sides of the fire as a stratified layer, but may become fully mixed over the tunnel cross-section within a short distance from the fire and within a short period of time following the start of the fire. Strong winds at the portal may limit or block the natural venting of smoke to the atmosphere. If smoke is still stratified as it approaches the portal, strong winds will cause this stratification to break down rapidly.

- Switch on some fans to generate a reduced airflow of 1 to 1.5 m/s - This low speed will help to minimise disruption of the stratified smoke layer, but it should be appreciated that a stratified layer may not actually exist due to traffic and wind effects. If the selected airflow
direction corresponds to the downhill direction at the location of the fire, then as the fire becomes fully developed, the smoke movement may reverse to the uphill direction. Strong winds at the portal may disrupt the venting of smoke to atmosphere. For congested traffic situations, the ventilation control would need to be linked to the detection of traffic queues ahead of a fire incident to determine when to use all jet fans and when to use a reduced number of jet fans. The PIARC ‘Fire and smoke control in tunnels’ report (1999) notes that putting the right number of jet fans into operation within a few minutes after the start of the fire is not an easy control task. Also, it is important that no jet fan is switched on in, or near, the section of tunnel with stratified smoke, because this would immediately destroy the stratification.

- Switch on all fans – This would generate an airflow speed in excess of the critical velocity and ensure no propagation of smoke upstream of the fire. Fully mixed smoke conditions would occur downstream of the fire. Strong ventilating airflows may cause the fire to develop more quickly in some cases compared to weak airflows, but may cool the fire in other cases. Downstream of the fire, the smoke will be diluted by the fresh air, which may improve tenability in some locations compared to the situation without fans operating.

### 2.6.6 Fire detection

For tunnels with different ventilation sections, it will be important for control purposes to know the fire location. A vehicle fire in the tunnel could be pinpointed by an automatic fire detection system, but it is also possible that a tunnel user would raise the alarm by using an emergency telephone or fire alarm call-point button or, in some tunnels, by calling from a mobile phone.

European directive 2004/54/EC specifies automatic fire detection systems to be installed in all tunnels which do not have a control centre where the operation of ventilation equipment for smoke control is different from the automatic operation of ventilation for the control of pollutants.

Automatic detection of the fire location can be achieved using a range of technologies:

- linear heat detection using a heat sensitive cable or cable with embedded temperature sensors running along the soffit of the tunnel;
- point heat or smoke detectors located at intervals along the soffit of the tunnel;
- video-based smoke detection (based on computer analysis of the video image seen by the CCTV cameras).

Demonstrations of video smoke detection systems suggest that this technology may be the most effective for fast detection. With cameras spaced at intervals along the tunnel (typically in the order of 50-100m), these systems are also capable of pinpointing the fire zone. One disadvantage is that they would provide little information on fire spread if the images are subsequently obscured by smoke. In comparison, linear heat detection has a slower response but will continue to provide information irrespective of smoke spread. The Benelux Tunnel tests (Rijkswaterstaat, 2002) provided a useful comparison of linear heat detection technologies. The results indicated that two systems with embedded temperature sensors were generally less sensitive than an optical fibre system in detecting smaller fires. The optical fibre system could detect a small pan fire while the wire-based systems needed a car fire or larger before detection was assured.

A review of these technologies was recently reported by Almand et al (2006).

### 2.6.7 Training and emergency exercises

The importance of training both for operators and the emergency services is widely recognised. Some tunnel operators are now seeking to implement a structured training programme. Notably, Mersey Tunnels has recently introduced a training programme for their staff. Mott MacDonald assisted by
providing course notes and test questions together with a computer-based tunnel ventilation simulator. The simulator was developed to provide the user with ‘hands-on’ experience of how their actions would affect smoke behaviour during an incident. The operator can activate any combination of the jet fans and axial supply fans in the tunnel and view the airflows generated and the resulting movement of smoke. Other inputs include the traffic mode and the fire size. Figure 2.6 shows a snapshot of the simulator screen. Crausaz et al (2003) describe the simulator developed for the Mont Blanc tunnel. Stroppa and Seebacher (2003) present another example.

Figure 2.6 Ventilation simulator for Mersey Kingsway Tunnel

Feedback from tunnel operators indicates that exercises have been conducted during the last 1-2 years at most tunnels. In most instances, this has been in the form of table-top exercises.

BD 78/99 recommends that “for tunnels with mechanical ventilation systems, full scale fire tests are carried out, prior to opening, to verify the emergency procedures, including fire detection and alarm, traffic control, emergency services response time and the smoke control system”. It advises further that cold smoke generators are not suitable sources “as the smoke does not have the correct buoyancy”, instead suggesting a suitable technique using “a mixture of 25 litres of petrol, 5 litres of gas oil and pieces of tyre in a 4 m³ steel tank placed above a heat insulated and protected road surface, burning a steel tray of oil within a large skip insulated from the road, or by burning an old car”.

The Benelux Tunnel tests (Rijkswaterstaat, 2002) provided a useful demonstration of suitable test arrangements for small fires of about 1 MW. The results of temperature measurements are given and this could be helpful for planning tests.

In Australia, the CSIRO and the South Australian Metropolitan Fire Services developed hot-smoke tests in the early 1990’s. During 1991-1992, a series of experiments was devised and carried out in order to standardise hot-smoke test methods. This was subsequently incorporated in the Australian standard for hot-smoke tests AS4391. The ‘Fire Safety Guidelines for Road Tunnels’, produced by the Australasian Fire Authorities Council (2001), recommend that hot-smoke tests be carried out to demonstrate and confirm the operation of the ventilation system and the interfaces with other systems.
In contrast to the BD 78/99 guidance, feedback from UK fire brigades suggests that the value of fire tests is actually questionable. The objectives of the exercises are generally to familiarise personnel with the tunnel arrangements (layout, control panels, hydrant system, etc) and to test the emergency procedures, rather than to provide fire fighting training. The use of small fires does not provide any real benefit for the fire crews. Instead artificial smoke would be acceptable in general for these purposes. Training for fighting fires can be carried out more effectively and safely at fire brigade training centres, which are equipped with surveillance and tracking systems.

There are concerns from tunnel operators and designers that full-scale fire tests might damage the tunnel infrastructure, particularly equipment above the carriageway.

The benefit of ‘live’ exercises was demonstrated by one conducted at the Butetown tunnel in South Wales, which led to the rendezvous points being re-located due to how far the smoke spread from the portal.

### 2.6.8 Discussion

It is judged that BD 78/99 does not adequately cover the issue of the operation of the ventilation system. The guidance should be improved for the more problematical situations.

It is notable that BD 78/99 recommends that if there are vehicles on both sides of an incident, the operator should verify that all persons have evacuated from the intended smoke clearance direction before switching on the fans. This may be difficult or indeed impossible in practice because the coverage of the CCTV cameras may not allow this in the first place and because smoke would probably obscure the views after a few minutes anyway. It is also relevant to consider how the Japanese Public Highway Corporation has recently changed the operating procedures for water spray systems in their tunnels for exactly the same reasons (Setoyama et al, 2003). Instead of advocating a manual response in which the operator checks that people have evacuated, the authorities have now chosen to operate their systems automatically, with a delay of 3 minutes (following detection) for uni-directional tunnels and a delay of 10 minutes for bi-directional tunnels.

The wisdom of switching off the ventilation system and awaiting instructions is questionable. The fire officer arriving at the incident may be unfamiliar with the ventilation system and the potential issues surrounding its operation such as the effects of ambient wind conditions. It is inappropriate to expect fire officers to make critical decisions affecting life safety on the basis of their limited experience of the issues. Time is also an issue since any delay in making a decision could also have life safety implications.

The involvement of dangerous goods could complicate the situation further. For example, if the natural airflows are in the opposite direction to that of normal traffic movement, then after a few minutes any smoke or gas could be blown past the vehicles and people located behind the incident. On arrival at the tunnel, the first priority for the incident commander would be to assess the situation and the potential risks to firefighters. Until this is completed, it is expected that no action would be taken to operate the fans. Depending on the circumstances, this could take 5 minutes or more and the ventilation system could then take a further 2 minutes or more to establish airflows. This delay could lead to fatalities.

It is recommended that attention is given to investigating the potential scenarios and ventilation responses in advance, in order to identify the overall safest responses. In the event of an incident, a pre-defined plan could then be used without delay. In some situations, the safest response may be to switch off the ventilation system, but if so this should be done on the basis of careful planning and not as a waiting option. For incidents involving dangerous goods, it may be necessary to consider the implications for people outside of the tunnel as well as road users. This could be carried out using the OECD-PIARC QRA Model for dangerous goods transport (Cassini et al, 2001).

Finally, it is recommended that the guidance in BD 78 is consistent with that given to fire brigades.
2.7 Recommendations arising from the review

Based on the review of literature and consultations, it is judged that BD 78 needs to be updated and improved in several main areas:

1. A framework for risk-based design is required. The feasibility of using Quantitative Risk Assessment techniques on a generic basis should be investigated. The framework should be capable of supporting key decisions such as:
   a) Choice of scenarios for ventilation design - It is also recommended that a comprehensive set of standard scenarios should be provided in BD 78. Specific scenarios could then be selected as appropriate for a given tunnel project using the risk framework.
   b) Selection and justification of ventilation configuration - Key design issues which need to be considered include the limiting lengths for naturally ventilated tunnels and for longitudinally ventilated tunnels. The methodology should take into account combinations of traffic, gradient and adverse portal winds.

2. Improved guidance for design:
   a) Smoke spread between bores, including re-circulation at portals and flow through cross passages.
   b) Ventilation systems with extract capability.
   c) Ventilation analysis – New guidance is needed on the appropriate numerical models and modelling strategies, the expertise required by the modeller, and the interpretation of results.

3. Improved guidance for operations and emergency response including:
   a) Roles and responsibilities of the tunnel operator and the fire brigade.
   b) Selection of ventilation responses, looking in particular at the justification for switching fans off and waiting for instructions from the fire brigade.
   c) Consistency between the guidance followed by fire brigades, tunnel operators and designers.
3 Evaluation of data and methods

3.1 Standardised design fires

Whilst the choice of fire size for a ventilation design should take into account a range of factors affecting risk, including the tunnel length, cross-section and traffic conditions, the characteristics of the fires are most closely related to the nature of the vehicles themselves. Since tunnels everywhere are used by the same types of vehicles, it is reasonable to consider standardised design fires. This will avoid subjective decision making and improve the consistency of ventilation design for UK road tunnels.

3.1.1 Classification of fires

In general, the design fire for a tunnel will relate to heavy vehicles. Buses, coaches or HGVs without highly combustible loads would typically generate a fire with a peak heat release rate in the order of 30 MW. HGVs loaded with highly combustible goods could generate a ‘severe’ fire, which may be defined as having a nominal peak heat release rate in the order of 100 MW.

It is possible that the fire would spread from the vehicle of origin to other nearby vehicles, leading to an increased peak fire size and/or longer fire duration. In addition, the Runehamar fire tests (Ingason and Lönnermark, 2003) carried out in Norway in 2003 demonstrated that very severe fires with peak fire sizes of approximately 200 MW can occur with ‘non-hazardous’ loads comprising pallets and packaging. It would be difficult to predict the proportion of HGV fires which would produce a peak heat release rate in the order of 200 MW, since this depends on many factors including vehicle construction and materials, and the packaging and arrangement of the goods.

For low headroom tunnels, design fires will depend on whether traffic comprises cars only or includes LGVs as well. Fires involving a single car are expected to have a peak fire size typically in the order of 3-5 MW. With 2-3 cars involved in a fire, a peak fire size of 6-10 MW is expected. A value of 8 MW is adopted in France (see Table 2.2). For LGVs, a fire size of up to about 15 MW is expected.

Table 3.1 presents a proposed list of standardised design fires for a revised BD 78.

Table 3.1 Standardised vehicle fire sizes proposed for ventilation design

<table>
<thead>
<tr>
<th>Type of traffic allowed in tunnel</th>
<th>Type of vehicle(s) involved in fire</th>
<th>Design fire size (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Existing</td>
</tr>
<tr>
<td>Cars only</td>
<td>2-3 cars</td>
<td>5 ^1</td>
</tr>
<tr>
<td>Cars and LGVs</td>
<td>Light goods vehicle (LGV)</td>
<td>17.5 ^1</td>
</tr>
<tr>
<td>All traffic</td>
<td>Bus, coach or HGV (without highly combustible load)</td>
<td>20 - 50 ^2</td>
</tr>
<tr>
<td></td>
<td>HGV carrying significant quantities of highly combustible goods</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Road tanker carrying flammable liquids in bulk, or HGV carrying easily liquefiable, combustible products</td>
<td>100 ^1</td>
</tr>
</tbody>
</table>

Notes: 1. Ventilation design fire in draft TD 43;
2. Minimum ventilation design fire in BD 78/99, dependent on type of road (see Table 2.1);
3. Maximum fire size considered in BD 78/99
3.1.2 Fire growth curves

When determining the capacity of ventilation fans, only the peak fire size is generally used. More information is needed in order to evaluate how a tunnel fire incident would develop over time and to determine the effects of heat and smoke on people. In particular, the designer needs to know how quickly the fire size increases since it is probably overly pessimistic to assume that vehicle fires instantaneously generate their peak rate of heat release. Fire tests show that it takes approximately 5 to 10 minutes for a vehicle fire to reach its peak intensity.

One possible approach is to assume that vehicle fires grow and subsequently decay linearly over time. This approach is adopted in the French guidance (CETU, 2003a) and leads to simple triangular or trapezoidal forms of fire development as illustrated in Figure 2.1.

An alternative approach is to adopt ‘t-squared’ (time-squared) fire growth curves, as commonly used for fire safety engineering design. This would provide some consistency with fire safety engineering guidance in the UK, for example as given in PD 7974-1 (British Standards, 2003) and CIBSE Guide E (2003). The fire size is then given by \( Q = \alpha t^2 \), where \( Q \) is the fire size (MW), \( \alpha \) is a constant (kW/s\(^2\)) and \( t \) is time (s). Table 3.2 gives the values of constant \( \alpha \) for various standard classes of fire growth. The characteristic growth time for a t-squared fire is the time taken to reach 1055 kW (approximately 1 MW).

### Table 3.2 Standard t-squared fire growth curves

<table>
<thead>
<tr>
<th>Fire classification</th>
<th>Characteristic growth time (s) (to approx 1 MW)</th>
<th>Constant ( \alpha ) (kW/s(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultra-fast</td>
<td>75</td>
<td>0.1876</td>
</tr>
<tr>
<td>Fast</td>
<td>150</td>
<td>0.0469</td>
</tr>
<tr>
<td>Medium</td>
<td>300</td>
<td>0.0117</td>
</tr>
<tr>
<td>Slow</td>
<td>600</td>
<td>0.0029</td>
</tr>
</tbody>
</table>

For road tunnels, slightly different curves to those in Table 3.2 would be appropriate for two reasons. Firstly, some types of vehicle fire may grow more rapidly than the Ultra-fast curve. Secondly, it is common practice to refer to a time interval of 5 or 10 minutes for the time taken to reach the peak fire size. For example, the French guidance refers to a ‘standard’ HGV fire growing to 30 MW in 10 minutes. Table 3.3 gives a set of modified fire curves.

### Table 3.3 Modified t-squared fire growth curves

<table>
<thead>
<tr>
<th>Peak fire size (MW)</th>
<th>Characteristic growth time (s) (to peak fire size)</th>
<th>Constant ( \alpha ) (kW/s(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>600</td>
<td>0.0223</td>
</tr>
<tr>
<td>30</td>
<td>600</td>
<td>0.0833</td>
</tr>
<tr>
<td>100</td>
<td>600</td>
<td>0.2778</td>
</tr>
<tr>
<td>200</td>
<td>600</td>
<td>0.5556</td>
</tr>
</tbody>
</table>

In terms of life safety, the initial 10-15 minutes of a fire incident are critical. An upper limit of 30 minutes seems reasonable for analyses. It is proposed therefore that default fire curves are defined for a period of 30 minutes only.
3.1.2.1 Fires involving lorries and tankers

Figures 3.1 to 3.3 compare linear, standard t-squared curves (Table 3.2) and alternative t-squared curves (Table 3.3) for 30, 100 and 200 MW fires. It is conservative to assume that such fires would maintain their peak intensity at least up to 30 minutes before starting to decay. The figures illustrate how onerous linear fire growth is compared to t-squared curves, during the first few minutes of a fire, and the extent to which the standard Fast and Ultra-fast fire growth curves do not match the expected behaviour for vehicle fires.

![Figure 3.1 Fire curves for 30 MW lorry fire](image1)

**Figure 3.1 Fire curves for 30 MW lorry fire**

![Figure 3.2 Fire curves for 100 MW lorry fire](image2)

**Figure 3.2 Fire curves for 100 MW lorry fire**
It is evident from the Runehamar fire tests (Ingason and Lönnemark, 2003) that a lorry fire could reach its peak in less than 10 minutes. Rather than defining a set of alternative curves for use in sensitivity studies, the 100 MW curve could be used for a 30 MW fire and the 200 MW curve used for a 100 MW fire.

If tunnel conditions need to be analysed for periods longer than 30 minutes, then the key assumptions should be discussed with the Tunnel Design and Safety Consultation Group (TDSCG). The duration of the peak and decay phases depend on the fire load of an HGV. A number of theoretical models are described in published papers. For example, a simple method for deriving the duration of the peak and decay phases, in combination with t-squared fire growth curves, is described by Ingason (1995).

### 3.1.2.2 Fires involving light vehicles

For low headroom tunnels, smaller design fires need to be defined. Figures 3.4 and 3.5 compare linear, standard Fast t-squared curve (Table 3.2) and alternative t-squared fire curves (Table 3.3) for car only tunnels (8 MW) and for tunnels allowing LGVs as well as cars (15 MW).
For the 8 MW fire, the linear curve is taken from the French guidance (CETU, 2003a) and is based on a combination of three burning cars, each growing to 4 MW in 5 minutes and then decaying over a further 45 minutes. The second and third cars are assumed to become involved at 5 and 15 minutes. The proposed t-squared curve reaches 4 MW in 7 minutes and the peak of 8 MW in 10 minutes.

For the 15 MW design fire, the growth rate is taken to be the same as for HGVs in general. This means that the peak of 15 MW is reached after approximately 7 minutes.

3.1.3 Smoke and carbon monoxide generation parameters

Assessments of smoke effects on people are sensitive to the assumptions about the composition of the burning vehicle. An indicative estimate of carbon monoxide and smoke yields based on the composition of an HGV is given in Table 3.4 (adapted from Malhotra and Hall, 1995). In this example, the load includes 1 tonne each of cardboard, PVC and polystyrene. If the load comprises mostly cellulose-based materials, then the smoke and CO yields would tend to 0.015 kg/kg and 0.004 kg/kg respectively, i.e. an order of magnitude lower than shown in Table 3.4.

<table>
<thead>
<tr>
<th>Material</th>
<th>Mass (kg)</th>
<th>Heat of Combustion (MJ/kg)</th>
<th>Smoke yield (kg/kg)</th>
<th>CO yield (kg/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cab</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyethylene</td>
<td>80</td>
<td>44</td>
<td>0.060</td>
<td>0.024</td>
</tr>
<tr>
<td>Polyurethane foam</td>
<td>25</td>
<td>26</td>
<td>0.198</td>
<td>0.042</td>
</tr>
<tr>
<td>Fuel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel</td>
<td>50</td>
<td>41</td>
<td>0.059</td>
<td>0.019</td>
</tr>
<tr>
<td>Tyres</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rubber</td>
<td>600</td>
<td>32</td>
<td>0.114</td>
<td>0.021</td>
</tr>
<tr>
<td>Wood</td>
<td>600</td>
<td>18</td>
<td>0.015</td>
<td>0.004</td>
</tr>
<tr>
<td>Flooring</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flooring (cellulosics)</td>
<td>1000</td>
<td>17</td>
<td>0.015</td>
<td>0.004</td>
</tr>
<tr>
<td>PVC</td>
<td>1000</td>
<td>17</td>
<td>0.172</td>
<td>0.063</td>
</tr>
<tr>
<td>Load</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cardboard</td>
<td>1000</td>
<td>17</td>
<td>0.164</td>
<td>0.06</td>
</tr>
<tr>
<td>Overall</td>
<td>4355</td>
<td>25.3</td>
<td>0.101</td>
<td>0.034</td>
</tr>
</tbody>
</table>

This example highlights the importance of understanding the sensitivity of tenability assessments to these assumptions.
3.2 Approaches to ventilation design

Ventilation design typically involves the following basic steps:

- select design fire size;
- propose candidate ventilation system, including number and distribution of fans (and dampers, if appropriate);
- undertake ventilation modelling for relevant combinations of fire location, traffic conditions, external wind, etc;
- review results against appropriate acceptance criteria to determine the effectiveness of the proposed design.

Depending on whether the ventilation modelling confirms that smoke is controlled, it may be necessary to modify the candidate design and repeat the modelling.

3.2.1 Conventional approach

A conventional approach can be illustrated by considering a simple example involving the design of a longitudinal ventilation system for a tunnel with a significant variation of gradient along its length. In this case, the acceptability of the design may be judged in terms of whether the critical velocities for longitudinal smoke control can be achieved for the relevant set of design cases.

Figure 2.5 illustrates the variation of critical velocity along both bores of a 2 km twin bore tunnel with respect to the local gradient of the bores. The critical velocity varies between about 2.3 and 2.6 m/s depending on the location of the fire. Ventilation modelling was undertaken using Mott MacDonald’s in-house Hotflow program (see section 2.5.2 of this report). Example results are shown in Table 3.5 for three fire locations in the Northbound bore: near the entry portal, in the middle of the tunnel, and near the exit portal respectively. It is assumed that the tunnel ventilation system comprises five pairs of jet fans near each end of the tunnel, i.e. a total of 20 jet fans. A pair of fans is assumed to be unavailable due to maintenance. In the entry portal and exit portal cases, where the fire occurs near to the fans, the pair of fans immediately downstream of the fire is assumed to be destroyed. The velocity achieved, measured immediately upstream of the fire, takes into account an adverse headwind at the north portal of 8 m/s. A wind speed of 8 m/s is exceeded 3.9% of the time. (Note that this design wind speed has not yet been corrected for portal size, orientation and local topographical effects, and may therefore appear to be quite high.)

<table>
<thead>
<tr>
<th>Table 3.5 Example results for longitudinal smoke control</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Section</strong></td>
</tr>
<tr>
<td>Section length</td>
</tr>
<tr>
<td>Fire location</td>
</tr>
<tr>
<td>Gradient (%)</td>
</tr>
<tr>
<td>Critical velocity (m/s)</td>
</tr>
<tr>
<td>Velocity achieved (m/s)</td>
</tr>
</tbody>
</table>

The most onerous case is a fire near the exit portal, in which case almost the whole length of tunnel is assumed to be full of stationary traffic. The velocity generated by the ventilation system is less than the critical velocity and consequently a smoke layer would spread perhaps 20-30m upstream of the fire. Although the extent of this ‘backlayering’ may be relatively modest, the temperature of this smoke layer could be high enough for the radiant heat flux to be hazardous to people in the vicinity.
Increased jet fan thrust could be achieved by installing extra fans (e.g. an extra row of fans) or slightly larger diameter fans. Clearly this would increase the installation cost of the system. Another option could be to increase the fan discharge velocity (leading to higher noise levels) and this would have negligible cost impact if the noise levels were acceptable. A further option is to examine the risks and judge whether the risk of ‘poor’ smoke control is acceptable.

The complete set of ventilation design cases can be represented using a logic diagram as illustrated in Figure 3.6. Each combination of bore, section and adverse headwind condition represents a design case to be confirmed by ventilation modelling. The percentages for ‘velocity > V_{crit}’ are given by the products of the relevant bore, section and adverse headwind percentages. For example, in the first row, $0.5 \times 0.175 \times 0.95 = 0.083$.

For the example in Table 3.5, further Hotflow analyses show that the ventilation system achieves the critical velocity for an adverse portal wind of 5 m/s. Overall, for the given design fire, effective smoke control would be achieved in approximately 92% of the possible combinations.

<table>
<thead>
<tr>
<th>bore</th>
<th>section</th>
<th>adverse headwind</th>
<th>velocity &gt; V_{crit} ?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northbound 1 (350m)</td>
<td>≤ 8 m/s</td>
<td>Yes</td>
<td>8.4%</td>
</tr>
<tr>
<td>50%</td>
<td>17.5%</td>
<td>96.1%</td>
<td>8.4%</td>
</tr>
<tr>
<td></td>
<td>&gt; 8 m/s</td>
<td>No</td>
<td>3.9%</td>
</tr>
<tr>
<td>2 (850m)</td>
<td>≤ 8 m/s</td>
<td>Yes</td>
<td>20.4%</td>
</tr>
<tr>
<td>42.5%</td>
<td>96.1%</td>
<td>20.4%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt; 8 m/s</td>
<td>No</td>
<td>3.9%</td>
</tr>
<tr>
<td>3 (800m)</td>
<td>≤ 5 m/s</td>
<td>Yes</td>
<td>15.2%</td>
</tr>
<tr>
<td>40.0%</td>
<td>76.0%</td>
<td>15.2%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt; 5 m/s</td>
<td>No</td>
<td>24.0%</td>
</tr>
</tbody>
</table>

| Southbound 1 (350m) | ≤ 8 m/s | Yes | 8.4% |
| 50% | 17.5% | 96.1% | 8.4% |
| | > 8 m/s | No | 3.9% |
| 2 (850m) | ≤ 8 m/s | Yes | 20.4% |
| 42.5% | 96.1% | 20.4% |
| | > 8 m/s | No | 3.9% |
| 3 (800m) | ≤ 8 m/s | Yes | 19.2% |
| 40.0% | 96.1% | 19.2% |
| | > 8 m/s | No | 3.9% |

<table>
<thead>
<tr>
<th>Totals:</th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>92.1%</td>
<td>7.9%</td>
<td></td>
</tr>
</tbody>
</table>
One option for a risk-based framework for ventilation design is a requirement that the ventilation system caters for at least 90% of cases, say. The problem with this approach, however, is that it takes no account of the length of the tunnel, the traffic flows, and the frequency of vehicle fires. In addition, it provides no solution to the choice of design fire size.

Another option is to take account of these parameters and to estimate the annual risk of the different outcomes.

### 3.2.2 Consideration of overall risk

Considering the example in Table 3.5, the risk of poor smoke control is given by the combined probability of an HGV fire occurring near the exit portal when the portal wind speed exceeds 5 m/s:

- The annual incidence of fires in the tunnel can be estimated by multiplying the fire frequency by the number of vehicle-kilometres per year (365 × daily traffic flow × bore length). For HGVs, the frequency of fires which are not brought under control is in the order of 0.5 per 100 million veh.km (e.g. CETU, 2003a). For a 2 km twin-bore tunnel carrying 20,000 vehicles per day in each direction, including 10% HGVs, the frequency of serious HGV fires is given by:

  \[
  \text{Frequency} = (0.5 \times 10^{-8}) \times (365 \times 20000 \times 0.1 \times 2.0 \times 2) \approx 0.015 \text{ fires/year}
  \]

  which equates to a serious fire occurring approximately once every 70 years.

- The affected fraction of the tunnel corresponds to 800m (in one bore) of a total length of 4 km (combined length of both bores), i.e. approximately 20% of the tunnel.

- It is estimated that the adverse wind speed at the north portal will exceed 5 m/s for about 24% of the time.

- Combining this information, the probability of these events occurring together is given by

  \[
  0.015 \times 0.2 \times 0.25 = 0.00075 \text{ per year, equivalent to a return period of over 1300 years.}
  \]

A return period of 1300 years is obviously greatly in excess of the design life of the tunnel. It might therefore be concluded that the performance limitation near the exit portal of one bore is acceptable. However, if the predicted return period was an order of magnitude smaller, the situation would be more difficult to judge. Currently, such judgements tend to be made on an ad-hoc, subjective basis. There is no available guidance and there is no clear precedent for road tunnels.

A further step which could be taken is to estimate how many casualties would arise in the event of such an event. The results can then be presented in terms of fatalities and injuries per year. One advantage is that this allows comparisons to be made between the risks from different hazards. Notably, this allows comparison between general traffic accidents and vehicle fires.

### 3.3 Risk-based framework for ventilation design

The development of a risk-based framework involves the classification of vehicles fires according to severity, calculation of their frequencies and consequences, and interpretation of the risk results. These aspects are dealt with in the following sub-sections.

#### 3.3.1 Classification of fires

An overall classification of vehicle fires has been considered in section 3.1.1. For the risk-based framework, only three categories are defined for vehicles not carrying dangerous goods. Fires involving only cars or light goods vehicles are classed as ‘minor’ with a peak heat release rate of up to about 15 MW. Buses, coaches or HGVs without highly combustible loads would typically generate a fire with a peak heat release rate in the order of 30 MW. This may be termed a ‘moderate’ fire. HGVs loaded with highly combustible goods could generate a ‘severe’ fire, which may be defined as
having a nominal peak heat release rate in the order of 100 MW. There is little evidence to suggest that the number of casualties would continue to increase in proportion to the peak heat release rate, for fires greater than 100 MW. Rather it is expected that the dominant factors will concern human behaviour and the effects of heat and smoke on people. All severe fires (broadly in the range of 50 to 200 MW) are therefore treated together in the same category.

The risks associated with dangerous goods transport through tunnels can be assessed using the OECD/PIARC QRA Model (Cassini et al, 2001).

3.3.2 Frequency of fires

In contrast to traffic accidents on open roads, there is relatively little data on incidents in UK tunnels. Fires have occurred, but none has caused significant injuries or damage. In order to estimate the tunnel incident risks, reference is often made to published information on road tunnel incidents worldwide. Even so, information on tunnel fires is still quite sparse. Statistics on fatal road tunnel fires worldwide show a total of only 16 incidents over the last 26 years, resulting in 115 fatalities. None of these incidents occurred in the UK.

When using incident statistics, it is important to reflect any differences in the underlying safety levels. In practice, the incident rates vary between tunnels depending on factors such as country, location, geometry, traffic modes and flows, tunnel safety systems and management procedures. There have been significant reductions in incident rates over the last 10-15 years. For example, Figure 3.7 shows the downward trend of accidental vehicle fire rates for the UK. Use of historical data without any correction for the trends and different circumstances will give misleading results which are inconsistent with general observations of the frequency of vehicle fires in tunnels and on open routes across the UK.

![Figure 3.7 Accidental vehicle fires, per 100 million vehicle km](Office of the Deputy Prime Minister, 2004)

The approach proposed here is to use personal injury accident rates for the appropriate category of road, as used in the COBA methodology (Highways Agency, 2002), and to derive an estimate for the ratio of serious fires to injury accidents. A similar approach was used in developing the OECD/PIARC QRA Model for dangerous goods transport through road tunnels (Cassini et al, 2001).

A key advantage of this approach is that the results will be consistent with traffic accident and vehicle fire statistics. Furthermore, by deriving the frequency of fires from the accident rates used in COBA, account can be taken of accident rate trends. This may be important when performing cost benefit analyses over the 120 year design life of a new tunnel.
It is assumed that the accident rates for tunnels are the same as for the adjacent open sections. This is probably a conservative assumption. A comprehensive accident investigation carried out some years ago in Norway (Amundsen et al, 1997) found that the personal accident injury (PAI) rate was almost twice as high in the open compared to tunnels. The PIARC report on road safety in tunnels states “road safety in tunnels is better than on open roads, except in case of failure in the geometric design”.

### Fire/accident ratio

Fault tree and event tree techniques can be used to relate the frequency of serious vehicle fires to accident rates. A serious fire is defined here as a vehicle fire which has the potential to spread to other vehicles and/or cause damage to the tunnel.

Firstly, the ratio of fires to injury accidents may be evaluated using a simple fault tree, as shown in Figure 3.8. This fault tree reflects the following:

- a vehicle fire may occur due to a traffic accident (i.e. a crash or collision) OR a vehicle defect OR another cause;
- a vehicle fire may occur due to an accident only if there is an accident AND ignition occurs;
- a traffic accident may involve injuries (as well as damage) OR damage only.

![Figure 3.8 Fault tree for evaluating the ratio of fires to accidents](image-url)

Input values are derived as follows:

- Vehicle fire statistics published by the Office of the Deputy Prime Minister (2004) for the period 1992 to 2002 provide a breakdown of the main causes of car fires. This shows that three-quarters of accidental car fires are caused by vehicle defects, with defects in wiring and batteries being the biggest single cause. A further 6% of accidental car fires are caused by a crash or collision. The Home Office statistics also indicate that during 2002, there were 1032 car fires caused by a crash or collision.
- Nationally it has been estimated (DfT Highways Economic Note No.1 2002) that there are an average of 17.7 damage-only accidents for every injury accident on built-up roads, 7.8 on non-built-up roads and 7.6 on motorways. The road accident statistics for 2002 (Department
of Transport, 2003) show approximately 200,000 personal injury accidents involving one or more cars. Assuming a ratio of 7.7 damage only accidents for every injury accident, this suggests the total number of accidents involving cars $\approx (1 + 7.7) \times 200,000 = 1.74$ million accidents. (Since many of these accidents occurred on built-up roads, the total number of accidents involving cars is expected to be greater than this.)

- A first estimate of the ratio of car fires to accidents is given by $1032 / 1.74 \times 10^6 \approx 0.0006$. In comparison, a value of 0.0008 was reported for Norway by Amundsen et al (1997). For the present purposes, a value of 0.001 has been adopted for all types of vehicles. A value of 0.001 is probably conservative and will lead to over-prediction of the fire rates.

Once a vehicle fire has occurred, the only consequences will be vehicle damage if it is extinguished early by the emergency services, tunnel staff or members of the public. On the other hand, if it is not extinguished early, the fire will grow and potentially have more serious consequences. This is illustrated in Figure 3.9. French statistics (CETU, 2003a) suggest that approximately 33% of fires involving heavy vehicles (not carrying dangerous goods) and 40% of fires involving dangerous goods vehicles are “not brought under control”.

Extinguished early? Outcome

<table>
<thead>
<tr>
<th>All fires</th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 3.9 Serious vehicle fires**

Using these two logic diagrams, it is estimated that for motorways and non-built up roads, it would be reasonable to assume one serious vehicle fire for every 20 injury accidents, i.e. the rate of serious fires is equivalent to 5% of the injury accident rate.

In comparison, the OECD-PIARC QRA Model (Cassini et al, 2001) also uses a ratio of 5% based on French accident data, while a recent study by the Norwegian Public Roads Administration (2002) on subsea road tunnels found that the rate of vehicle fires (all magnitudes) was less than 10% of the injury accident rate.

Considering motor spirits tankers, it was assessed during the development of the OECD-PIARC QRA Model that the rate of fires was approximately 2% of the tanker accident rate. This rate is less than for HGVs in general and reflects the increased safety awareness and standards applied to dangerous goods transport.

### 3.3.2.2 Quantitative analysis of fire frequencies

The estimated frequency of fires in a given tunnel is given by the product of traffic flow (veh.km/year), accident rate (accidents/veh.km) and fire/accident ratio. This will vary between traffic modes, vehicle types and potential fire sizes.

A logic diagram (along the lines of an event tree) can be used to represent the combination of cases as shown in Figure 3.10. From left to right, this firstly splits the traffic between normal (free flowing) uni-directional, congested uni-directional and bi-directional (contraflow) modes, then distinguishes between light and heavy vehicles, and finally between potential fire sizes.
The probability that a fire involving an HGV will develop into a severe fire (i.e. the split between 30 MW and 100 MW fires) may be estimated as follows:

- Statistics suggest that in the case of HGVs, the fire involves the load in about 50% of cases (Cassini et al, 2002).
- It is estimated that combustible products represent about two-thirds (67%) of the goods carried by HGVs (Department of Transport statistics (2003)).
- On average about 25% of HGVs are actually empty, i.e. about 75% of HGVs are actually carrying loads (Department of Transport, 2003)
- Combining the above values, the proportion of HGV fires developing into a severe fire is estimated as 25% (= 50% × 67% × 75%).

### 3.3.3 Consequences of fire

Since the primary purpose of a tunnel ventilation system is to ensure that injuries and fatalities do not occur, the consequences are considered here in terms of casualties only. In practice, there are likely to be other benefits arising from limiting smoke spread and reducing smoke temperatures; damage to the tunnel infrastructure may be reduced and subsequent traffic disruption avoided.

To predict the possible number of casualties, the following aspects must be taken into account:

- transient spread of smoke;
- the effects of heat and toxic combustion products on people, i.e. tenability;
- tunnel occupancy, i.e. how many people are present;
- evacuation, including both the pre-movement and movement phases.

Ventilation modelling can be carried out to determine whether conditions would remain tenable for a length of time to allow people to reach a place of safety. For longitudinal smoke control, 1-D ventilation models can generally be used. For natural ventilation or when a smoke extraction-based system is used, stratified smoke conditions may occur and CFD modelling may be necessary.

The reliable prediction of the numbers of fatalities and injuries is difficult to make because of the dominant and uncertain influence of human behaviour and the effects of hazardous conditions on
people. Whilst tenability and evacuation modelling can be carried out, the results relate only to specific circumstances and assumptions.

It is possible to derive indicative estimates of the numbers of casualties from published tunnel incident reports. This approach is complicated by lack of information on the actual fire size in most cases. The fire size cannot be estimated from the number of casualties which occurred, but may be estimated from knowledge of the fire loads and conditions prevailing at the time of the fire and from an assessment of the extent of damage to the infrastructure. In drawing general conclusions from such an assessment, the interpretation is inevitably subjective.

For the present purposes, a simplified approach is proposed as the default option:

- Smoke conditions are judged to be ‘good’ or ‘poor’. For example, a longitudinal ventilation system designed on the basis of a 30 MW fire would control smoke from such a fire. Smoke conditions can therefore be described as ‘good’ under such circumstances. In the event of a 100 MW fire, the ventilation system would still provide some benefit, although it is expected that a smoke layer would spread some distance upstream of the fire.

- An indicative order of magnitude estimate is derived for the number of fatalities, according to ‘good’ or ‘poor’ smoke conditions. The suggested values, derived from tunnel fire statistics, are set out in Table 3.6. The values reflect the size of fire and whether smoke control is achieved. They take no account of safety features such as automatic incident and fire detection systems, effective warning and communications systems, and emergency exits spaced 100m apart. Instead the values are influenced more by past tunnel fire incidents. The fatality rates are presented ‘per lane per direction’. To determine the value to use in the risk analysis, the fatality rate in Table 3.6 should be multiplied by the number of lanes and direction for a severe fire, when smoke is not controlled. For a uni-directional tunnel with two lanes of traffic on one side of the fire, the number of fatalities is $2 \times 1 \times 5 = 10$. For a congested tunnel with 3 lanes on traffic on both sides of the fire, the number of fatalities is given by $3 \times 2 \times 5 = 30$. Further examples are given in Table 3.7.

### Table 3.6 Fatality indicator rates, per occupied lane on each side of the fire

<table>
<thead>
<tr>
<th></th>
<th>Minor fire (15 MW)</th>
<th>Moderate fire (30 MW)</th>
<th>Severe fire (100 MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘Good’ smoke behaviour</td>
<td>0.005</td>
<td>0.05</td>
<td>0.5</td>
</tr>
<tr>
<td>‘Poor’ smoke behaviour</td>
<td>0.05</td>
<td>0.5</td>
<td>5</td>
</tr>
</tbody>
</table>

### Table 3.7 Examples of indicative number of fatalities per incident

<table>
<thead>
<tr>
<th>Example 1: Uni-directional traffic, 2 lane tunnel (or bi-directional, 1 lane in each direction)</th>
<th>Minor fire</th>
<th>Moderate fire</th>
<th>Severe fire</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘Good’ smoke behaviour</td>
<td>0.01</td>
<td>0.1</td>
<td>1</td>
</tr>
<tr>
<td>‘Poor’ smoke behaviour</td>
<td>0.1</td>
<td>1</td>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Example 2: Congested, uni-directional traffic, 3 lane motorway tunnel</th>
<th>Minor fire</th>
<th>Moderate fire</th>
<th>Severe fire</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘Good’ smoke behaviour</td>
<td>0.03</td>
<td>0.3</td>
<td>3</td>
</tr>
<tr>
<td>‘Poor’ smoke behaviour</td>
<td>0.3</td>
<td>3</td>
<td>30</td>
</tr>
</tbody>
</table>
As an alternative to the simplified default option, modelling of smoke spread, tenability and evacuation could be carried out for each combination of traffic, fire size and ventilation set-up. For each scenario, the annual risk of fatalities is given by multiplying the number of fires per year by the number of fatalities per event.

### 3.3.4 Risk results

Figure 3.11 shows an example of a risk calculation for one tunnel/ventilation case (see Tunnel 2 in Table 3.8 for a 30 MW design fire). On the left hand side, the total traffic is sub-divided firstly according to traffic mode, then vehicle type and then potential fire size. The respective traffic flows are then multiplied by the appropriate accident rate and the fire/accident rate to give the number of fires per year.
Table 3.8 presents the results for four hypothetical tunnels:

- Tunnel 1 represents a short tunnel, perhaps close to the threshold for installing a mechanical ventilation system;
- Tunnel 2 represents a motorway tunnel with regular congestion;
- Tunnel 3 represents a longer motorway tunnel without a congestion problem;
- Tunnel 4 represents a tunnel on a rural trunk road.

For tunnel 1, the injury accident rate is representative of a single carriageway urban A road (Department for Transport, 2002). For tunnel 4, the accident rate is representative of a rural, modern dual-carriageway with hard strips. Tunnels 2 and 3 are both motorway tunnels.

Table 3.8

<table>
<thead>
<tr>
<th>total traffic veh.km/yr</th>
<th>traffic modes -</th>
<th>vehicles -</th>
<th>potential fire sizes MW</th>
<th>traffic rates veh.km/yr</th>
<th>accident rate PIA/veh.km</th>
<th>fire/acc. ratio -</th>
<th>serious fires per year</th>
<th>smoke conditions -</th>
<th>fatality rate per fire -</th>
<th>fatalities per year -</th>
</tr>
</thead>
<tbody>
<tr>
<td>uni-directional light 15 MW</td>
<td>2.19E+07</td>
<td>0.95</td>
<td>0.85</td>
<td>1.00</td>
<td>1.77E+07</td>
<td>1.20E-07</td>
<td>0.016</td>
<td>3.35E+02</td>
<td>1.00</td>
<td>0.015</td>
</tr>
<tr>
<td>heavy 30 MW</td>
<td>0.15</td>
<td>0.75</td>
<td>2.34E+06</td>
<td>1.20E-07</td>
<td>0.016</td>
<td>4.43E-03</td>
<td>1.00</td>
<td>0.015</td>
<td>6.64E-04</td>
<td></td>
</tr>
<tr>
<td>100 MW</td>
<td>0.25</td>
<td>7.80E+05</td>
<td>1.20E-07</td>
<td>0.016</td>
<td>1.48E-03</td>
<td>1.00</td>
<td>0.015</td>
<td>7.38E-04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>congested light 15 MW</td>
<td>0.05</td>
<td>0.85</td>
<td>1.00</td>
<td>9.31E+05</td>
<td>1.20E-07</td>
<td>0.016</td>
<td>1.76E-03</td>
<td>1.00</td>
<td>0.015</td>
<td>5.28E-05</td>
</tr>
<tr>
<td>heavy 30 MW</td>
<td>0.15</td>
<td>0.75</td>
<td>1.23E+05</td>
<td>1.20E-07</td>
<td>0.016</td>
<td>2.33E-04</td>
<td>1.00</td>
<td>0.015</td>
<td>6.99E-05</td>
<td></td>
</tr>
<tr>
<td>100 MW</td>
<td>0.25</td>
<td>4.11E+04</td>
<td>1.20E-07</td>
<td>0.016</td>
<td>7.77E-05</td>
<td>1.00</td>
<td>0.015</td>
<td>7.77E-05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>bi-directional light 15 MW</td>
<td>0.00</td>
<td>0.85</td>
<td>1.00</td>
<td>0.00E+00</td>
<td>1.20E-07</td>
<td>0.016</td>
<td>0.00E+00</td>
<td>1.00</td>
<td>0.015</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>heavy 30 MW</td>
<td>0.15</td>
<td>0.75</td>
<td>0.00E+00</td>
<td>1.20E-07</td>
<td>0.016</td>
<td>0.00E+00</td>
<td>1.00</td>
<td>0.015</td>
<td>0.00E+00</td>
<td></td>
</tr>
<tr>
<td>100 MW</td>
<td>0.25</td>
<td>0.00E+00</td>
<td>1.20E-07</td>
<td>0.016</td>
<td>0.00E+00</td>
<td>1.00</td>
<td>0.015</td>
<td>0.00E+00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.11 Example risk calculation (Tunnel 2, 30 MW design fire)
Table 3.8 presents the results for four hypothetical tunnels:

- Tunnel 1 represents a short tunnel, perhaps close to the threshold for installing a mechanical ventilation system;
- Tunnel 2 represents a motorway tunnel with regular congestion;
- Tunnel 3 represents a longer motorway tunnel without a congestion problem;
- Tunnel 4 represents a tunnel on a rural trunk road.

For tunnel 1, the injury accident rate is representative of a single carriageway urban A road (Department for Transport, 2002). For tunnel 4, the accident rate is representative of a rural, modern dual-carriageway with hard strips. Tunnels 2 and 3 are both motorway tunnels.

Table 3.8 Risk results for example tunnels

<table>
<thead>
<tr>
<th></th>
<th>Tunnel 1</th>
<th>Tunnel 2</th>
<th>Tunnel 3</th>
<th>Tunnel 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (km)</td>
<td>0.3</td>
<td>0.5</td>
<td>1.0</td>
<td>2</td>
</tr>
<tr>
<td>Number of lanes and bores</td>
<td>2 x 1</td>
<td>3 x 2</td>
<td>3 x 2</td>
<td>2 x 2</td>
</tr>
<tr>
<td>Annual average daily traffic (AADT)</td>
<td>20000</td>
<td>120000</td>
<td>100000</td>
<td>40000</td>
</tr>
<tr>
<td>Congested fraction</td>
<td>0%</td>
<td>5%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>HGV fraction (% of all traffic)</td>
<td>10%</td>
<td>15%</td>
<td>15%</td>
<td>10%</td>
</tr>
<tr>
<td>Personal injury accident rate (PIA/veh.km)</td>
<td>5.0E-07</td>
<td>1.0E-07</td>
<td>1.0E-07</td>
<td>1.0E-07</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Natural ventilation</th>
<th>fatality risk per year:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor fires</td>
<td>0.002</td>
</tr>
<tr>
<td>Moderate fires</td>
<td>0.001</td>
</tr>
<tr>
<td>Severe fires</td>
<td>0.004</td>
</tr>
<tr>
<td>Total</td>
<td>0.007</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ventilation designed for 30 MW fire</th>
<th>fatality risk per year:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor fires</td>
<td>0.000</td>
</tr>
<tr>
<td>Moderate fires</td>
<td>0.000</td>
</tr>
<tr>
<td>Severe fires</td>
<td>0.003</td>
</tr>
<tr>
<td>Total</td>
<td>0.003</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ventilation designed for 100 MW fire</th>
<th>fatality risk per year:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor fires</td>
<td>0.000</td>
</tr>
<tr>
<td>Moderate fires</td>
<td>0.000</td>
</tr>
<tr>
<td>Severe fires</td>
<td>0.000</td>
</tr>
<tr>
<td>Total</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Examination of the results suggests that an acceptance criterion of 0.01 fatalities per year would be reasonably consistent with current practice:

- For Tunnel 1, natural ventilation is acceptable;
- Tunnels 2 and 3 both require a mechanical ventilation system capable of controlling a fire of between 30 and 100 MW;
- For Tunnel 4, a mechanical ventilation system designed on the basis of a 30 MW fire should be acceptable, although more detailed analysis is probably necessary.
It is emphasised that the fatality rates in Table 3.6 and the acceptance criterion of 0.01 fatalities per year are arbitrary. Their absolute values are not critical since the methodology is intended for use in a comparative way.

Assessing the tolerability of the absolute risk of multiple fatalities occurring in a single event is difficult. HSE discusses the issues in its report ‘Reducing Risks, Protecting People’ (2001) and proposes that “the risk of an accident causing the death of 50 people or more in a single event should be regarded as intolerable if the frequency is estimated to be more than one in five thousand per annum”. This criterion can be expressed as 50 deaths per 5,000 years, which can arguably be considered as equivalent to 1 death per one hundred years, i.e. an annual risk of 0.01 fatalities per year. It is emphasised that this refers to single major hazardous sites and not to roads or road tunnels.

3.3.5 Discussion

The proposed methodology provides a framework for consistent decision making. It provides a means of determining whether natural ventilation is acceptable. If the risk level exceeds the threshold then this indicates that a mechanical ventilation system would be required. The calculation can be repeated for 30 MW and 100 MW design fire sizes to determine the appropriate design fire size that ensures the risk level lies below the acceptance threshold.

The methodology allows the safety levels to be compared between different tunnels.

For simplicity, default fatality rates are used. However, the framework also allows the use of casualty estimates obtained from tunnel-specific ventilation, tenability and evacuation modelling. This may be appropriate if the risk results lie close to the acceptance threshold. In addition, this would allow the designer to take account of safety features such as systems providing early warning and effective communications.

The methodology offers greater design flexibility by allowing alternative risk reduction measures to be used, where appropriate, instead of increasing the capacity of the ventilation system.

The acceptance threshold itself could be replaced, perhaps, by a value based on the fatality rates observed on open sections of the same route.

3.4 Natural Ventilation

3.4.1 Introduction

For longitudinally ventilated tunnels, critical velocity formulae (section 2.5.1) and 1-D ventilation models (section 2.5.2) can be used to evaluate the performance of a given ventilation system. For naturally ventilated tunnels, the position is less straightforward. Stratification phenomena need to be considered but there are relatively few 2-D models available (section 2.5.3). Furthermore, existing 2-D models tend not to be applicable to tunnels with steep gradients or large cross-sections and do not take account of the effects of vehicles and jet fans. This is a potential problem for design because in the absence of simple tools, complex CFD modelling would have to be used to determine the acceptability of natural ventilation for the shortest (and, in principle, simplest) road tunnels.

CFD modelling was carried out as part of this study using the FDS software (see section 2.5.4) in order to provide a better understanding of smoke behaviour under natural ventilation conditions. A base case (300m long × 10m width × 6m height, 0% gradient, 30 MW, 10%HGVs) was examined first, and then selected parameters were varied in turn to enable the following comparisons to be made:

- effect of number of HGVs (10% and 20%);
- effect of fire size (30 and 100 MW);
- effect of tunnel length (200, 300, 400 and 500m);
- effect of tunnel gradient (0, 2.5 and 5%);
- effect of tunnel width (5m and 10m);
- effect of low headroom (3.5m height and 8 or 15 MW compared to 6m height and 30 MW).

Although portal wind effects can be important, they have not been considered in this CFD study because that would require treatment of the local topography and wind environment, which would greatly increase the complexity of the modelling.

Simple criteria have been used to assess the acceptability of conditions for escape, based pessimistically on an exposure period of 30 minutes:

- air temperature \(\leq 60^\circ\text{C}\);
- radiant heat flux < 2.5 kW/m\(^2\), corresponding to a smoke layer temperature \(\leq 200^\circ\text{C}\);
- Carbon Monoxide concentration \(\leq 350\text{ ppm}\);
- visibility \(\geq 10\text{ m}\).

### 3.4.2 Base case

The base case involves a 30 MW fire, located 50m from the portal, within a level, 300m long tunnel, 6m in height and 10m in width. For simplicity, the fire is modelled as a hydrocarbon pool fire of dimensions 10m in length by 4m in width, raised 1m above the road surface. The fire grows to 30 MW in 10 minutes.

Figure 3.12 shows the predictions of smoke layer temperature and smoke layer height, together with the temperature, carbon monoxide (CO) concentration and visibility at a height of 1.5m above the floor, corresponding to head height. The predictions are shown at times of 5, 10, 15, 20 and 30 minutes from the start of the fire.

Considering the threat of radiant heat from the hot smoke layer, smoke layer temperatures in excess of 200\(^\circ\text{C}\) are predicted over an 80-100m long section by 10 minutes (top left). The extent of this region grows steadily thereafter. By 30 minutes, the region extends nearly 100m from the fire.

The smoke layer remains stratified throughout the 30 minute period (middle left). The height of the smoke layer is a little less than 2m. On this basis, the conditions at 1.5m above the floor represent conditions below the smoke layer. The temperatures at 1.5m above the floor (top right) remain below 60\(^\circ\text{C}\) for more than 20 minutes. By 30 minutes, there is a small region close to the fire where the temperature exceeds 60\(^\circ\text{C}\). CO concentrations (middle right) remain below an incapacitation level of 350 ppm for 30 minutes. Visibility (bottom right) drops rapidly to less than 5m by 5 minutes and to 1m by 10 minutes.

Overall, the principal threats to life safety are the radiant heat from the smoke layer and the poor visibility. The poor visibility would clearly hamper evacuation.
Figure 3.12: Base case
It is important to consider the sensitivity of results to key modelling assumptions. As an example, Figure 3.13 shows the effects of increasing the number of HGVs in the tunnel relative to the base case.

The results are shown for 15 minutes after the start of the fire. The main differences are higher CO concentrations and even worse visibility, presumably due to the increased turbulence caused by the large bluff-shaped vehicles.

![Figure 3.13: Sensitivity of base case results to the number of HGVs modelled (conditions at 15 minutes)]
3.4.3 Effect of fire size

Figure 3.14 compares the conditions, after 15 minutes, for 30 and 100 MW fires. Compared to the 30 MW base case, smoke layer temperatures are not surprisingly rather higher. The smoke layer height remains comparable to the base case. Below the stratified smoke layer, at a height of 1.5m, the air temperatures are significantly higher. They exceed the 60°C threshold along a 200m section of the tunnel. The CO concentrations exceed the safe 30-minute exposure level of 350 ppm along a 200m section of the tunnel. Visibility is very poor throughout the tunnel (except near to the portals).

![Graphs showing effect of fire size on temperature, layer height, CO concentration, and visibility.](image)

Figure 3.14: Effect of fire size (conditions at 15 minutes)
3.4.4 Effect of tunnel length

Figure 3.15 compares the conditions, at 15 minutes, for tunnel lengths of 200, 300, 400 and 500m.

The temperature of the smoke layer remains largely unchanged. The smoke layer remains stratified in all cases, with its height gradually decreasing as tunnel length increases. At 1.5m above the road surface, the air temperatures increase with tunnel length, however the temperatures remain below 60°C in all cases. CO concentrations also increase with tunnel length however only the 200m and 300m tunnels have levels below the safe 30-minute exposure level. Visibility is poor in all cases, and there appears to be a significant deterioration between lengths of 200m and 300m.

Figure 3.15: Effect of tunnel length (conditions at 15 minutes)
3.4.5 Effect of tunnel gradient

Figure 3.16 compares the conditions, at 15 minutes, for tunnel gradients of 0, 2.5 and 5%, with ventilation blowing smoke down the slope (against the smoke buoyancy).

The smoke layer temperatures increase slightly away from the fire, for the sloping tunnels. The smoke layer remains stratified in the three cases. At 1.5m above the road surface, the air temperatures increase with tunnel gradient, and exceed 60°C in much of the sloping tunnels. CO concentration levels in all cases are below the safe 30-minute exposure level. Visibility is poor in all cases.

Figure 3.16: Effect of tunnel gradient (conditions at 15 minutes)
3.4.6 Effect of tunnel width

Figure 3.17 compares the smoke conditions for two different widths, 10m and 5m, corresponding to two-lane and single lane tunnels respectively.

A 30 MW fire is represented in both cases. The results show higher smoke layer temperatures in the smaller tunnel. The extent of the region which poses a radiation hazard grows by 20-30m compared to the base case. The smoke layer heights are generally lower. The temperature at head-height is 10-20ºC higher than in the base case. Temperatures exceed 60ºC up to 150m from the fire. CO concentration levels are much higher and exceed 500 ppm up to 200m from the fire. Visibility is poor in both cases.

Figure 3.17: Effect of tunnel width (conditions at 15 minutes)
3.4.7 Low headroom tunnels

Figure 3.18 compares the conditions in three cases:

- normal headroom (6m height), 30 MW fire
- low headroom (3.5m height), 15 MW fire
- low headroom (3.5m height), 8 MW

The smoke layer temperatures are lower for the low headroom cases due to the smaller fires. At the same time, the smoke layer drops to about 1m above the floor. The conditions at 1.5m therefore represent conditions within the smoke layer. Not surprisingly, temperatures and CO concentrations are much higher and visibility worse, compared to the normal headroom base case.

![Graphs showing temperature, layer height, CO concentration, and visibility at 1.5m above floor for different scenarios.](image)

Figure 3.18: Low headroom tunnels (conditions at 15 minutes)
### 3.4.8 General observations

The following observations can be made:

- The CFD modelling results should be treated as indicative only. As shown by the sensitivity case with extra HGVs, the results do not represent worst credible scenarios.
- The principal concern arising from the modelling is the rapid loss of visibility throughout a large part of the tunnel. This would seriously hamper evacuation.
- The occurrence of a severe 100 MW fire in a naturally ventilated tunnel would lead rapidly to untenable conditions along a large extent of the tunnel.
- For level, normal headroom, two-lane tunnels, the maximum length should not exceed 300m. Visibility remains a concern even for tunnels shorter than 300m. Other factors which will have a detrimental effect on conditions in the tunnel include gradient and small cross-section.
- The results suggest that low headroom tunnels always require a mechanical ventilation system.

### 3.5 Strategies for preventing smoke entering via the cross-passages

The basic means of preventing smoke entering at cross-passages (CP) is for the pressure in the non-incident bore to be held at a higher value than in the incident bore. Tunnel ventilation systems are capable of this to various degrees. The principles are demonstrated below for a twin bore tunnel with a longitudinal ventilation system comprising jet fans.

The effectiveness of using the jet fans in the non-incident bore to pressurise the cross passages is demonstrated by four example cases, summarised in Table 3.9 and illustrated in Figures 3.6 to 3.9. The tunnel in these examples is approximately 1900 m long and comprises twin bores (Northbound and Southbound) linked by 17 cross passages. Each cross passage consists of a single open door leaf measuring 2.1m high by 1.0m wide; an area of 2.1 m$^2$. A 30 MW fire in the Northbound bore is assumed in the calculations. The tunnel ventilation system comprises 20 jet fans mounted in pairs along each of the traffic bores. Each of the jet fans in the calculations has a static thrust of 710 N and outlet velocity of 28 m/s. Calculations were carried out using the Mott MacDonald Hotflow program.

#### Table 3.9 Airflow velocities through open cross passages, in the event of a fire

<table>
<thead>
<tr>
<th>Case</th>
<th>Fire location in Northbound bore</th>
<th>Airflow velocity in incident bore upstream of fire (m/s)</th>
<th>Airflow velocity through the open cross passages (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2nd CP upstream</td>
<td>1st CP upstream</td>
</tr>
<tr>
<td>1</td>
<td>nr. South portal</td>
<td>4.3</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>nr. South portal</td>
<td>4.4</td>
<td>-1.2</td>
</tr>
<tr>
<td>3</td>
<td>Mid-tunnel</td>
<td>4.1</td>
<td>3.3</td>
</tr>
<tr>
<td>4</td>
<td>nr. North portal</td>
<td>3.7</td>
<td>2.7</td>
</tr>
</tbody>
</table>

Note: +ve cross passage airflow is from non-incident bore to incident bore  
-ve cross passage airflow is from incident bore to non-incident bore

In the figures, the arrows shown on the plan of the tunnel each denote a pair of jet fans in use. One pair of jet fans near the north portal in the non-incident (Southbound) bore is operating in the reverse
direction while the other four pairs of jet fans at this location remain switched-off. A ‘crossed out’ arrow denotes a pair of fans assumed to be destroyed by fire or unavailable due to mechanical failure. There are 3 pressure profiles along the tunnel in each figure:

- Northbound (incident) bore, hot flow – pressure changes due to the jet fans and the air expansion due to the fire, i.e. hot flow (Red curve);
- Northbound bore, cold flow – pressure changes due to the jet fans only (Blue curve);
- Southbound (non-incident) bore – pressure changes due to the jet fans (Black curve).

In Case 1, the fire is located close to the South portal and 2 cross passages downstream of fire are open. The predicted airflow velocities through these open cross passages are 2.7 and 3.5 m/s into the incident bore.

In Case 2, the fire is located between the second and third cross passages. In the cross passages upstream of the fire, the airflow velocities are about 1 m/s. In one of the cross passages, the airflow direction is from the incident bore to the non-incident bore. However, this is not a problem because of the smoke-free conditions upstream of the fire. In the cross passages downstream of the fire, the airflow velocities exceed 3 m/s into the incident bore.

Case 3 concerns a fire located mid-way along the length of the tunnel. The airflow velocities exceed 3 m/s into the incident bore, in all four open cross passages.

Case 4 concerns a fire located near the North portal. The airflow velocities exceed 2.4 m/s into the incident bore, in the two open cross passages downstream of the fire. The airflow velocities are lower in the two upstream cross passages, but this is not a problem because of the smoke-free conditions in the incident bore upstream of the fire.

Figure 3.19 Example of tunnel pressures for fire located next to entry portal
Figure 3.20 Example of tunnel pressures for fire located near entry portal

Figure 3.21 Example of tunnel pressures for fire located mid-way along tunnel
3.6 Cost and environmental implications

3.6.1 Cost implications of ventilation design criteria

The cost implications of design criteria such as the fire size and adverse wind conditions can be shown by a simple parametric analysis. Tunnels of length 500m and 1000m, together with fire sizes of 30, 50 and 100 MW and adverse portal wind speeds of 0, 5 and 8 m/s were considered. The tunnels are assumed to consist of two lanes, with a ceiling height at 7 m, and have zero gradients. The jet fans are assumed to have a thrust of 710 N.

The minimum number of jet fans required to achieve the critical velocity is calculated in each case, using the HOTFLOW program (Mott MacDonald). Then, based on the current requirement of BD 78/99, an additional number of jet fans assumed to be destroyed is included. The total number of jet fans thus required to be installed in each tunnel is given in Table 3.10.

Table 3.10 Number of jet fans required for longitudinal ventilation

<table>
<thead>
<tr>
<th>Fire size</th>
<th>500m tunnel</th>
<th>1000m tunnel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 m/s</td>
<td>5 m/s</td>
</tr>
<tr>
<td>30 MW</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>50 MW</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>100 MW</td>
<td>9</td>
<td>9</td>
</tr>
</tbody>
</table>

The estimated supply and installation cost of a single jet fan (of the size considered in Table 3.10) is currently in the order of £7,500.
The cost of the whole system will be directly proportional to the number of jet fans. The percentage increase in system cost for the different cases can therefore be determined from Table 3.10. A number of observations can be made:

- By considering the design adverse wind conditions (at 5m/s), the cost of a system increases roughly by 30%.
- If the design adverse wind condition is increased to 8 m/s, the increase in system cost can exceed 50%.
- Increasing the design fire size from 30 MW to 50 MW does not have a significant impact on the cost.

Adverse portal wind conditions can influence the required capacity of the longitudinal ventilation system. The risk of combined occurrence of vehicle fire and adverse winds can also be considered (see section 2.4.4.1). If the risk is high, neglecting adverse wind conditions can result in possible failure of smoke control, resulting in fatalities in accidents. On the other hand, if the risk is insignificant, designing the ventilation system to extreme adverse wind conditions can add an unnecessary cost to the overall construction of the tunnel.

The values used in this parametric study are indicative only. Other important factors such as increased tunnel length, steeper tunnel gradient, reduced tunnel cross sectional area, alternative installation arrangement for the jet fans, etc., can easily affect the performance as well as the installation cost of the ventilation system.

### 3.6.2 Additional considerations for the choice of ventilation system

As mentioned in BD 78/99, longitudinal ventilation using jet fans is the cheapest option to ventilate a tunnel, but there are disadvantages in terms of the restricted access for maintenance, which can only be carried out during lane or bore closures.

Longitudinal ventilation can also be implemented using axial fans located in ventilation shafts (i.e. using the ‘push-pull’ concept) but shafts incur additional costs for construction and possibly land acquisition. Also, at environmentally sensitive locations and in heavily built-up areas, it might not be permissible to construct shafts and associated surface structures.

The issue of ventilation shafts is also relevant for transverse and semi-transverse systems. However, since the supply air is ducted along the tunnel, the locations of shafts are far more flexible than for a longitudinal ventilation system with ventilation shafts. Therefore the impact on land costs and to the environment can be minimised.

It should also be noted that the ventilation capacity of the transverse system is affected much more by fire size than that of the longitudinal system. For instance, a two-fold increase in fire size would produce a similar increase in order of magnitude to the smoke production rate. Therefore the transverse system will need to be increased accordingly to extract the smoke. However, the same increase in fire size would only increase the critical velocity to prevent smoke backlayering by less than 20%.

Emergency operations do not contribute significantly to the operating costs of the ventilation system, due to the rarity of emergency situations.
4 Recommended revisions to existing guidance

This section presents the new and revised guidance recommended for inclusion in BD 78 and TD 43.

4.1 Scope
BD 78/99 defines a road tunnel as “a subsurface highway structure enclosed for a length of 150m, or more”. Whilst there is no reason to question this in general, the situation is different for low headroom tunnels. Smoke is unlikely to remain above head height, even for relatively short tunnel lengths. It is recommended that mechanical ventilation should always be considered for such tunnels, unless CFD and evacuation analyses indicate that the people can evacuate safely under natural ventilation conditions.

4.2 Standardised design fires
Standardised vehicle fire scenarios for ventilation design are listed in Table 4.1. Peak fire sizes are given together with the time taken for the fire to reach this magnitude. It should be assumed that fire growth follows a ‘t-squared’ (time-squared) curve such that the fire size is given by \( Q = \alpha t^2 \), where \( Q \) is the fire size (MW), \( \alpha \) is a constant (kW/s\(^2\)) and \( t \) is time (s). The constant \( \alpha \) can be derived from Table 4.1. Once the peak fire size is reached, the fire size should then be maintained at this magnitude up to 30 minutes after the start of the fire.

<table>
<thead>
<tr>
<th>Type of traffic allowed in tunnel</th>
<th>Type of vehicle(s) involved in fire</th>
<th>Peak fire size (MW)</th>
<th>Tgrowth (mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cars only</td>
<td>2-3 cars</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Cars and LGVs</td>
<td>Light goods vehicle (LGV)</td>
<td>15 (10 mins to 30 MW)</td>
<td></td>
</tr>
<tr>
<td>All traffic</td>
<td>Bus, coach or HGV (without highly combustible load)</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>HGV carrying significant quantities of highly combustible goods</td>
<td>100</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Road tanker carrying flammable liquids in bulk, or HGV carrying easily liquefiable, combustible products</td>
<td>200</td>
<td>10</td>
</tr>
</tbody>
</table>

4.3 Risk-based framework for design
The main principle for design should be to achieve a level of safety in the tunnel that is comparable to the level of safety on the adjoining open sections of the route.

A possible methodology is described in section 3.3 of this report. This involves the following steps:

a) Calculation of tunnel fire frequencies

b) Calculation of the likely numbers of casualties for each combination of traffic and fire size, for the proposed ventilation system.
c) Calculation of the overall risk, using logic diagrams.

d) Evaluation against an acceptance criterion.

If the overall risk exceeds the acceptance criterion, the proposed ventilation system should be improved and steps b) to d) repeated.

If the Design Organisation wishes to use an alternative methodology, the following conditions should be observed:

a) Historical fire frequency data may be used but this should be adjusted to reflect any underlying differences in safety levels as evidenced by different traffic accident and breakdown rates.

b) Estimates of the numbers of casualties may be made using appropriate modelling techniques and tools, e.g. CFD modelling combined with evacuation and tenability analyses, but this should take account of the ventilation analysis recommendations made in section 4.5.

4.4 Preventing smoke spread between bores

In a twin bore tunnel, the preferred strategy for the evacuation of the vehicle occupants from the incident bore is through one or more cross-connections to the adjacent non-incident bore. Smoke could enter the non-incident bore either at the inflow portal or through a cross-connection. The ventilation system should ensure that the non-incident bore is kept clear of smoke.

4.4.1 Strategies for preventing smoke entering via the portals

The ventilation systems in each bore can be controlled in such a way as to prevent smoke entering the inflow portal of the non-incident bore. The strategy for the exclusion of smoke depends on the type of ventilation system (longitudinal, transverse, etc.) that is installed in the tunnel. In particular:

- For a longitudinal ventilation system, the ventilating airflows in the two bores should be in the same direction.

- For a fully transverse ventilation system, the rate at which air is supplied to the non-incident bore should substantially exceed the rate of extraction. The excess supply air will then pressurise the non-incident bore.

- For a semi-transverse supply ventilation system, a similar strategy can be adopted.

- For a semi-transverse extract ventilation system, the fans should be turned off or, if possible, reversed to supply air to the non-incident bore. There is no reliable means of preventing smoke ingress to the non-incident bore of a tunnel that is equipped only with extract fans.

4.4.2 Strategies for preventing smoke entering via the cross-connections

The basic means of preventing smoke entering at cross-passages is for the pressure in the non-incident bore to be held at a higher value than in the incident bore. Tunnel ventilation systems are capable of this to various degrees.

When a longitudinal ventilation system is designed specifically with cross pressurisation in mind, a pressure difference between the two bores can be established at all the cross-passage locations. The following principles should be observed:

- The velocity of the airflow in the non-incident bore should be lower than that in the incident bore, as this helps to maintain the higher pressure along the length of the non-incident bore.

- One or more group of jet fans should be located near to the inflow portal of the non-incident tunnel so that the location of the cross-passages is not compromised.
• Jet fans near to the exit portal of the non-incident tunnel can be made to blow backwards (against the flow in the non-incident tunnel). By these means the velocity of the airflow in the non-incident bore is reduced, and the pressure between the extreme groups of jet fans is increased. Note that these jet fans must be between the portal and the first cross-passage. It follows that jet fans should be located near to both portals of both bores.

Transverse and semi-transverse ventilation systems can be set to help provide pressurisation of the non-incident bore, though the effect is weaker than that of a longitudinal system. The following principles should be observed:

• In a tunnel with fine control over the supply ventilation settings, supply more air to the non-incident bore than to the incident bore. This raises the pressure in the non-incident tunnel.

• Extract downstream of the fire in the incident tunnel and stop the extract fans in the non-incident tunnel.

A number of UK tunnels across estuaries have hybrid ventilation systems, consisting of semi-transverse ventilation, extract shafts and jet fans. The ventilation systems in these tunnels can be made to provide the control of smoke and pressurisation at cross-passages over part of the length of the tunnels.

The guidance in the preceding two sections applies to these tunnels, in particular those parts relating to higher supply flow rates in the non-incident bore and jet fans operated near to the inflow portal of the non-incident bore.

4.4.3 Design guidance for modelling cross-passages

The flow through cross-passages can be modelled in most common one-dimensional tunnel ventilation models (section 2.5.2). The aerodynamic resistance of a cross-passage determines the predicted airflow for a given pressure difference, and this section is intended to give guidance on an appropriate resistance of a typical cross-passage.

The simplest approach is to take the resistance of a cross-passage door from British Standard 5588: Part4 1998. BS 5588 treats each open door as a leakage air path with a resistance given by,

\[ Q_D = 0.83 \times A_D \times p^{1/2} \]

where \( Q_D \) = volume flow rate through the door (m³/s)
\( A_D \) = cross-sectional area of the open door (m²)
\( p \) = pressure difference across the door (N/m²).

If rearranged and expressed in the standard form for resistance of air paths,

\[ p = 0.5 \times k \times \rho \times \left( \frac{Q_D}{A_D} \right)^2 \]

where \( \rho \) = density of air (kg/m³)
\( k \) = pressure loss coefficient (dimensionless)

A typical calculated value of the pressure loss coefficient, \( k \), is 2.4. Commissioning tests on a completed tunnel indicate that a \( k \) value of 2.4 for each set of cross-passage doors is a suitable, if conservative, value.

4.5 Ventilation systems with extract capability

Ventilation systems with extraction capability traditionally include fully-transverse and perhaps semi-transverse systems. However, there are initiatives towards including dedicated smoke control capabilities in tunnels with longitudinal or hybrid ventilation strategies. The strategy is to use smoke
extract ducts at high level in tunnels where the risks justify the expense. The considerations that enter
the assessment of risk include:

- length of the tunnel;
- number of vehicles using the tunnel;
- nature of traffic operations, whether uni-directional or bi-directional;
- traffic mix, speed limits, etc.

Generally, a smoke extract duct above the carriageway is used to capture and extract smoke local to
the site of the fire. This is achieved by opening dampers only in the ventilation section of the fire. The
dampers are typically large, with a face area of perhaps 5.0-10.0 m², and the response might require
only three or four such dampers to be opened, depending upon the design of the tunnel and the fire
size.

The claimed advantages of this approach include:

- The provisions for the controlled longitudinal ventilation of smoke, as in a conventional
  longitudinally ventilated tunnel, with smoke-free conditions upstream of the fire where
  vehicles are stopped behind the incident;
- The possibility to improve conditions on the downstream side of the fire where there are
  vehicles on both sides of the incident, as in bi-directional operations or an incident in
  congested traffic.

The response to an incident, in a particular tunnel, is determined by the nature of the traffic
operations, uni-directional or bi-directional, in the tunnel at the time of the incident. It can be assumed
that, in the case of uni-directional traffic flows, the vehicles downstream of the incident continue out
of the tunnel and are unaffected by the incident. It may also be necessary to consider the case of a
secondary incident, or an incident that occurs within a line of congested traffic. In the case of bi-
directional traffic flows, it should be assumed there are stationary vehicles on both sides of the
incident.

4.5.1 Uni-directional, free flowing traffic

The response is to set up a longitudinal ventilating airflow, using the installed jet fans for example, to
provide a super-critical airflow velocity and control backlayering. A group of dampers, at the fire
location and downstream of the fire, are opened to extract the smoke. The purpose of using the smoke
extract duct in these circumstances is to:

- help preserve the buoyant smoke layer, assisting in the evacuation and intervention
  procedures; and
- extract the smoke as near to the source as possible, reducing consequential smoke damage to
  the downstream sections of the tunnel.

In this, the reference case for the use of the smoke extract duct, the control of smoke is defined as the
prevention of back-layering and the prevention of carry-over; the capture of all smoke by the extract
duct. A similar definition applies to the other cases.

4.5.2 Uni-directional, congested traffic

If an incident occurs within congested traffic, the nominal flow of the traffic is in one direction but
there are stationary vehicles both upstream and downstream of the incident. In addition, the vehicles
may be locked into that configuration for some time after the incident occurs.

Under these circumstances it is critically important to maintain the stratification of buoyant smoke
layer, and the ventilation response is modified in the following areas:
The velocity of the longitudinal airflow may be reduced to limit the rate of turbulent mixing, at least during the early stages of the incident while the vehicle occupants evacuate; Jet fans in the incident ventilation section, and immediately upstream of the incident ventilation section, remain turned-off so that they do not encourage mixing; The longitudinal ventilation flow may be sub-critical as a consequence of the modifications described above, and it may be necessary to open one or more additional dampers upstream of the fire to ensure capture of the smoke.

4.5.3 Bi-directional traffic
In the case of bi-directional traffic in a tunnel it is accepted that, in the event of an incident, vehicles will be stationary on both sides of the fire. If the tunnel is ventilated longitudinally, the vehicles and their occupants on one side of the fire will be affected. In principle, the situation is similar to an incident in uni-directional, congested traffic, and the considerations during the response are identical.

4.5.4 Design recommendations
The following guidance is given for the design of ventilation systems with extraction capability:
- Ventilation sections should limited in length, up to 400m in urban tunnels, and up to 600m in rural tunnels;
- Smoke extract dampers should be spaced at intervals of 50m in urban tunnels, and 100m rural tunnels;
- Careful control of longitudinal airflow velocities to less that 1.5 m/s in the vicinity of the fire, in order to reduce the risk of de-stratification;
- Extraction flow rate is to be greater than the rate of smoke production in order to accommodate the smoke-free air that is entrained at the extract points;
- Where the predictions indicate that the smoke is controlled, it is recommended that a contingency of 30% is added to the extract flow rate. For a 30 MW design fire producing 80 m³/s of smoke, the extract flow rate should be at least 110 m³/s.
- Where the predictions indicate that the smoke is not controlled, it is recommended that a contingency of 50%, based upon the cross sectional area of the tunnel, is added to the extract flow rate. If a fire produces 80 m³/s of smoke in a tunnel with a cross section of 60 m², the recommended extract flow rate is 80 + 1.5 × 60 = 170 m³/s.
- The mean velocity in the smoke extract duct should be limited to 15 m/s.

4.6 Ventilation analysis

4.6.1 Requirements
A range of analysis techniques is available for aspects of ventilation design including computer modelling of tunnel airflows, stratified smoke layers, fluid flow and heat transfer phenomena in complex geometries, evacuation, and the effects of hazardous conditions on people. Key requirements common to all types of analysis are:
- appropriate tools;
- experienced practitioners, with prior first-hand experience of modelling the types of problems in question;
c) adequate resources and realistic timescales;
d) careful choice of modelling strategy and interpretation of results, with due consideration
given to the sensitivity of the results to key assumptions and simplifications;
e) detailed reporting.

4.6.2 Choice of methodology

The choice of methodology for ventilation analysis is important.

One-dimensional ventilation models are widely used because of their cost effectiveness. Their main
limitations are the inability to simulate the complex 3-D fluid flow and heat transfer phenomena
involved in vehicle fires, including, for example, smoke stratification and backlayering. When
calculating the critical velocity for longitudinal smoke control, designers need to be aware of the
limitations of the commonly used simple formulae. Critical velocities may be under-predicted for
small fires and over-predicted for severe fires. It is recommended that comparisons are made using
alternative methods to check the sensitivity of results.

The applicability of two-dimensional smoke models to scenarios involving steep gradients, large
tunnel cross-sections and the effects of vehicles and jet fans is uncertain.

Computational fluid dynamics (CFD) modelling is capable of simulating the complex 3-D fluid flow
and heat transfer phenomena involved in vehicle fires, including smoke stratification and
backlayering. However, there are important concerns associated with how CFD is used.

CFD modelling is a complex activity requiring specialist expertise. The results obtained by different
users, even when using the same software, can vary appreciably. Due to the sensitivity of results to
the detailed modelling strategy, it is essential that CFD users are knowledgeable and well trained both
in CFD and fire science. They should have experience of using the particular CFD software for the
type of problem in question.

A set of simulations, focusing on potentially sensitive aspects, should be carried out rather than a one-
off case. Care should be taken when simplifying the problem. For example, the types and
arrangement of vehicles in the vicinity of a fire can have a significant effect on the spread of smoke
and gas, and worst case conditions may occur when large vehicles are skewed across the carriageway
rather than aligned neatly along the carriageway.

4.6.3 Assessing tenability

Simple criteria for assessing the acceptability of conditions for escape, for an exposure period of up to
30 minutes, may be defined as:

- air temperature ≤ 60ºC;
- radiant heat flux < 2.5 kW/m²;
- Carbon Monoxide concentration ≤ 350 ppm;
- visibility ≥ 10m.

More complex criteria will need to be considered when assessing the effects on people evacuating
through smoke rather than under a smoke layer. Reference should be made to the international
standard ISO/TIS 13571 (2003), which presents guidelines for the estimation of time available for
escape, and/or PD 7974: Part 6 on ‘human factors’ (British Standards, 2004), which supports the
standard BS 7974 on the application of fire safety engineering principles.

When assessing conditions at ‘head-height’, a height in the range of 1.5 to 2m is relevant. A height of
1.75m above road level would be consistent with BS 5588: Part 5 (2004). The sensitivity of
conclusions to the precise height needs to be considered, and particular care is needed when the
smoke layer height is near to head-height.
Careful consideration should be given to the uncertainties involved in modelling, particularly those associated with assessing the time taken for tunnel users to reach a place of safety. Key assumptions include pre-movement times and evacuation behaviour under conditions of poor visibility. All assumptions should be justified. Techniques for taking uncertainties into account, such as Monte Carlo analysis, may be useful.

4.6.4 Reporting

A detailed report should be produced, justifying the choice of methodology and describing the modelling strategy and interpretation of results. Due consideration should be given to the sensitivity of the results to key assumptions and simplifications.

For CFD studies, the description of the modelling strategy should include details of the computational mesh, boundary conditions, turbulence and heat transfer modelling assumptions, and the representation of the fire, including the yield of soot and the toxicity of the products of combustion.

4.7 Guidance for operations and emergency response

It is likely that fire brigade attendance times to the incident itself will be greater than 15 minutes, which may be too late to prevent casualties. Therefore, the proper ventilation mode should be activated by the tunnel operator as early as possible to provide smoke control in the tunnel. The ventilation response should not be delayed until the fire brigade arrives at the tunnel. Subsequently, the ventilation mode can be changed by the tunnel operator according to the instructions of the fire brigade.

It is probably not feasible to derive a single ventilation response for all possible emergency scenarios which might occur during bi-directional or congested operations. The best ventilation response can be decided only after balancing the risks involved in the different options available to the ventilation system controller. It is important that these options are investigated beforehand to develop a pre-defined emergency plan. Should a satisfactory solution not be achievable after reviewing all the options, then steps should be taken to prevent or limit the problematic traffic conditions, such as congested uni-directional or bi-directional traffic. Additional safety measures, such as the control of traffic at entry portals and enhanced means of escape, should be provided in the tunnel to mitigate the risks.

In some situations, the safest response may be to switch off the ventilation system, but if so this should be done on the basis of careful planning and not as a waiting option. For incidents involving dangerous goods, it may be necessary to consider the implications for people outside of the tunnel as well as road users. This could be carried out using the OECD-PIARC QRA Model for dangerous goods transport.

The importance of regular and comprehensive operator training and emergency exercises cannot be over-emphasised.

4.8 Guidance for limited facility tunnels

The standardised vehicle fire scenarios and risk-based framework for ventilation design can be applied to any road tunnel, including those with low headroom and restricted to use by cars only or cars and LGVs. However, the only question arising in terms of smoke control design criteria is whether a 15 MW or 8 MW fire size should be used for tunnels used by LGVs as well as cars. To answer this question, the risk framework could be adapted to reflect the LGV fraction of the total traffic.

In the event of a vehicle fire occurring in a tunnel with low headroom, smoke is unlikely to remain above head height for any significant distance or duration. It must be assumed that smoke will spread downwards to road level and visibility will deteriorate rapidly.
Mechanical ventilation systems may therefore be required for all low headroom tunnels irrespective of length. Another option to mitigate the risks is to reduce the spacing between emergency exits.

Due to reverberation, noise generated in a low headroom tunnel would pose a more significant problem than that in the normal headroom tunnel. Also, due to the restricted headroom, ventilation equipment may be installed nearer to the road level, at locations where evacuees would be exposed to high velocity airflows during evacuation. These factors need to be taken into consideration in the system design as well as the selection of equipment. However, the performance criteria for noise and airflow velocity should not be different from what is used for a normal headroom tunnel, i.e. a maximum level of NR85 at a plane 1.5m above the road surface, and a local air velocity of no more than 10 m/s. These criteria are achievable through various design means, such as careful segregation of evacuation path and equipment space, and the choice of equipment that gives better acoustic performance.

4.9 Site tests and commissioning trials

It may be impracticable to test the performance of the ventilation system directly against severe fires in the tunnel. For the purposes of testing and commissioning, the performance of the ventilation system should therefore be evaluated against a representative set of cold flow cases, which have been identified and analysed during design.

The site tests should include the:

- Functional testing of individual items of equipment
- The performance of individual items of equipment, including start up time, the measurement of noise and vibration levels if applicable, installation effects, power consumption, etc
- The integrated operation of systems, including the co-ordinated operation of individual items of equipment and their interlocks
- The performance of the system, operating in each of its design modes or configurations, including noise measurements etc as for the individual items of equipment.

Air velocity measurements should be taken at appropriate locations along the tunnel, depending on the configuration of the tunnel in question. At each location along the tunnel, measurements should be taken at a suitable number of points in the cross-section, for example, in accordance with ISO 5802 ‘Fans for general purpose – performance testing in situ’, in order to determine the bulk mean airflow velocity and volumetric flow.

In each case, a set of noise measurements should also be taken at locations along the tunnel, in the vicinity of the fan installations, in order to confirm that the design criteria are satisfied.

The commissioning trials should include the correct operation of the ventilation system:

- Across the design interfaces, including the local control and SCADA, and power supplies
- Through the local and central control points for all standard responses, degraded modes and hand-over routines as applicable
- In response to inputs made by the operator, or from nominated sensors in the tunnel

In addition, the system and equipment status indicators should be confirmed at central control and at the smoke control panels if applicable.
5 General conclusions and recommendations

BD 78/99 provides good guidance in general, but there is a number of areas in which improvements should be made. Recommendations have therefore been made as follows:

a) A set of standardised vehicle fire scenarios and a framework for risk-based design have been proposed. A key objective is to ensure better consistency between tunnel designs and with current international best practice. The proposed framework is capable of supporting key decisions such as the choice of design scenario for a particular tunnel and the selection and justification of the ventilation configuration.

b) Improved design guidance is given on minimising smoke spread between bores and defining ventilation systems with smoke extract capability. New guidance is proposed on ventilation analysis, covering the choice of ventilation model and modelling strategies, the expertise required by the user, and the interpretation and reporting of results.

c) Improved guidance is also given for operations and emergency response. This covers the roles and responsibilities of the tunnel operator and the fire brigade, and the selection of ventilation responses. A key aspect is the need for pre-defined ventilation plans, which can be used without delay by the tunnel operator.

For low headroom tunnels, covered by the draft standard TD 43, attention is drawn to the potential for rapid deterioration of conditions in the event of a fire, even when only light vehicles are involved. Even relatively short tunnels may need mechanical ventilation and/or enhanced life safety measures.

Further work is recommended as follows:

a) There is a need for consistency between the guidance followed by fire brigades, tunnel operators and designers. This could be achieved through a working party comprising representatives drawn from tunnel operators, designers and the National Operations Committee of the Chief Fire Officers Association.

b) There appears to be relatively little information on visibility and toxicity levels for large vehicle fires under natural ventilation conditions. Opportunities should be investigated to participate in future tunnel fire test programmes with a view to obtaining such information, which would help to improve confidence in modelling predictions of visibility in particular.

c) There is a need for statistical information about HGV fires, to help estimate the risk of severe fires in road tunnels. For example, it would be useful to know how often the load is involved in the fire and the proportion of incidents in which the load is completely destroyed.
6 Acknowledgements

The work described in this report was carried out in the Infrastructure Division of TRL Limited and was funded by the SSR Asset Performance Division of the Highways Agency. The HA Project Sponsor for the study was Mr L Brown. The major part of the study was subcontracted by TRL to Mott MacDonald Limited.

At TRL, the Project Manager was Dr D Carder and technical advice was provided by Dr M P O’Reilly.

The Mott MacDonald project team included Mr R C Hall, Mr W G Gray, Mr E C Bennett, Mr P Leung, Dr J N’Kaoua and Dr P Sabapathy.

Grateful thanks are due to those who responded to the questionnaire and contributed in meetings.
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**Conference Series**

International Conference on Aerodynamics & Ventilation of Vehicle Tunnels

International Conference on Safety in Road and Rail Tunnels

International Conference on Tunnel Fires and Escape from Tunnels


1st International Symposium on Safe & Reliable Tunnels, Prague, Czech Republic, 4-6 February 2004.
Glossary of Terms

AADT: Annual Average Daily Traffic

Annual risk: The annual chance of a certain event occurring. The event may be an accident, fire or dangerous goods incident, or a person being injured or killed. Where the annual risk is expressed as ‘1 in N’, N represents the average number of years between events.

Backlayering: The spreading of a smoke layer upstream of the fire location, when the longitudinal airflow velocity is below the critical velocity.

Critical velocity: The longitudinal airflow velocity required to prevent smoke spreading upstream of the fire location.

CFD: Computational Fluid Dynamics

CP: Cross passage

DGV: Dangerous goods vehicle, carrying substances such as explosives, flammables or corrosives, and identified by orange-coloured plates showing the UN number of the substance being transported.

Heat release rate: The size of a fire, typically expressed in MW (megawatts). A vehicle fire would normally peak after about 10 minutes. This heat release rate would be maintained for several minutes and then gradually decay.

HGV: Heavy goods vehicle

LGV: Light goods vehicle

Longitudinal ventilation: A tunnel ventilation system designed or operated in such a manner that air flows along the axis of the tunnel (but not necessarily in the same direction as normal traffic).

MTFVTP: Memorial Tunnel Fire Ventilation Test Program

Natural ventilation: Airflow through a tunnel which is generated either by piston action of vehicles, tunnel gradient, ambient meteorological conditions or a combination of such factors.

PIARC: World Road Association

QRA: Quantitative Risk Assessment

Semi-transverse ventilation: A tunnel ventilation system designed or operated in such a manner that fresh air is uniformly supplied over a given tunnel length, or exhaust air is extracted in a similar uniform manner.

Tenability: Acceptability of hazardous conditions for survival

Transverse ventilation: A tunnel ventilation system designed or operated in such a manner that air is uniformly supplied and exhausted along the full length of a tunnel or section of tunnel.

TDSCG: Tunnel Design and Safety Consultation Group
Appendix A  Questionnaire
Questionnaire on
Ventilation during Road Tunnel Emergencies

This questionnaire is in support of research being performed on behalf of the UK Highways Agency by Mott MacDonald and TRL.

The objectives of the project are to review the requirements and advice on ventilation in emergencies contained in the UK standard for design of road tunnels (BD 78/99), and to recommend how this should be amended and updated (if appropriate) in the light of current knowledge and best practice. All issues that are relevant to the design and operation of tunnel ventilation systems are being considered.

As part of this research, we are seeking the views of organisations involved in design, operation, emergency response, research and regulation in this field. We hope you will be able to assist in this by completing this questionnaire. In return, we will provide you with feedback from the exercise within 2-3 months, when we have received and analysed the responses.

There are a total of 26 questions covering design standards and practice, tunnel operations and emergency response. Please skip any questions relating to areas outside of your field of activity or expertise.

Responses can be entered directly in each of the fields, but feel free to print this form and provide handwritten responses if you prefer.

In responding to the questionnaire, please be aware that the findings of the research will be published. If we refer to specific questionnaire responses in our report, we would keep the identity of the responder(s) confidential.

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<td>Briefly describe your area(s) of activity and expertise</td>
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TRL Limited

PPR140
### Design Standards

1. Briefly outline your experience of using BD 78/99, the UK standard ‘Design of Road Tunnels’. Please highlight any aspects of BD 78 that you refer to in particular for emergency ventilation.

2. When defining design fire scenarios, would you normally use the data from BD 78/99, follow other guidance or derive value(s) from ‘first principles’?

3. Are there any aspects of BD 78/99, relating to emergency ventilation, which you feel require improvement? If so, please give details.

4. Briefly outline your experience, if any, of using non-UK standards or guidance for ventilation design. Please highlight any good aspects of non-UK standards and guidance.
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<th>Design Practice</th>
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</table>
14 How do you define your tunnel specifications? Do you use Highways Agency standard specifications directly, modify these specifications or use other specifications?

15 Do you undertake fire/smoke testing when commissioning a tunnel ventilation system? If so, what test protocol do you follow?

**Tunnel Operations**

16 Briefly describe the nature of your tunnel, its ventilation system, mode(s) of traffic operation and the control philosophy for emergencies.
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<tr>
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<tr>
<td>17</td>
<td>Briefly describe how the ventilation is controlled. Include the inputs used to define the ventilation response and the level of automation in the control system.</td>
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<td>18</td>
<td>Who is responsible for control of the ventilation system during tunnel emergencies?</td>
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<td>19</td>
<td>What training is given to traffic and tunnel controllers and response teams, and how often is this refreshed?</td>
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<td>20</td>
<td>What procedures do you have for flammable spillages in the tunnel?</td>
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<td>21</td>
<td>What procedures do you have for toxic gas incidents in the tunnel?</td>
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## Emergency Response

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<td>22</td>
<td>How frequently are emergency planning meetings, table top exercises and full-scale exercises held, and who attends?</td>
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<td>23</td>
<td>How much time does the fire brigade take to reach the tunnel? How much additional time is required before commencing fire-fighting operations inside the tunnel?</td>
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<td>24</td>
<td>Briefly describe the nature of firefighter training for tunnel incidents. Does this include any tunnel-specific theory or practical exercises? Are there any differences in training for part-time crews?</td>
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<td>25</td>
<td>Are there procedures specifically for tunnel incidents? How do these differ from the corresponding procedures for open air incidents?</td>
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</table>
26. How effective are the communication systems in the tunnel environment? Are there any noise problems?

27. Please provide brief details of any notable tunnel incidents and any lessons learned that relate to emergency ventilation.

Please return this form to:
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Thank you for your assistance
Appendix B  Calculation of critical velocity for longitudinal smoke control

Atkinson et al (1996) describe a method for calculating the critical velocity for longitudinal smoke control, based on dimensional analysis and consideration of the buoyancy produced by fire plumes with flames falling well short of, or extending along, the ceiling.

\[ V^* = \frac{V_{\text{crit}}}{\sqrt{gH}} \]

\[ Q^* = \frac{Q}{\rho_o c_p T_o \sqrt{g H^5}} \]

where \(V^*\) is the dimensionless critical velocity (\(\text{-}\)), \(V_{\text{crit}}\) is the critical velocity (\(m/s\)), \(g\) is the acceleration due to gravity (\(m/s^2\)), \(H\) is the height of the tunnel (\(m\)) (see comment below on hydraulic diameter), \(Q\) is the heat release rate (\(kW\)), \(Q^*\) is the dimensionless heat release rate (\(\text{-}\)), \(\rho_o\) is the ambient air density (\(kg/m^3\)), \(c_p\) is the specific heat capacity of air (\(kJ/kg K\)), \(T_o\) is the ambient air temperature (\(K\)).

The above equations are governed by the following constraints:

\[ V^* = V_{\text{max}}^* \left( \frac{Q^*}{0.12} \right)^{\frac{1}{3}} \quad \text{for } Q^* < 0.12 \]

\[ V^* = V_{\text{max}}^* \quad \text{for } Q^* > 0.12 \]

The value of \(V_{\text{max}}^*\) varies between 0.31 for a fire stretching right across the tunnel to 0.35 for fires with a height and width much smaller than that of the tunnel.

Having calculated \(Q^*\) and then \(V^*\), the critical velocity is given by \(V_{\text{crit}} = V^* \sqrt{gH}\).

Wu et al (1997) suggested that a hydraulic diameter should be used instead of tunnel height on the basis of experimental tests. This would lead to different critical velocities for tunnels with the same height but different aspect ratios.

More recently, Wu (2003) proposed a correction factor for downhill slopes between 0 and 10º, based on a series of experimental tests using a reduced-scale tunnel rig:

\[ V_{\text{crit}, \theta} = V_{\text{crit}} (1 + 0.008 \theta) \]

where the slope angle \(\theta\) is expressed as a percentage.