

Guide to Road Tunnel Safety Documentation

Booklet 4

Specific Hazard Investigations

September 2003



Guide to road tunnel safety documentation

For every tunnel in the national road network whose length is over 300 metres, safety documentation has to be compiled and submitted to the prefect, who refers it to the CESTR (Comité d'Evaluation de la Sécurité des Tunnels Routiers / road tunnel safety assessment committee) for its opinion.

All the persons and services involved in tunnel safety (the owner, the operator, the maintenance and repair and emergency services, the prefecture) must assist with the compilation of this dossier which in its final version will contain among other things the essential aspects of tunnel operation under any and all circumstances.

This **safety documentation guide** is intended for the above services, the owner and the relevant engineering and design offices.

The introductory document, "Safety Documentation Objectives" was issued in March 2003; it should be read by every person required to understand the general purport of the recommended procedures and how the various documents contained in the safety documentation are organised.

The **safety documentation guide**, of which the above-mentioned introductory document may be regarded as "Booklet 0", comprises the following **five booklets**, either issued or due to be issued in 2003 and 2004:

Booklet 1: Practical method of compiling the safety documentation

Booklet 2: Tunnels in Operation: "From the Existing Condition to the Reference Condition" (June 2003)

Booklet 3: Comparative risk analyses

Booklet 4: Specific hazard investigations (September 2003)

Booklet 5: Emergency response plan

Statutory Background

- Interministerial circular no. 2000-63 of 25 August 2000 concerning the safety of tunnels in the national road network requires the owner (jointly with the operator in the case of tunnels in service) to compile a safety documentation for all tunnels in the national road network of over 300 metres in length.
- Circular no. 2000-82 of 30 November 2000 supplemented the above circular in regard to regulations governing dangerous goods transport vehicles in road tunnels belonging to the national network.
- The implementing order for the Law of 3 January 2002 in respect of the safety of infrastructures and transport systems, which has yet to be finalised, is designed to confirm this statute and extend it to all local authority tunnels of over 300 metres in length.

¹ This guide enlarges on and replaces the document entitled *Specific hazard investigations of Tunnels in the Road Network, Guide to Methods, Provisional Version*, issued July 2001.

Booklet 4

Specific Hazard Investigations

Introduction

The specific hazard investigation looks at the tunnel as a comprehensive entity comprising the users, the tunnel itself together with its facilities and its environment, the operator, and the maintenance, repair and emergency services.

It is a key document in the safety documentation, irrespective of the stage concerned (tunnel at the project stage, to be put into operation or already in operation).

Part A of this booklet describes the function of the specific hazard investigation in the safety documentation and gives the owner advice of a general nature.

Part B presents the chapter by chapter content of the specific hazard investigation and the investigation methodology recommended, with particular emphasis on the choice of scenarios (chapter B3).

Lastly, in the **appendixes**, the persons responsible for planning and/or conducting the investigation, notably the engineering and design offices, will find practical recommendations and standardised values for a number of parameters.

Part A – The Function of the Specific Hazard Investigation in the safety documentation

Appendix 1 of the circular 2000-63 of 25 August 2000 specifies that the safety documentation of any tunnel of over 300 metres in length (whether at the project stage, to be put into operation or already in operation) must include a **specific hazard investigation**. It is further specified that the investigation:

- must "describe any accidents, whatever their cause, that may occur once the tunnel is in operation together with their extent and possible consequences";
- must "describe and explain the measures required in order to reduce the probability of these accidents and their consequences".

1 Composition of the investigation

Both the preparation of a tunnel project and the inspection of a tunnel in operation are done on a component-by-component basis, although interactions between components necessarily form part of the **investigation**.

Compared with these basically sector-based and technical approaches, the specific hazard investigation is a multidisciplinary process that looks at the tunnel as a comprehensive entity comprising the users, the tunnel itself together with its facilities and its environment, the operator, and the emergency services. It is based explicitly on a study of the chains of events likely to result in serious personal injury.

The investigation is conducted in accordance with the following plan (described with comments in Part B):

- *Chapter 1: Overview of the tunnel and its environment*
- *Chapter 2: Functional description of the tunnel*
- *Chapter 3: Identification of hazards and choice of scenarios*
- *Chapter 4: Examination of the scenarios*
- *Chapter 5: Summary*

2 Place of the investigation in the safety documentation

The specific hazard investigation is a key document in the safety documentation. It is based on the reference condition of the tunnel and may result in the need for improvements. It provides the data required in order to compile the operating documents.

With a **new tunnel**, the technical and organisational reference condition is the condition planned for when the tunnel is opened to traffic.

At the **Tunnel Project** stage, a certain number of facilities may be defined as they are in principle but not necessarily as they will be once operational. The situation is similar as regards organisation of the operation and the emergency procedures (internal and external). Even if the performance and operation of the tunnel remain, for this reason partly, at the "principle" stage, the specific hazard investigation must deal consistently and comprehensively with all aspects of safety so as to provide the basis for a reference condition in regard to safety (the condition planned for when the tunnel is opened to traffic and then in operation). It should in particular examine the impact on safety of any departures from the technical instruction and the arrangements made to compensate for them.

At the stage at which the tunnel is to be **opened to traffic**, compared with the safety documentation compiled for the previous stage¹ and on which the assessment committee and the prefect will have given their opinion, the investigation may need to be updated to include the information provided and the changes made since then (traffic forecasts, safety measures implemented, etc.). It should also show that the principles set out in the previous investigation have in fact been applied.

With a **tunnel in operation** on the date of signature of the circular, all of the data concerning the tunnel and its operation are available together with the feedback obtained since it came into operation. Booklet 2, Tunnels in Operation "from the existing condition to the reference condition", provides the data required for the existing condition report and the definition of the technical and organisational upgrade programme which, once completed, will achieve the reference condition. The **specific hazard investigation** is based on the reference condition and in particular examines whether the departures from the technical instruction², accompanied where applicable by compensatory arrangements, are still acceptable.

¹ Except for temporary situations which should no longer exist for tunnels in the national network.

² Strictly speaking, the technical instruction of 25 August 2000 only applies to new tunnels.

The information taken from the specific hazard investigation makes it possible to:

- suggest, if need be, improvements to the reference condition or even, in exceptional cases, to question the decisions taken;
- have in every case the basic data the owner needs to draw up operating instructions (including the minimum operating conditions) and, in collaboration with the emergency services, the required emergency response plans³ (see **Booklet 5**).

³ The definition of the exact operating and emergency conditions draws on the specific hazard investigation but is not part of it; rather, it comes under the operating documents (instructions, emergency and safety plans, etc.).

3 Recommendations to Owners and Operators

**The specific hazard investigation is usually subcontracted to engineering and design offices specialising in hazard investigations.
The owner and the operator must, however, fully involve themselves in the investigation in order for it to be effective.**

3.1 Owner and Operator Involvement

The owner (and the operator in the case of a tunnel to be put into operation or already in operation) must be fully involved in the investigation:

- to ensure that all the specific features of the local environment are taken into account when identifying hazards and also when choosing and analysing relevant scenarios (e.g. sporadic tourist coach traffic, isolated mountainous roads, emergency services arriving much later than expected, etc.);
- To ensure effective coordination with the other parties concerned (fire brigade, police, ambulance services, etc.) which must necessarily be involved in one or other stage of the investigation.

Stopping points are necessary throughout the preparation of the investigation.

For tunnels in operation, a minimum of four meetings are required:

- one meeting to present the reference condition decided on by the owner (established beforehand in collaboration with the other players, fire brigade, police, etc.);
- one meeting to approve chapters 1 and 2 and decide on the choice of scenarios, during the preparation of chapter 3;
- one meeting to present the events in the scenarios during the preparation of chapter 4;
- one meeting to summarise the scenarios on completion of the specific hazard investigation.

In the case of tunnels at the project stage, the number of meetings could be reduced.

Depending on the complexity of the tunnel, additional meetings may be necessary.

The total time taken to complete a specific hazard investigation is two to three months, depending on the complexity of the tunnel. This timescale could be extended in special cases.

3.2 The characteristics of the reference condition decided on must be clear and unambiguous

The reference condition and the traffic data, including the speed of vehicles transporting dangerous goods, are essential components of the specific hazard investigation.

As already mentioned in chapter 2, the investigation looks at the tunnel (technical and organisational arrangements) in its **reference condition**, which has to be defined accurately prior to commencement of the investigation. Should the investigation require improvements to be made to the reference condition, there are two possible situations:

- Either these improvements do not significantly affect either identification of the hazards or the choice of and events in the scenarios. The investigation remains based on the initial reference condition, clearly described, and includes in its conclusion proposals in regard to the improvements envisaged; these are then adopted (or not) by the owner in his report concluding the safety documentation.
- Or these improvements seriously call the reference condition into question, in which case a new reference condition is approved by the owner and serves as the basis of the investigation in its final form.

In any case the results and conclusions of the final investigation must apply to the tunnel assumed to be in a well defined condition, namely the reference condition.

A knowledge of the traffic patterns is essential to any evaluation of the safety conditions as vehicles and users alike are both the causes and the victims of incidents and accidents. The speed at which the action and emergency teams can get to and inside the tunnel also depends on the prevailing traffic conditions. Refer to **Booklet 1**, "Method of Compiling the Safety Documentation" for details on the content of traffic surveys.

The specific hazard investigation takes account of the decisions made at a previous stage regarding **dangerous goods** transport vehicles Refer to **Booklet 3**, "Comparative risk analyses".

3.3 Judicious use of modelling tools

The purpose of checking and improving safety must not be overshadowed by the use of modelling tools.

The specific hazard investigation usually uses models of smoke movement and user behaviour.

Every model has a degree of uncertainty. This is particularly the case for tunnels as smoke propagation phenomena are highly sensitive to small variations in numerous parameters, and because user behaviour, which is often unpredictable, is a preponderating factor.

If a greater knowledge of the smoke propagation patterns can suggest more efficient operating and emergency procedures, and if the resulting changes can be effectively implemented, then the modelling tools used will be extremely useful.

Conversely, with tunnels whose facilities are so simple that their functions are self-evident and in which a high degree of surveillance could never be achieved, sophisticated modelling tools are of little use in decisions regarding modifications or as aids to tunnel operations.

3.4 The specific hazard investigation: a fundamental training document

For both new tunnels and tunnels in operation, the first submission of the safety documentation to the assessment committee is a significant stage in the whole safety procedure. The specific hazard investigation conducted at this time is fundamental to the safety of the structure.

Throughout the life of the tunnel, the feedback obtained and the annual exercises give operators and outside services more points to consider; consequently, the operator should update certain aspects of the safety documentation, notably the emergency and safety plan, as often as required.

On the other hand the specific hazard investigation is a permanent document, (except if substantial modifications are made to the tunnel, its environment, its traffic and its operation calling for a fresh examination of the dossier by the CESTR). It is not meant to gather dust on a shelf; on the contrary, it is a valuable training document and one which should be read and understood by every person responsible for safety in the tunnel (including and especially newly-employed personnel).

Notes

Part B – Methodology and content of the specific hazard investigation

The five chapters in Part B each give recommendations for the compilation of the same chapter of the specific hazard investigation.

Chapters 1 and 2 describe the tunnel, its environment and its functionalities in the reference condition.

1 The tunnel and its environment

The tunnel is described in other documents in the safety documentation. The purpose of this chapter of the specific hazard investigation is to emphasise solely what is important from a safety point of view, even if this means referring the reader to other documents. The following aspects are of particular interest:

- tunnel characteristics;
- the situation of the operating centres and emergency centres in relation to the tunnel;
- the natural environment (geology, hydrogeology, meteorology, etc.);
- the human environment (population and nearby activities, whether permanent or temporary);
- roads: chief routes and their general traffic conditions;
- the composition of the traffic;
- any other related aspects.

2 Functional description of the tunnel

This chapter describes the safety functions in place together with the principal structural elements, equipment and operating arrangements ensuring their effective performance.

This description should be functional in the sense that it describes the safety functions but does not extend to analysing the functional reliability. The level of analysis required in this description is the same as that indicated in Appendix 1 of **Booklet 2**⁴.

A report analysing compliance with the technical instruction appended to circular 2000-63 may be helpful, especially in the case of existing tunnels.

⁴ The examples of the functional description given in Booklet 2 apply to the existing condition, i.e. the condition of the tunnel prior to completion of the safety upgrade programme. Here, it is a question of the reference condition, which may be the same or different depending on the functions considered and the modifications envisaged.

3 Identification of hazards and choice of scenarios

This phase of the investigation should be conducted in close collaboration with the different parties concerned: the owner, the operator and the police and emergency services.

This phase meets two requirements:

- an **exhaustive inventory** of possible events: this serves both as a preliminary to the choice of scenarios and as a basis for finalising the operating documents, notably the emergency and safety plan described in **Booklet 5**;
- the selection of a **small number** of scenarios to be analysed in detail (see chapter B.4).

3.1 Definitions

In the remainder of the text the following definitions will be used:

- **accident-causing situations** (speeding, vehicle stopped in the roadway, etc.) are those which, while they may not create an immediate hazard, are likely to increase the probability of a trigger event or several events triggering a chain reaction;
- **trigger events** are events that mark the onset of a highly dangerous situation for the users (accident, fire, etc.); these trigger events are the point of departure of the scenarios;
- **aggravating factors** are contextual factors that are such as to worsen the consequences of a trigger event (tunnel ventilation malfunctioning, bad weather, secondary accidents involving the vehicles behind, etc.);
- a **scenario** is the sequence of events stemming from a trigger event, placed in its context and which therefore includes any aggravating factors.

3.2 Identification of hazards

To help identify the hazards, Appendix A contains a guide listing hazardous events that can occur in a tunnel. **This list must be tailored to the particular characteristics of the tunnel being investigated and to its environment.** The investigation could also use the same method of analysis as those used in industrial safety, in which case it will be even more important to keep in mind the particular characteristics of the tunnel (user behaviour, smoke movements, etc.).

Certain tunnel malfunctions should not be considered when for preventive reasons they lead to the immediate closure of the tunnel (loss of the central management system, serious power cut, lighting not working and so on). On the other hand, when the possibility that the loss of a function goes unnoticed cannot be ruled out, or when it may have been caused by a trigger event (e.g. loss due to a short circuit caused by a fire), then any such loss of a function should be regarded as an aggravating factor.

3.3 Choice of trigger events

The choice of scenarios to be analysed in chapter 4 begins with the choice of trigger events (rarely more than three or four).

Under the traffic regulations applicable to the tunnel, the standardised trigger events⁵ that it is advisable to choose are as follows:

1. Tunnels authorised for use by HGVs except those carrying dangerous goods:
 - (a) HGV fire
 - (b) fire in an HGV carrying a liquid or easily liquefiable load with a high heat potential
2. Tunnels authorised for use by HGVs including those carrying dangerous goods:
 - (a) HGV fire
 - (b) fire in an HGV or an HGV carrying dangerous goods (20 tonne fuel tanker)
3. Tunnel clearance height 2m to 3.5m:
 - (a) fire in a van carrying a flammable liquid, no spillage
 - (b) fire in a small HGV
4. Tunnel clearance height under 2m:
 - (a) fire in a light vehicle spreading to one or two other light vehicles
 - (b) fire in a van carrying a flammable liquid, no spillage

In addition to the above standardised events, other events may be included if warranted by a particularity of the tunnel concerned (atmospheric conditions, steep gradients, emergency service access time, heavily congested urban motorway environment, etc.).

If the assessment of risks attaching to dangerous goods transport vehicles (see **Booklet 3**) shows that dangerous goods other than liquid hydrocarbons significantly increase the risk, the trigger events endangering these goods should be taken into account.

⁵ Chapter 4 gives the quantitative factors used to standardise the modelling of these events and their consequences.

When choosing the trigger events, a frequency-severity matrix representation could be used, relating the probability of occurrence of the trigger events to their presumed consequences. This tool and its limitations are described in **Appendix B**.

3.4 Choice of scenarios associated with trigger events

Once the trigger events (including standardised events) have been selected from the list of identified hazards, defining the scenarios consists of associating them with a context. For example, the "HGV fire" trigger event could be associated with this context: "this fire occurred at MP 650 at 18.30 hours in bad weather and congested traffic conditions", etc.

Whilst there must not be an excessive number of contexts, on the basis of few scenarios variants can be examined subsequently to test the sensitivity of the consequences to a parameter which has shown itself to be particularly influential.

The scenarios should be chosen with care; the least favourable context should not always be chosen as it could hide the advantages of measures specially selected in order to improve safety; for example, a fire occurring near an emergency exit to be built in a tunnel in operation and rendering that exit inaccessible.

Exhaustiveness is not the purpose here, but rather the instructive nature of the scenarios, i.e. their ability to demonstrate the link between the facilities and the operating and emergency provisions designed to meet the safety requirements. For example, a scenario might be chosen that deploys all the various services to test for weak points in their coordination. In this regard, the scenarios complement the identification of hazards, thus helping with drawing up the operating instructions and the emergency and safety plan, and with organising the routine exercises.

As a general rule, scenarios are limited to just the first 30 minutes, the most crucial period for ascertaining the consequences for user safety⁶.

In the face of extreme scenarios (e.g. an explosion following an accident or a fire involving an LPG tanker), the only course of action is to note the virtually inevitable consequences (the death of all the persons present in the tunnel), given the suddenness of the event. The action possible can only be of a preventive nature (restrictions on traffic or building above the tunnel, etc.). Studying a scenario of this type will not highlight any directly useful lessons. A toxic gas leak, on the other hand, calls for reactions that can be determined by analysis. Depending on the traffic using the tunnel, a scenario of this type might well be considered.

⁶ The time required to evacuate persons in shelters may make it necessary to extend this period.

4 Examination of the scenarios

4.1 Sequence of a scenario

The description of the sequence of events and the action required should illustrate the contribution of each material and organisational factor of tunnel safety and the way in which these factors interact.

Due to the numerous uncertainties liable to affect any simulation, the quantified results of any models should be regarded with caution.

Each scenario starts with a trigger event and continues with the sequence of events right up to ensuring user safety or the arrival of the emergency services if this occurs later.

These events involve:

- the progress of a phenomenon in a confined space (smoke propagation, liquids, gases and heat in the tunnel under the effect of the prevailing geometric, mechanical and air flow conditions plus the characteristics and movements of the vehicles);
- user behaviour (to do mainly with walking towards the emergency exits);
- implementation of the safety systems and procedures (detection systems, activation and operation of the required facilities, the operator's reactions, action by the emergency services, etc.).

Examination of the scenarios should be such as to:

- show concretely the function of each system or procedure designed to minimise effects likely to endanger the persons using the tunnel;
- reveal the interactions between the different systems and procedures;
- identify the weak points of each individual system and of the operation as a whole;
- highlight more or less hazardous areas of both the tunnel and its environment (opacity, poison gases, temperatures, overpressures, projectiles, etc.) and make it possible to assess the number of persons likely to be present and endangered⁷.

⁷ Even when it is done with the aid of models, assessing high-risk areas and the associated events is affected by major uncertainties in the analysis of the results. In this respect, any calculation of the "number of deaths per scenario" is necessarily an approximation as the figures are necessarily founded on very fragile bases.

The fact that an advisable trigger event corresponds to the design fire or to an even more powerful fire does not mean that the design has to be checked or re-examined but is intended to check the operating provisions and performance of the system as a whole, as defined by its reference condition, or to suggest how they may be modified.

4.2 Standardised criteria governing examination of the scenarios

Just as the particular characteristics of each tunnel have to be considered in detail, so there is no justification for a case-by-case examination to specify the values of items for which the tunnel manager has very few means of taking action. That is why a certain number of criteria that have a decisive influence have been standardised⁸.

Consequently, the elements that have been standardised are as follows:

- the "fire source terms" , i.e. the amount of heat, smoke and poison gas given off by a fire as a function of time and according to the type of vehicle for which the fire has been chosen as a trigger event;
- the criteria of survival in a smoke-laden atmosphere;
- user behaviour (as regards both the formation of tailbacks and users having left their vehicles to walk to the emergency exits.

Although standardised values have to be adopted, if in exceptional cases it turns out they are inapplicable to the tunnel concerned, additional scenarios using other values can be adopted.

4.2.1 Standardised source terms: fires

These are given in Appendix C for each of the standardised trigger events in paragraph 3.3.

4.2.2 High-risk areas

As shown in the basic diagram below, the areas at risk due to a fire in the tunnel depend on the stratification of the smoke as well as the degree of opacity, the toxicity and the temperature, and the amount of radiant heat to which the users are exposed⁹.

⁸ This also enables comparisons to be made between the specific hazard investigations of different tunnels owing to the absence of any disparity in the assumptions made.

⁹ The risk of a structure collapsing at survivable temperatures is practically non-existent: the design of the structural works is in fact such that conditions inside the tunnel will have become unbearable long before any possible collapse of the ceiling or the vault.



**Risk Factors associated with a Tunnel Fire
(left: unstratified area; right: stratified area)**

In the left of the figure, the smoke is not stratified; it takes up the whole section and the movements of the users are impeded by its opacity. They are also affected by the toxicity and the temperature of the smoke. It is the time they have to spend in this environment before reaching an emergency exit and the aggressiveness of the environment that determines the consequences. It is considered that a carbon monoxide (CO) content of over 3000 ppm or a temperature in excess of 80°C will not allow a user to keep walking for more than about a quarter of an hour¹⁰.

In the right of the figure, the smoke is stratified and the users can usually survive the conditions of visibility and toxicity. They are, however, affected by the heat radiation (represented in the diagram by red arrows)¹¹. A radiation value of 2 kW/m² is the maximum that can be tolerated by a user for just a few minutes¹².

4.2.3 User behaviour

Appendix E gives the data required for modelling user behaviour in respect of:

- the formation of tailbacks;
- the speed of escape to the emergency exits according to the conditions prevailing in the tunnel.

The data are of course simplified and approximate but they do represent average behaviour. They could only be overcome by extremely burdensome user education and training.

¹⁰ The toxicity of a fire is normally measured by the CO content. For tunnels used by traffic likely to give off particular poison gases, refer to the toxicity values given on the Ineris website: <http://www.ineris.fr>.

¹¹ Users can protect themselves from the radiation given off by fire by sheltering behind an obstacle (typically a vehicle). It is in fact the radiation given off by the layer of hot smoke just under the ceiling that poses the greatest problem; and the time spent by the users under this layer of smoke in the course of their evacuation and the temperature of the smoke determine the consequences.

¹² 5 kW/m² for suitably equipped firemen.

4.3 Smoke movement representation

When studying a fire scenario, describing the high-risk areas requires a fairly good idea of how the heat environment evolves and more especially of how the smoke moves in a tunnel during the first fifteen to thirty minutes following the onset of the fire.

Depending on the type of tunnel, ventilation to maintain the conditions required for survival and visibility employs several strategies (see the *Ventilation* section of the pilot tunnel safety documentation, available shortly from CETU):

- pushing the smoke in the same direction as the traffic, which will enable the users behind the fire to walk to the emergency exits. In this case, the users located in the area to which the smoke is being directed must be able to drive off freely before the part of the tunnel they are occupying becomes smoke-laden; this particular smoke extraction strategy only applies to tunnels characterised by one-way uncongested traffic (longitudinal ventilation).
- In all other cases (transverse ventilation, longitudinal ventilation with a massive extraction system, longitudinal ventilation activated in two phases), the initial aim is to limit the velocity of the air flow such as to maintain the smoke in its stratified state; this enables users impeded by the fire to make their way on foot to the emergency exits, possibly under a layer of smoke located in the vault.

Three levels of complexity may be envisaged with smoke movement models:

- level I: qualitative analysis (made without the use of specific modelling, but relying if necessary on graphs, nomograms or equations);
- level II: qualitative analysis + one-dimensional model¹³;
- level III: qualitative analysis + one-dimensional model + three-dimensional model.

In the vast majority of cases, the owner will choose level II.

For tunnels with non-standard geometry (four or more traffic lanes, vault height over 7 to 10 metres, complex underground interchange, etc.) level III modelling may be advantageous, in which case the owner may need to conduct a preliminary analysis so as to determine the level he will specify in the invitations to tender. For further information, refer to **Appendix D**, which lists the usual precautions to be taken when using this type of model.

¹³ Level II also includes zone models adapted to tunnels.

5 Summary

This chapter of the specific hazard investigation should include the following in as concise a form as possible:

1. A summary of the scenarios examined and their consequences.

2. A recapitulation of the observations made in the course of chapters 2 and 3 on safety measures and any proposals for improvement:
 - the compliance with widely accepted practice of the measures intended to reduce the probability of occurrence of accidents;
 - for tunnels in operation not compliant with the technical instruction, an assessment of the level of safety compared with the safety level that would be achieved by strict application of this instruction;
 - the scope of the measures intended to reduce both the occurrence and the consequences of accidents;
 - the adequacy of the measures taken to reduce the consequences of equipment failures and the absence of a common failure mode for equipment designed to ensure safety;
 - where applicable, proposals for the improvement of the provisions adopted.

3. a summary of the items required in order to draw up:
 - the operating instructions (concerning among other things the unavailability of equipment or personnel compatible or not with the task of keeping the traffic moving in the tunnel;
 - the emergency and safety plan;
 - the action plans of the public emergency services.

Notes

Appendixes

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|------------|--|
| Appendix A | Guide to the identification of hazards A.1 to A.4 |
| Appendix B | Criteria governing the assessment of accident and fire risks B.1 to B.4 |
| Appendix C | Standardisation of source terms: fires and dangerous goods C.1 to C.12 |
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Appendix A Guide to the Identification of Hazards

There are many ways in which to classify hazardous situations. For the sake of simplicity, we suggest the list below, which is based on the three families of hazards defined in Part B, paragraph 3.1. The reader may use other methods if s/he wishes.

A.1 Accident-causing Situations

A.1.1 User Hazards

- Speeding
- Peak hour traffic (tailbacks)
- Users failing to keep their distance from the vehicle in front
- Lane-hopping
- Dangerous driving (braking suddenly, skidding)
- Light vehicle broken down or stopped
- Motorcycle broken down or stopped
- HGV broken down or stopped
- Coach broken down or stopped
- Users driving in the wrong direction
- Vehicle convoys (events)
- Oversize vehicles, wide/long/dangerous loads
- Pedestrian in the roadway, accidentally or deliberately
- Demonstrations
- Wild animal or pet in the roadway
- Pet escaped from a vehicle
- etc.

A.1.2 Hazards arising from the Outside Physical Environment

- Flooding in the tunnel
- Fog (visibility reduced to tunnel entrances and exits)
- Violent wind (uncontrolled movements, falling objects)
- Persistent rain (visibility reduced to entrances and exits, film of water on the roadway)
- Roadway snowed under at tunnel portals, roadway slippery
- Ice (roadway slippery at tunnel entrance and exit)
- Infiltration of water into the tunnel
- Smoke from a fire outside the tunnel (forest fire, rubbish tip, etc.)
- etc.

A.1.3 Hazards due to tunnel infrastructures and safety equipment malfunctions

- Steep incline, change of horizontal alignment radius
- Disrepair, some equipment not maintained
- Hard shoulder congested
- Pool of oil or worn roadway (loss of grip)
- etc.

A.1.4 Hazards due to Personnel (tunnel staff and external services)

- Tunnel operation badly organised
- Personnel not trained
- No special measures implemented even though minimum operating requirements no longer complied with

A.2 Trigger Events

A.2.1 User Hazards

- User taken ill in the tunnel
- Fallen/falling load (partial or total)
- Trailer come uncoupled
- Accident to light vehicle, no one injured
- Accident to two-wheeled vehicle, no one injured
- Accident to HGV, no one injured
- Accident to coach, no one injured
- Accident to light vehicle, person(s) injured
- Accident to motorcycle, person(s) injured
- Accident to HGV, person(s) injured
- Accident to coach, person(s) injured
- Accident to HGV carrying dangerous goods
- Light vehicle fire, no one injured
- HGV fire, no one injured
- Fire involving HGV carrying dangerous goods, no one injured
- Coach fire, no one injured
- Light vehicle fire, person(s) injured
- HGV fire, person(s) injured
- Fire involving HGV carrying dangerous goods, person(s) injured
- Coach fire, person(s) injured
- Booby-trapped car (explosives on board)

- Malicious damage (deliberately destructive acts)
- Vandalism (spontaneous act)
- Terrorist act
- Pedestrian fallen in the roadway (accident or suicide)
- Objects thrown at tunnel portals
- etc.

A.2.2 Hazards arising from the outside physical environment

- Avalanche at tunnel portals
- Falling stones or collapse at tunnel portals
- Earthquake
- Excessively high temperature (vehicles, equipment, etc. overheating)
- etc.

A.2.3 Hazards due to tunnel infrastructures and safety equipment malfunction

- Fall of heavy equipment suspended from the vault (e.g. accelerator)
- Tunnel equipment on fire

A.2.4 Hazards due to personnel (tunnel staff and external services)

- Operator error

A.3 Aggravating factors

A.3.1 User hazards

- Failure to comply with safety instructions in the event of an accident or a fire

A.3.2 Hazards arising from the outside physical environment

- Atmospheric back pressures
- Temperature too low (fire water supply pipe frozen, etc.)
- Pollution from a local industry
- Listed site
- etc.

A.3.3 Hazards due to tunnel infrastructures and safety equipment malfunction

- Footway congestion
- Gutters (& gully holes, etc.) blocked
- Storage tank full or insufficient capacity
- Emergency exits not large enough and too far apart
- Inter-tube passageway opening directly on to the roadway
- Ventilation system malfunction
- CO/NO analyser, opacimeters, anemometer malfunction
- Unprotected air intake
- General power supply failure
- Power supply unit malfunction
- Inverter switchover time overshoot
- Lighting failure
- Dynamic signalling malfunction
- Tunnel closure system malfunction
- Video surveillance malfunction
- Automatic incident detection malfunction
- Emergency call system malfunction
- Fire detection malfunction
- Radio retransmission system malfunction
- Central management system fault
- Fire water tank accidentally drained
- Fire water network failure
- etc.

A.3.4 Hazards due to personnel (tunnel staff and external services)

- Console operator late in detecting an incident
- Console operator late in confirming an incident
- Console operator late in closing the tunnel
- Console operator late in activating the ventilation system
- Console operator late in activating the emergency alarm procedure
- Loss of time due to late arrival of emergency services
- Loss of time in the emergency services' progress in the tunnel
- Emergency vehicle unavailable when needed
- Bad radio communication within the site
- Bad communication between the PC and the site
- etc.

Appendix B Criteria governing the assessment of accident and fire risks

B.1 Incidence of tunnel fires

As regards failures and accidents to equipment and persons, there is no significant difference between journeys in a tunnel and journeys in the open air. So we can take as a basis the standard results for the whole of the road, details of which are not given here (differences between roads and motorways, links with inclines, curves, etc.). Moreover, the consequences of these events are also similar to those occurring in the open air, including the same ease of access for the emergency services (hard shoulders and service entrances, for example).

This is not at all the case with fires.

Tunnel fire statistics can only be based on a small number of occurrences, which makes their use in probability calculations somewhat tricky. Furthermore, fire statistics for the whole of the road network are incomplete as they are not compiled under accident studies (unless a collision was involved or the fire was a major one).

The table below gives typical fire figures per 100 million vehicle-kilometres for each type of vehicle; these are rounded off to simple values with equally simple relations between them.

| | Minimum | Maximum | Non-standard Cases |
|--|---------|---------|--------------------|
| Light Vehicles | 2 | 2 | 2 |
| HGVs and Coaches | 1.5 | 4.5 | 13.5 |
| <i>of which: not brought under control</i> | 0.5 | 1.5 | 4.5 |
| Vehicles transporting dangerous goods | 0.5 | 1.5 | 4.5 |
| <i>of which: not brought under control</i> | 0.2 | 0.6 | 1.8 |

The figures applied for light vehicles do not depend on the nature of the tunnel.

Figures for HGVs depend to a great extent on the nature of the tunnel. Minimum figures are obtained in motorway and/or urban tunnels with no special access ramps; maximum figures on somewhat difficult motorway journeys (steep inclines and curves) and on trunk roads and in non-standard cases in tunnels with access routes that put a particular strain on the vehicle.

The figure to be applied to a particular tunnel is fixed during the specific hazard investigation according to the characteristics of the tunnel and its access route.

Fires described as not brought under control are fires that the users were unable to extinguish by themselves and which may have destroyed the vehicle and its load completely. There is only an overall figure for the incidence of these fires, irrespective of their size.

Of the fires shown in the table above, only a small proportion involve fires breaking out following a collision. The few data available would suggest that these fires account for about one fire in thirty for all vehicle categories. The table below shows the figures for fires occurring as the result of a collision per 100 million vehicle-kilometres.

| | Motorway | Road |
|--|-----------------|-------------|
| Light Vehicles | 0.07 | 0.2 |
| HGVs / Coaches | 0.05 | 0.15 |
| Vehicles transporting dangerous goods | 0.02 | 0.06 |

In the case of a spontaneous fire, the driver's reflex action will be to try to get out of the tunnel. If the tunnel is sufficiently short, he will usually manage to do this. Consequently, the figures given above have to be adapted to short non-urban (and not usually congested) tunnels. On the assumption that if the fire occurs at less than 200 metres from the exit the driver will not stop the vehicle in the tunnel, the correction factor is $(1 - (200/L))$, where L is the length of the tunnel in metres. This means, for example, dividing the figure by three for a 300-metre tunnel, and by two for a 400-metre tunnel.

In the case of fires resulting from a collision, no correction is made for short tunnels¹. The probability of the collision involving several vehicles, or of a spontaneous fire spreading to several vehicles, will depend mainly on traffic conditions and not on the length of the tunnel.

Fire incidence calculation

The annual incidence of the fires in a tube is obtained by multiplying the figures (i.e. the values given above multiplied by 10^{-8}) by the number of vehicle-kilometres per year ($365 \times \text{AADT}^*/\text{tube}$, where L is the length in kilometres). Given the dispersion of the AADT* figures, there are very large frequency differences between one tunnel and another (at least 0.001 for HGV fires alone).

* Annual Average Daily Traffic

¹ Indeed accidents occur more frequently at the start or end of a tunnel than in the centre.

B.2 Severity-Event Matrices

So as to simplify analysis and base it on quantitative elements it may be decided to use a severity-event matrix data representation method. If so, a few standardised elements are suggested below.

Severity classes

The consequences for personal safety in the tunnel and its environment fall into five classes of severity (minor injuries, serious injuries, death). These classes are subdivided in the table below.

| Degree of severity | |
|---------------------|---|
| I Minor or none | Material damage |
| II Significant | Slightly injured persons |
| III Critical | Seriously injured persons or < 5 fatalities |
| IV Catastrophic | > 5 to < 50 fatalities |
| V Major catastrophe | > 50 fatalities |

The specific hazard investigation does not include material damage to the tunnel, the nuisance to traffic caused by tunnel repairs, or the number of vehicles destroyed.

Classes of frequency

Six classes of frequency of event will be used (A to F). These are shown in the table below. **The designations "frequent", "rare", etc. used refer to a class of frequency specific to the family of tunnel events and not to an absolute scale.**

As a rule, the various events involving the transport of dangerous goods, with the exception of fires, will be grouped under a single class (usually F). A more detailed analysis of their frequency is made in the QRA* model (for further information, see **Booklet 3**).

* Quantitative Risk Assessment

The matrix resulting from the above severity and frequency classes is shown below.

| | I Minor or None | II Significant | III Critical | IV Catastrophic | V Major Catastrophe |
|------------------|--------------------------------|---------------------------|-------------------------|----------------------------|------------------------------------|
| A Very frequent | | | | | |
| B Frequent | | | | | |
| C Occasional | | | | | |
| D Rare | | | | | |
| E Very rare | | | | | |
| F Extremely rare | | | | | |

An overall quantitative index of criticality, cross-linking frequency and severity classes and applying a quantified weighting to each class (A, B, etc., I, II, etc) should not be drawn up as it would be arbitrary.

The severity-event matrix analysis is done at the hazard identification stage, i.e. prior to examination of the scenarios. Therefore it is impossible to determine the class of severity of a trigger event with any accuracy. Besides, it is not the purpose when examining the scenarios, which concerns only a small number of cases, to define the classes of severity. The matrices should only be used to do the spadework on the choice of trigger events selected as the points of departure of the different scenarios.

Notes

Appendix C Standardisation of source terms: fires and dangerous goods

In the technical instruction of 25 August 2000, the source terms in regard to fire are expressed in levels of power (MW). For road vehicles, the working party applied the principle of defining the energetic and chemical temporal approaches to standardised source terms for 8, 15, 30, 100 and 200 MW, these being regarded as reasonable.

C.1 Overall Assumptions

C.1.1 Fire Development

The development of the fire is assumed to be rapid (the upper bound assumption for testing the strength of the equipment and the organisation as well as the possibilities regarding user evacuation).

For the sake of simplicity, two forms of temporal development have been adopted:

- triangular: most isolated fires (with no spread) fall into this category;
- trapezoid: this type of fire can develop in the following situations:
 - vehicle fire that spreads more or less rapidly to other vehicles;
 - vehicle fire in which the load plays the larger part and somehow imposes its own speed of combustion and the related power;
 - a fire that has developed in under-ventilated conditions (and whose power is limited by the air intake).

C.1.2 Choice of source terms

Our thinking was addressed to the consistency of the following criteria: heat potential, duration of the fire and speed of combustion. More especially, in the case of HGV loads, it is hard to imagine that a fire involving liquid or easily liquefiable products (apart from dangerous goods) could be contained on the trailer bed without any spillage.

Today, fires involving light vehicles have formed the subject of test programmes [3], whereas far less is known about heavy goods vehicle fires. Source terms relating to heavy goods vehicles could therefore be refined for both fires to isolated vehicles and fires spreading from one HGV to another, a situation not examined here.

There are few or no source terms relating to coach fires as there is no up-to-date information on the heat potentials to be considered.

C.2 Standardised terms: specific hazard investigations

The table below gives the standardised source terms recommended for use in specific hazard investigations from an energy point of view.

| P_{\max} (MW) | t_m (min) | t_{\max} (min) | t_d (min) | Air Flow required for P_{\max} (m ³ /s) | Energy Released (MJ) | Figure No. |
|--------------------|----------------|---------------------|----------------|--|----------------------------|------------|
| 8 | 5 | 25 | 20 | 4.8 | 18,000 | 3 and 4 |
| 15 | 5 | 60 | 15 | 9 | 63,000 | 8 |
| 30 | 5 | 0 | 45 | 18 | 50,000 | 9 |
| 30 | 10 | 50 | 30 | 18 | 125,000 | 10 |
| 100 | 10 | 60 | 20 | 60 | 450,000 | 12 |
| 200 | 10 | 60 | 30 | 120 | 960,000 | 13 |

The power curve figures are grouped together at the end of Appendix C.

The principal criteria governing the chemical effects are also given:

Oxygen consumption : 1 kg of O₂ per 13.1 MJ
CO₂ production : 0.1 kg/s of CO₂ per MW
CO production : [CO₂] / [CO] = 25 for well ventilated fires
[CO₂] / [CO] = 5 for under-ventilated fires

If necessary, a special study of the production of other toxicants could be made.

C.2.1 Energy aspects

The heat potentials of the different vehicles considered (and their loads if applicable) have been updated. Combustion is assumed to be complete.

C.2.1.1 Source terms applicable to passenger cars

Isolated passenger cars:

- Small cars with a heat potential of 6000 MJ [3] (see Figure 1).
- Large cars and people carriers with a heat potential of 12,000 MJ [3], hereafter referred to as large cars (see Figure 2).

Passenger cars, fire spreading, standardised source term 8 MW:

- 1 small car, fire spreads to 2 small cars, time 0 + 5 min and 0 + 15 min (see Figure 3).
- 1 large car, fire spreads to 1 small car, time 0 + 10 min (see Figure 4).

In both cases the heat potential is 18,000 MJ and the power of the fire is in the region of 8 MW.

Tourist vehicles, fire spreading:

There are two cases here, which consider first a large car fire that spreads to another large car ($t_0 + 5$ min) and then the same fire that spreads to a small car ($t_0 + 10$ or $0 + 15$ min). Maximum power in these cases is 15 MW (see figures 5 and 6).

C.2.1.2 Source terms applicable to a loaded van

The van is assumed to be carrying a load (1200 kg – load area 6 m²). Two cases are assessed:

(a) Air-filled load: Cellulose Products:

Heat potential 33,000 MJ (vehicle 9000 MJ, load 24,000 MJ). The air-filled load gives a high speed of combustion (~ 120 g/m².s) (see Figure 7).

*(b) Flammable liquid load packed to prevent spillage (6 m² fire), **standardised source term 15 MW:***

Heat potential 63,000 MJ (vehicle 9000 MJ, load 54,000 MJ). Combustion speed ~ 60 g/m².s (surface fire) (see Figure 8).

These two fires can produce a power of 15 MW, with the duration of the fire varying according to the nature of the load. The second case is taken as the standardised source term.

C.2.1.3 Source terms applicable to an HGV (not carrying dangerous goods)

The large goods vehicle consists of a tractor and a semi-trailer. The nature of the load (10 tonnes) varies. The estimated heat potential of the tractor and semi-trailer is 50,000 MJ (tractor 7000 MJ, 500 litres of diesel 18,000 MJ and 25,000 MJ for the semi-trailer (including 12 tyres).

*(a) Fire involving a small HGV or an unladen HGV, **standardised source term 30 MW peak***

The fire lasts slightly less than one hour, with a very short 30 MW peak power value. The heat potential is 50,000 MJ (see Figure 9).

*(b) Fire involving an HGV, **standardised source term 30 MW***

HGV carrying, for example, fruit and vegetables (9 tonnes) + packing (1 tonne). At the onset of the fire, the load dictates the course of the fire, in which it gradually plays an increasingly large part. The heat potential is 125,000 MJ and the fire has a plateau power value of 30 MW. This case has been selected as standardised source term (see Figure 10).

(c) Fire involving an HGV carrying a highly combustible load (air-filled cellulose materials):

Here, the load imposes its own combustion speed (120 g/m².s) and the power of the fire can be as high as 100 MW. The heat potential is 330,000 MJ (50,000 MJ for the HGV and 280,000 for the load) and the fire has a plateau power of 100 MW (see Figure 11).

(d) Fire involving an HGV carrying a liquid or easily liquefiable load with a high heat potential, standardised source term 100 MW:

In this case, the power of the fire, with no spillage, is an estimated 60 MW with the fire lasting more than 2 hours (area ~ 30m² – combustion speed 50 g/m².s). This hypothesis is not accepted as the trailer would lose its integrity and there would be at least partial spillage. The power of the fire will in fact depend on the size of the overall pool of liquid created. As regards determining the standard source terms, we shall take a power plateau of 100 MW (i.e. a total area on fire of 50m²) for a total heat potential of 450,000 MJ (see Figure 12).

C.2.1.4 Fuel tanker, standardised source term 200 MW

The HGV carrying dangerous goods consists of a tractor and a 20,000 tonne fuel tanker trailer. The heat potential is in the region of 960,000 MJ, and the power applied in the standardised source term is 200 MW, which is that of a surface fire of some 80m² (see Figure 13). Provided there is sufficient air supply, extremely powerful fires (a larger pool of fuel) should be regarded as likely. Conversely, the power of the fire may be limited due to insufficient oxygen for combustion.

C.2.2 Toxic gases and smoke

A fire in a ventilated confined space may be characterised by the effects described below; the extent to which they are dangerous is assessed from the point of view of the users and the emergency services.

Lack of oxygen:

The source terms are based on Thornton's principle, whereby combustion giving off 13.1 MJ equals the consumption of 1 kg of oxygen.

NB: the air flow required in order to generate maximum power is based on an oxygen consumption value of 45% of the oxygen from the fresh air (hypothesis given in the DSC/DR draft guide of 213 August 1999 [4]).

CO₂ production

The records of some overall hydrocarbon combustion reactions (C₇H₁₆, for example) and oxygenated plastic materials (C_{11.4}H₁₄O_{2.22} polyester, for example) give respective production values of 67 g/s of CO₂ for 1 MW and 85 g/s of CO₂ for 1 MW. The combustion of wood (CH_{1.7}O_{0.72}

gives a theoretical production of 102 g/s of CO₂ for 1 MW. The hypothesis chosen is 100 g/s of CO₂ for a fire of 1 MW, that proposed by the DSC/DR draft guide [4]; this value is slightly upper bound for a large number of materials and substances.

CO production

Taking the values listed by Tewarson [1] for the different (well ventilated) tests:

$$\text{Mineral oil: } R = \frac{([\text{CO}_2])}{([\text{CO}]_{\text{vol}})} \approx 38$$

Oxygenated plastic: R ~ 13

Rigid polyurethane: R ~ 24

For **well ventilated fires**, we propose to assign an R value of 25. However, in the case of under-ventilated fires, and on the basis of Ineris's experience [2], the R value taken is 5.

Specific toxicity

The specific hazard investigations include a survey of the traffic and the environment. Whenever required, and more particularly in the case of HGV traffic, an examination should be made of the specific nature of certain loads that are not necessarily classed as dangerous goods, such as synthetics (vinyl polychloride and the production of hydrochloric acid, polyurethane and the production of hydrocyanic acid and nitrous oxides, etc.). The frequent transport of such products should come under a special source term in a specific hazard investigation. More especially, the production of harmful products such as HCl, HCN, NO_x and SO₂ would then need to be defined.

C.2.3 Opacity

The opacity of the smoke in the tunnel can be determined by the relation¹:

$$K = 83,000 C_{\text{CO}_2} / T_g$$

| | | |
|-------------------|--|--------------------|
| K | Coefficient of extinction | [m ⁻¹] |
| T_g | Temperature of the gaseous mixture at a point in the tunnel | [K] |
| C_{CO_2} | Volumetric fraction of the CO ₂ at the same point (m ³ of CO ₂ / m ³ of mixture) | [-] |

The range of visibility is then given as follows:

$$d = C/K$$

where C is a coefficient that depends on lighting conditions and contrast with the object concerned. C is usually taken as somewhere between 2 and 6.

C.3 Bibliography

[1] A. TEWARSON, "Generation of Heat and Fire Products", Technical Report, Factory Mutual Research, May 1995

[2] G. MARLAIR, J.P. BERTRAND and S. BROHEZ, Use of the ASTM E 2058 Fire Propagation Apparatus for the Evaluation of Under-ventilated Fires, Fire and Materials 2001. San Francisco (USA), January 2001

[3] CEC Agreement 7210 – SA/211/318/518/620/933, Development of Design Rules for Steel Structures subjected to Natural Fires in Closed Car Parks, Draft Final Report, Profil Arbed (L), Université de Liège (B), CTICM (F), TNO (NL), Labein (E), March 1997

[4] Projet de Guide DSC/DR, Incendies dans les tunnels routiers: objectifs et hypothèses en matière de désenfumage et de comportement au feu, CETU, octobre 1999

C.4 Figures

Shown below are the development curves of the power released as a function of time for different types of fire. The curves in respect of O₂ consumption, CO₂ production, CO production and opacity emission are inferred directly from the power curves using the factors of proportionality given in paragraphs C.2.2 and C.2.3.



Figure 1

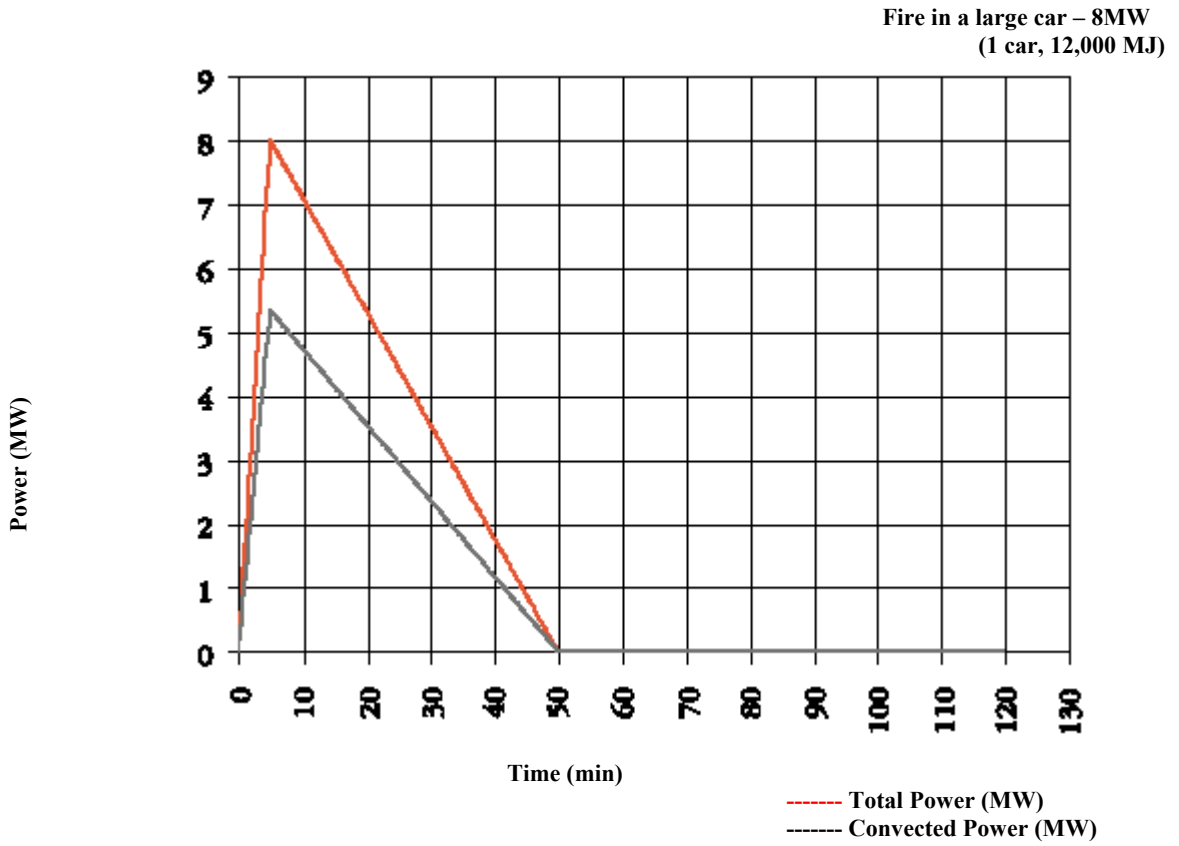


Figure 2

Standardised Curve

**Fire in three small cars - Propagation $t_0 + 5$ and $t_0 + 15$ minutes
(3 cars, 18,000 MJ)**

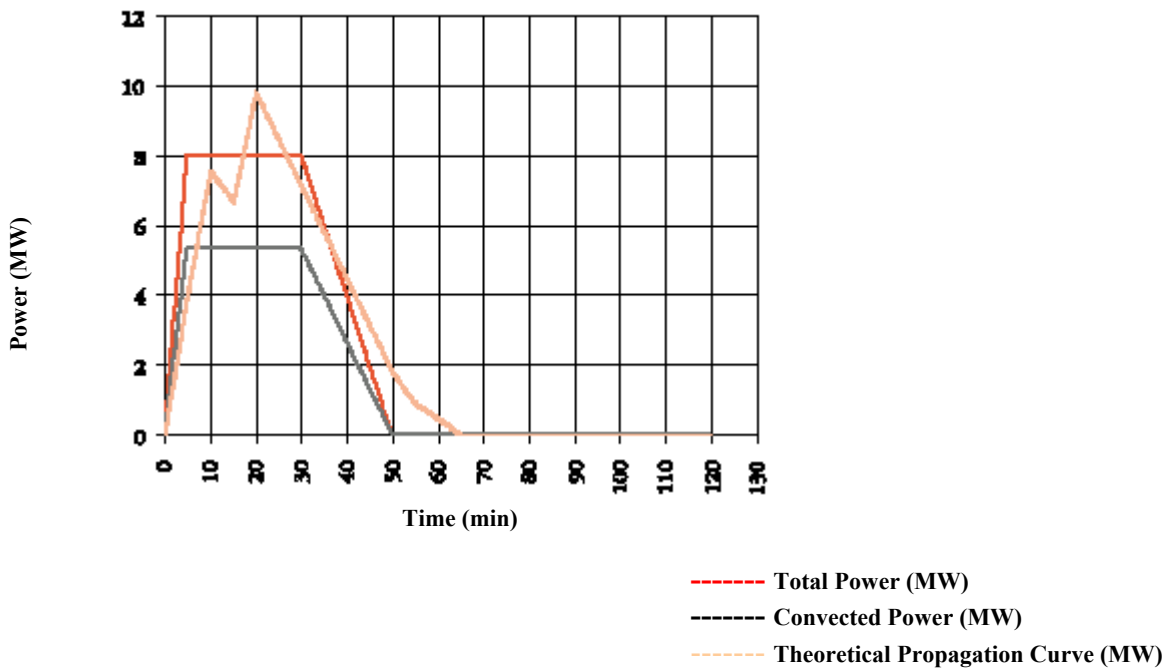


Figure 3

Standardised Curve

Fire in A large car followed by fire in a small car
in 10 minutes (2 cars, 18,000 MJ)

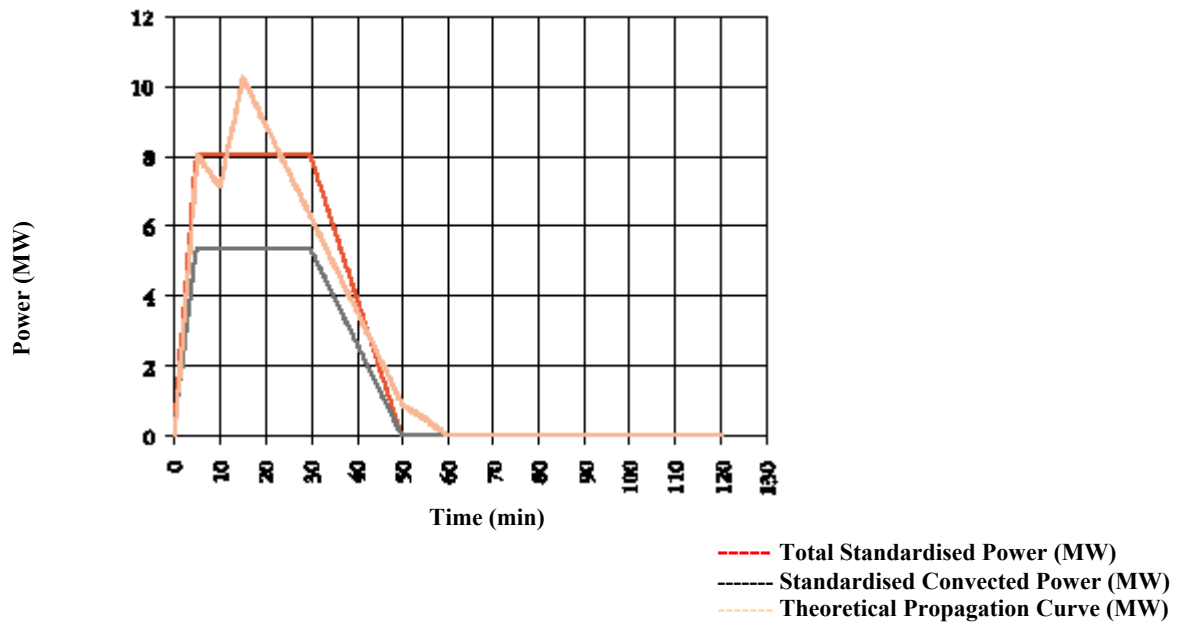


Figure 4

Fire in three cars (two large, one small) propagation $t_0 + 5$
and $t_0 + 10$ minutes

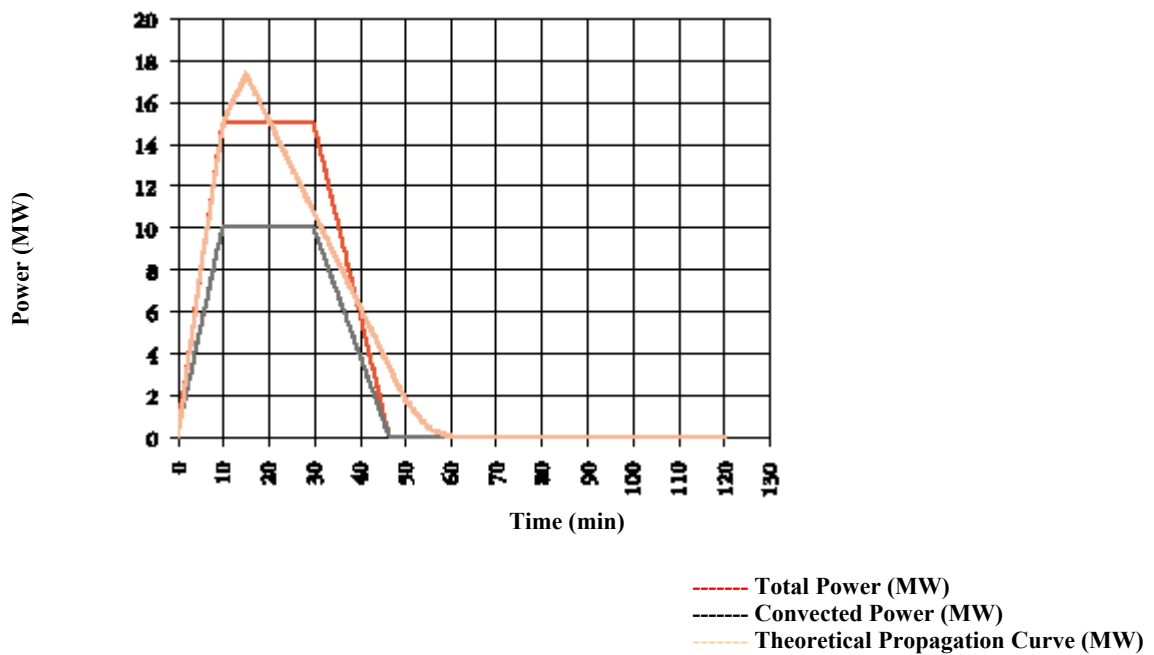


Figure 5

Fire in three cars (two large, one small)
propagation $t_0 + 5$ and $t_0 + 15$ minutes

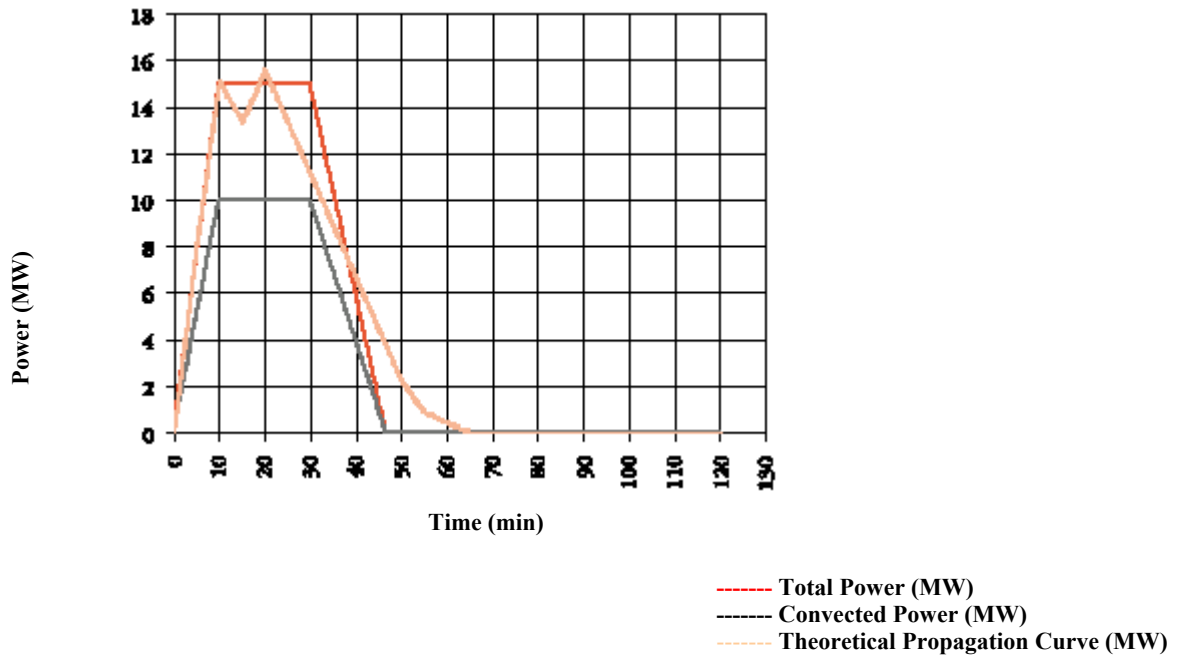


Figure 6

Fire in lorry carrying wood
(1 lorry, 33,000 MJ)

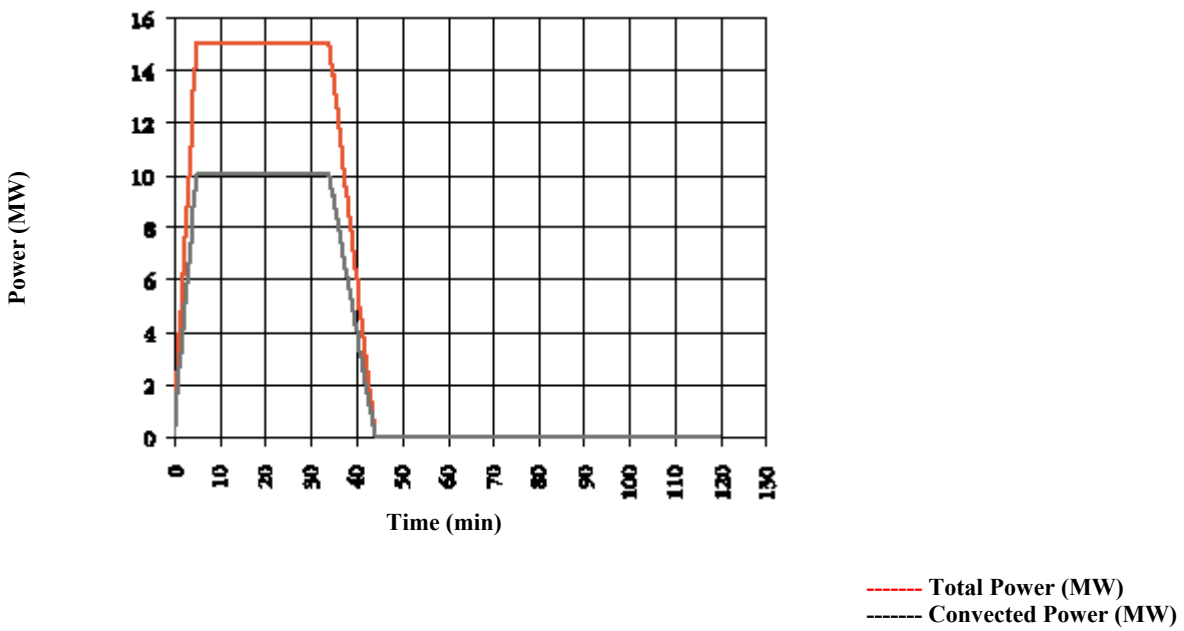
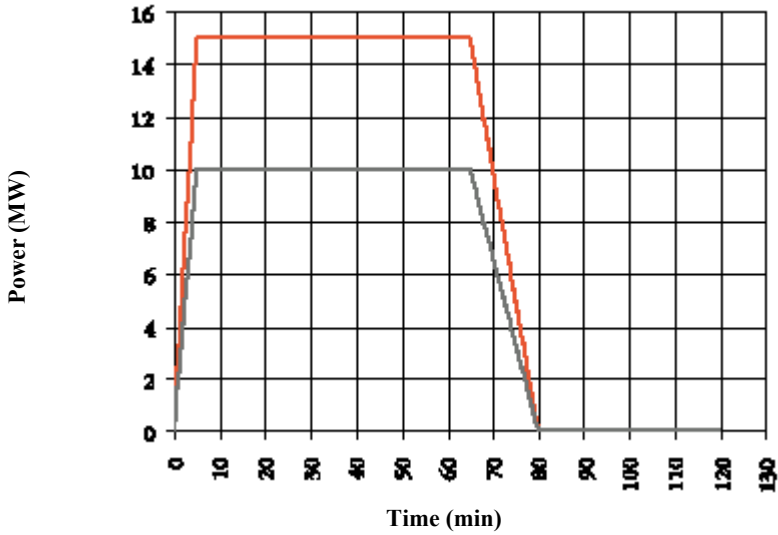


Figure 7

Standardised Curve

Fire in lorry carrying combustible liquid
(1 lorry, 63,000 MJ)

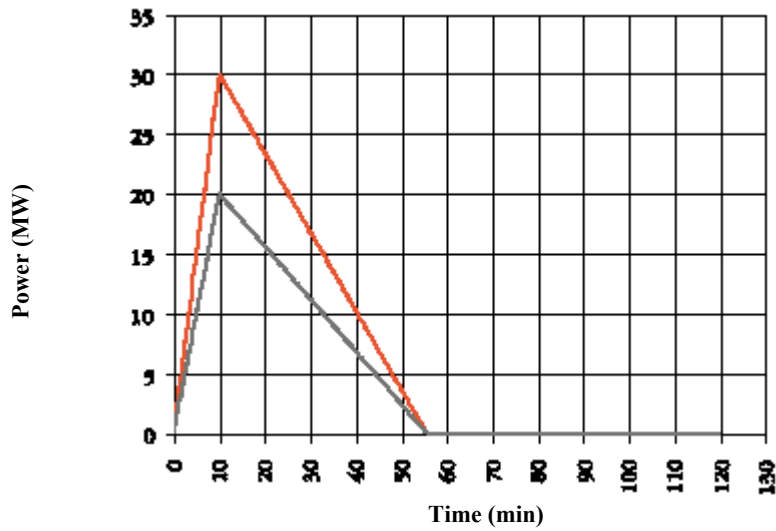


----- Total Power (MW)
----- Convected Power (MW)

Figure 8

Standardised Curve

Fire in unladen HGV or small HGV
(1 HGV 35t, 50,000 MJ)



----- Total Power (MW)
----- Convected Power (MW)

Figure 9

Standardised Curve

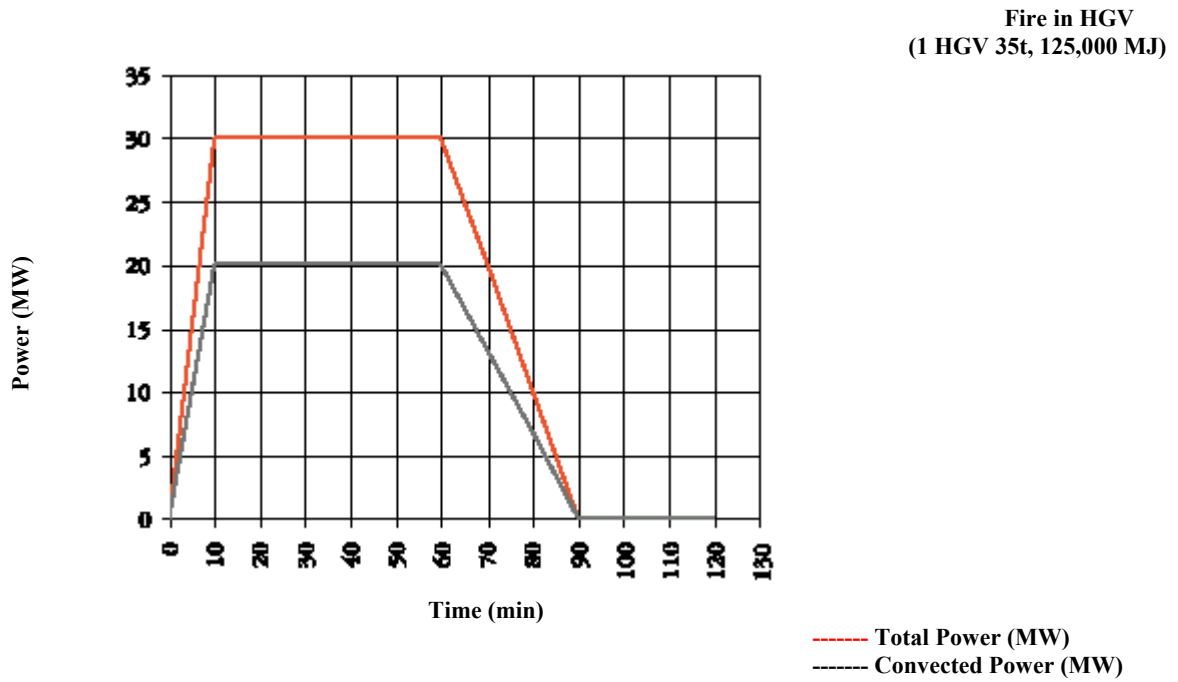


Figure 10

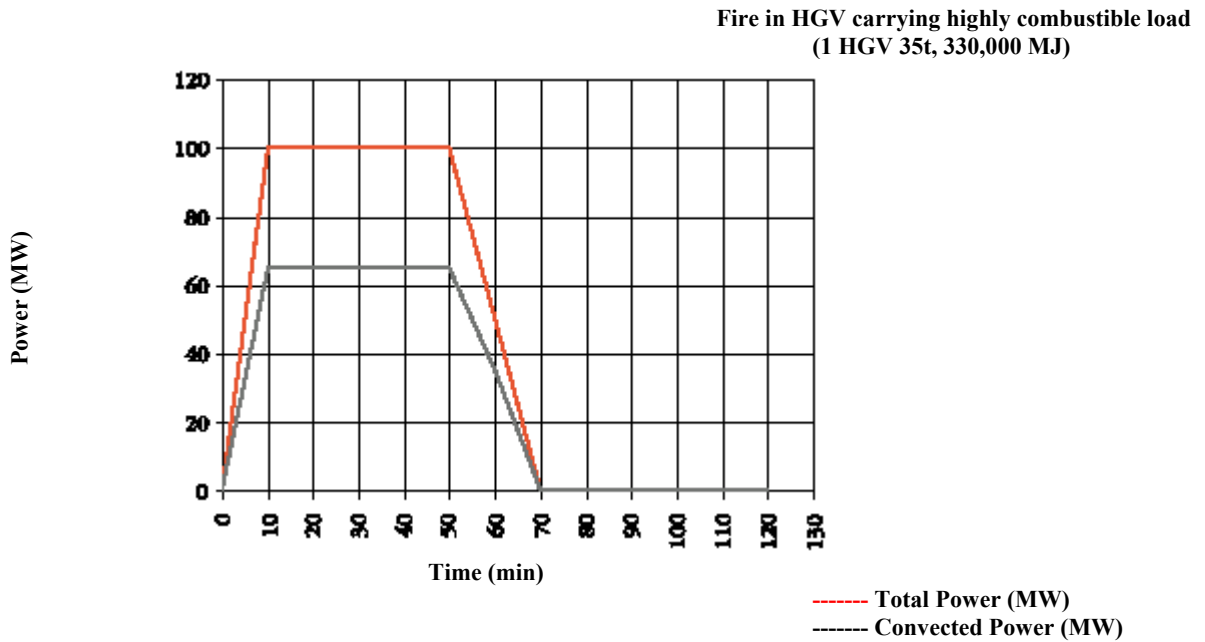


Figure 11

Standardised Curve

Fire in HGV carrying 10 tonnes of combustible liquid (excl. dangerous goods) (1 HGV 35t, 450,000 MJ)

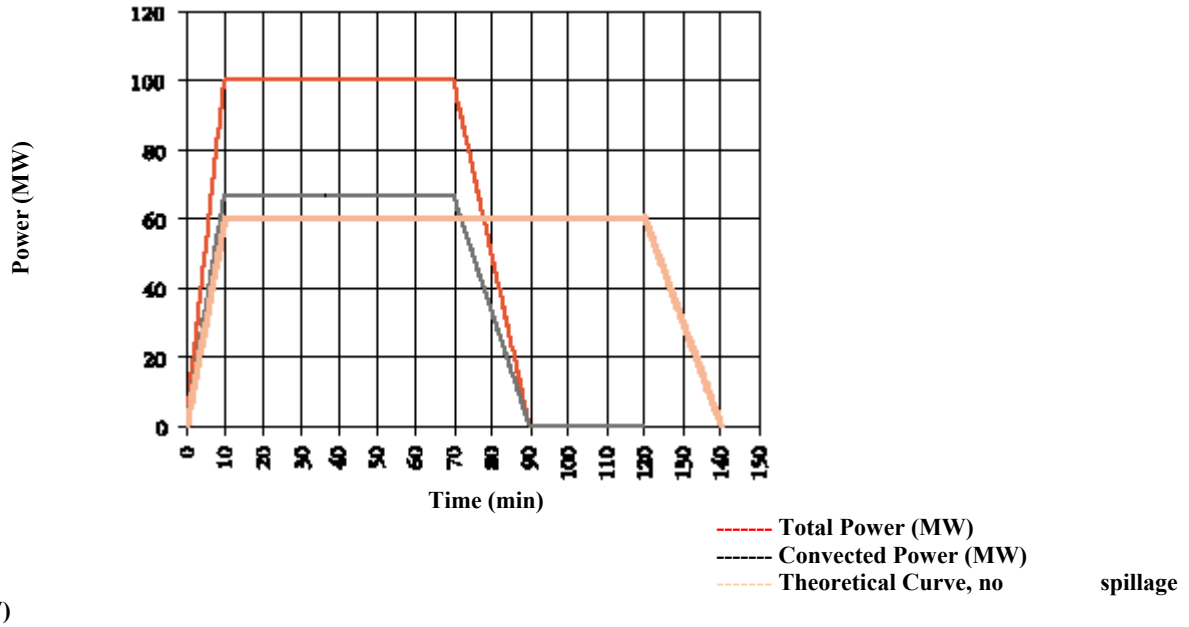


Figure 12

Standardised Curve

Fire in HGV carrying 20 tonnes of flammable liquid (1 tanker, 960,000 MJ)

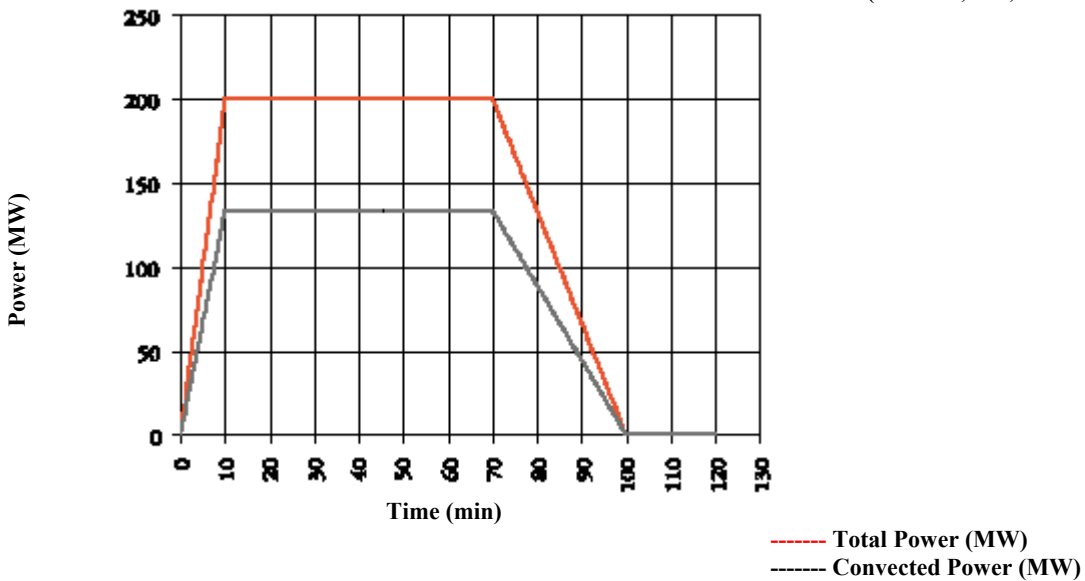


Figure 13

Appendix D Smoke movement modelling specifications

D.1 Description of smoke movement

Smoke movement from a fire in a tunnel is influenced by a number of factors, in particular the geometry of the tunnel, the difference in atmospheric pressure between the two tunnel portals (known as counter pressure), ventilation control, the characteristics and location of the fire, the air displacement caused by the vehicles, the chimney effect, heat losses at the tunnel walls, etc.¹

These phenomena are governed by the following physical equations:

- the mass balance equation;
- the heat balance equation;
- the amount of momentum balance equation (scalar or vector depending on the number of dimensions);
- the pollutant transport equation.

Because of the numerous phenomena involved and the complexity of the equations, numerical models are usually used. That said, in many cases the most basic elements can be determined without the need for a complicated model, by means of a few simple equations. These equations are used not only to obtain orders of magnitude before using models, but also to make a critical interpretation of the results provided by the models. This appendix starts by describing these simplified methods and then goes on to discuss the numerical models used to describe the movement of the smoke.

D.1.1 Temperature calculation

With a strong longitudinal air flow, the smoke is forced on only one side of the fire and it is easy to calculate the average temperature for one section just downwind of the fire. When the flow is completely destratified, this temperature is in fact the maximum temperature the air could reach away from the flames.

The thermal power of the fire Q_{tot} is dissipated by direct radiation on to the tunnel walls and by convective transfer in the air in the tunnel. The power transferred by air convection Q_c may be taken as equal to around two-thirds of the total power given off Q_{tot} .

¹ For further details on the physics of tunnel fires and the equations describing this type of problem, the reader may refer to the section on ventilation in the tunnel pilot dossier and to the CAMATT software user instructions, available at the Tunnel Studies Centre (CETU).

The average air temperature immediately downwind of the fire can be formulated as follows:

$$T_{max} = \frac{Q_c}{\rho_o C_p A V_o} + T_o$$

| | | |
|----------|--|--|
| Q_c | Convective power of the fire | [W] |
| ρ_o | Fresh air density | [kg.m ⁻³] |
| C_p | Specific heat at constant air pressure | [J.kg ⁻¹ .K ⁻¹] |
| A | Cross-sectional area of the tunnel | [m ²] |
| T_o | Fresh air temperature | [°C] |
| V_o | Fresh air velocity | [m.s ⁻¹] |

The longitudinal evolution of the temperature downwind of the fire is then expressed as follows:

$$T(x) = T_\infty + (T_{max} - T_\infty)e^{-x/x_e} \quad \text{where} \quad x_e = \frac{C_p \rho_o V_o}{4h_{app}} . D_H$$

| | | |
|------------|--|---------------------------------------|
| x | Curvilinear abscissa from the fire | [m] |
| D_H | Hydraulic diameter of the tunnel | [m] |
| T_∞ | Temperature in the surrounding rock at some distance from the tunnel | [°C] |
| h_{app} | Apparent heat exchange coefficient | [W.m ⁻² .K ⁻¹] |

The apparent heat exchange coefficient h_{app} includes the convective and radiative transfers at the tunnel walls and the heating up of the walls as a function of the time elapsed since the fire started. As a general rule, the values applied for the apparent heat exchange coefficient are between 10 and 50 W.m⁻².K⁻¹. The table below shows the very conservative values applied in the *Ventilation* section of the tunnel pilot dossier.

| Air Current Velocity | 15 min | 60 min | 120 min |
|----------------------|---------------------------------------|---------------------------------------|--------------------------------------|
| 3 m/s | 10 W.m ⁻² .K ⁻¹ | 7 W.m ⁻² .K ⁻¹ | 6 W.m ⁻² .K ⁻¹ |
| 4 m/s | 14 W.m ⁻² .K ⁻¹ | 10 W.m ⁻² .K ⁻¹ | 7 W.m ⁻² .K ⁻¹ |

Critical velocity is defined as the velocity of the air on the foreside of the fire such that there is no backlayering of the smoke when it meets the main direction of the air flow in the tunnel. The critical velocity depends chiefly on the thermal power of the fire and the slope and cross-sectional area of the tunnel. Danziger and Kennedy's formula² is the one most widely used.

² Danziger N.H. AND Kennedy W.D., 1982. Longitudinal Ventilation Analysis for the Glenwood Canyon Tunnels. In 4th Int. Symp. on the Aerodynamics and Ventilation of Vehicle Tunnels, pp. 169-186, BHRA Fluid Engineering.

This formula uses the following two coupled relations, which can be reduced to a few iterations:

$$V_c = 0.61K_p \left(\frac{gQ_c H}{\rho_o C_p A T_f} \right)^{1/3}$$

$$T_f = \frac{Q_c}{\rho_o C_p A V_c} + T_o$$

| | | |
|----------|--|--|
| A | Cross-sectional area of the tunnel | [m ²] |
| C_p | Specific heat of the air | [J.kg ⁻¹ .K ⁻¹] |
| g | Gravitational acceleration | [m.s ⁻²] |
| H | Height of the tunnel | [m] |
| K_p | Slope coefficient Varies from 1.0 (no slope) to 1.23 (slope 1 in 10) | [-] |
| Q_c | Convective power of the fire | [W] |
| T_o | Air temperature on foreside of the fire | [K] |
| T_f | Temperature of the smoke mixture at the fire | [K] |
| V_c | Critical velocity | [m.s ⁻¹] |
| ρ_o | Air density on the foreside of the fire | [kg.m ⁻³] |

D.2 Models

D.2.1 - 1D Models

1D models resolve fluid mechanics equations by assuming that the physical parameters (velocity, temperature, pressure and concentration) are all uniform in the section (see CAMATT software user instructions, available at the Tunnel Studies Centre). More particularly, a 1D model provides no direct information on the layering of the smoke.

The existing 1D models offer different modelling levels. They do not all take account of either the transient or the thermal effects. Some are permanent isotherm, others transient isotherm, still others transient anisotherm models. We shall only be considering the CAMATT or equivalent transient anisotherm models unless simpler models will suffice. Whatever the model used, when showing the calculations, the different simulation parameters used must be specified; for example, the input/output portal loss coefficients applied, the roughness of the walls, the aerodynamic characteristics of the vehicles used to calculate air displacement, the accelerator efficiency factor, how section changes and heat exchanges at the walls are dealt with, and so on.

The advantage of 1D models lies in their flexibility, which makes it possible to examine a large number of scenarios and multiply the variants to be examined at low cost.

Additionally, they always provide valuable information to assist understanding of the tunnel's air flow mechanisms, including transverse-ventilated tunnels (and especially those comprising several ventilation sections). They also enable ventilation response time to be accurately assessed. Concerning these last two points, 1D models are usually more effective than 3D models.

These models are especially well suited to the study of longitudinal ventilation. With other ventilation systems, using them requires more expertise. For example, a 1D model cannot reproduce the phenomenon of backlayering that occurs when air current velocity is below critical velocity. The temperature provided by a 1D model, which represents a temperature that is assumed to be uniform throughout the section, includes no data on the conditions required for personal survival or on the maximum temperatures reached at the top of the section, or even on the average temperature when air velocity is virtually nil next to the fire³.

Thus interpretation of the results obtained with a 1D model is based chiefly on rational analysis of the air velocities calculated⁴, which is essential to the specific hazard investigation.

D.2.2 - 3D Models

Here, the models used to resolve fluid mechanics equations on a 3D calculation grid are referred to as CFD (Computational Fluid Dynamics) models⁵.

The use of these models requires fairly advanced knowledge of numerous realms of physics (fluid mechanics, thermodynamics, heat transfer, radiation and combustion). Progress continues to be made in the modelling of a number of physical phenomena, which means keeping well abreast of recent developments; this applies among other things to turbulence, combustion and radiation models. Consequently, using these models for very powerful fires, on which there is little in the way of confirmatory experimental data, is not without its risks. That the results obtained in regard to backlayering or stratification are realistic is far from certain. And this is an aspect that always needs to be clearly argued when analysing the results provided by the calculation code.

³ Temperatures above 1000°C are to be interpreted cautiously, in both the very hot sections and the adjacent sections.

⁴ We know, for example, that with air velocities above the critical velocity the model provides reliable and realistic results. When air velocity is below critical velocity, a stratified surface layer develops upwind of the fire. We also know that when air current velocity is low (less than 1.5 m/s), flow downwind of the fire is very likely to be stratified.

⁵ It will be noted that these models are not usable in 2D when there is a longitudinal air current, as the structure of the flow is strongly three-dimensional in the area of the fire.

User training plays an important part in the quality of the results obtained. It is generally felt that a postgraduate qualification in CFD modelling or an equivalent qualification is required. The user must also be familiar with the particular calculation code s/he is using, and ideally will have considerable experience of modelling the problems of smoke extraction in road tunnels. The results obtained from one user to another and from one calculation code to another can in fact vary appreciably, even in the case of industrial quality codes. The reason is that the CFD models require detailed input data (initial calculation conditions, limit conditions, especially the turbulent and dissipation energy levels, representation of the fire, the representation of immobilised vehicles, heat exchanges at the walls, and so on). The different assumptions and approximations applied when defining the calculations greatly influence the results. A further point calling for considerable expertise is assessing the convergence of the calculations. Indeed, compliance with the criterion of convergence is no guarantee that the computer model has converged to a physically plausible solution: that is usually due to excessive numerical viscosity, itself linked to the choices made, explicitly or otherwise, by the user.

Moreover, major computer resources are needed, with some simulations requiring very long calculation times on workstations. The scope of calculation is necessarily limited and the 3D modelling of a tunnel section of 1 kilometre is currently regarded as a reasonable limit. For longer tunnels, the 3D calculation has to be combined with a 1D calculation (or failing that the input/output limit conditions of the section have to be established using the results provided by a 1D code).

Each stage of simulation calls for the appropriate quality procedure, using, for example, the guide published by ERCOFTAC⁶.

D.2.3 Choice of the Relevant Modelling Level

The factors to be considered when deciding on the level of complexity of the smoke modelling are the smoke extraction strategy employed, the user evacuation plan and whether or not the scenario concerned is covered by the design of the tunnel. The lessons that hopefully will be drawn from the simulation also have a major influence on the choice.

Deciding on the level required, except for special cases, could initially be based on the cross-section of the tunnel in question:

- for three-lane tunnels or less, with a standard vault height, 1D modelling is sufficient. In fact,

⁶ Special Interest Group on "Quality and Trust in Industrial CFD" – Best Practice Guidelines, ERCOFTAC, January 2000; see websites <http://imhefwww.epfl.ch/ERCOFTAC/> and <http://www.qnet-cfd.net/>

when the tunnel uses a longitudinal ventilation system, 1D modelling is clearly the most appropriate. In the case of long tunnels using a transverse-ventilation system, the 1D model is the only one capable of modelling the system in its entirety, hence of checking air current limitation in the area of the fire;

- For tunnels whose vault height is more than 7 to 10 metres, and with four or more traffic lanes, or which have complex underground interchanges, three-dimensional CFD simulation is probably more appropriate: it can show that the tunnel is less hazardous than would be shown by 1D simulation in which by definition smoke fills the whole section.

In principle, there is nothing to prevent using a CFD tool in relatively simple cases. On the other hand, **where a CFD model is used for the specific hazard investigation, a preliminary 1D calculation always has to be made and interpreted.** This makes it possible to determine the right initial and limit conditions to be applied in the CFD calculation. The results of the 1D model also provide useful information and help to interpret the CFD results. **The specific hazard investigation must always include an appendix enabling an assessment to be made of its degree of realism.** The purpose of the following paragraph is to suggest a typical plan for this appendix.

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D.3 Typical outline of the "Three-dimensional calculations" appendix

An appendix showing the three-dimensional calculations and the assumptions made must be included in every specific hazard investigation using models of this type. The information given must be sufficiently detailed in the case of at least one of the scenarios examined, preferably one involving the power of a fire for which the literature contains sufficient feedback to assess the degree of realism of the simulation.

The appendix should include the elements listed in the typical outline below. Although this is a long list, the checks it requires are part of the good practices governing the use of CFD models, and the engineering and design offices usually perform these checks in-house. Thus the appendix is simply a question of incorporating into the specific hazard investigation the elements needed to complete it; in this way, the reader will understand the assumptions applied to the simulation.

1. Physical modelling principles

Assumptions concerning the nature of the simulated flow patterns.

Variables included.

Equations resolved, turbulence model, principles of wall modelling, buoyancy terms included.

Details of any radiation or combustion models used.

2. Principles of resolution

Numerical solutions in time and space, resolution algorithm, time increments used, convergence criterion applied.

3. Scope of calculation

Dimensions of the tunnel section represented, cross-sectional dimensions, description of any geometric simplifications introduced into the modelling.

Description of the grid⁷: longitudinal view, transverse views in different sections (next to the fire, jet fan, extraction vent, etc.), total number of grid points, number of grid points in a section, grid size at the walls.

⁷ Grid definition is one of the first sources of variability in the results of a CFD code. The grid has to be refined in the area of the fire, near the calculation area entrance and exit, next to the ventilation equipment (accelerators, smoke extraction access panels, blower openings), next to the walls (for compliance with the criteria governing the application of the principles of walls). A score or so of meshes in the height of the tunnel is the minimum required if it is hoped to reproduce smoke stratification with any accuracy. Ideally, a sensitivity test should be included in a scenario, using 2 grids with different levels of refinement. This last point is not compulsory, merely recommended.

4. Choice, description and explanation of assumptions

Entrance/exit conditions at the tunnel portals.

Nature of the boundary conditions used: pressure, mass flow rate, velocity, etc.

Variations over time of the values assigned to the different variables.

Indication of the levels of turbulence when required.

Explanation of the values chosen (on the basis of the results provided by a 1D model, etc.).

Representation of the vehicles (say whether or not the air displacement and immobilisation by the vehicles is taken into account, and if so, how).

Representation of the fire⁸.

Representation of any jet fans (modelling by meshing the accelerator or for information on the amount of movement and turbulence, for example).

Representation of the smoke extraction and fresh air injection vents (say whether blowing is reproduced by modelling each of the openings or if distribution per unit length is used).

Wall roughness.

Wall heating if taken into account. If not, why not?

Analysis and Presentation of Results

Results of the calculations used to examine the hazards:

- criterion applied to determine smoke stratification characteristics;
- method of calculating visibility;
- model used to calculate the radiated power experienced by the users.

Additional outputs describing the degree of realism of the simulation:

- details of flow patterns (direction, velocity, turbulence variables) in addition to the temperature/concentration profiles at key moments;
- vertical concentration profiles at significant locations (e.g. emergency exits);
- average source of heat temperature;
- extent of the area of combustion, where a combustion model is used;
- any other factor deemed necessary by the engineering and design office.

⁸ In reality, little is known about the influence of a fire on smoke stratification. In fact, not all fires produce stratified smoke layers. Fires of very low power can produce smoke that is not very hot, thus a low buoyancy force. On the other hand, turbulence caused by the combustion at the fire can destratify the smoke, even under favourable air flow conditions (weak longitudinal air current). Therefore, the manner in which the fire is represented in the numerical model greatly influences the results. Ideally, a sensitivity test should be included in a given scenario, by means of two calculations using different but physically plausible representations of the fire. This last point is not compulsory, merely recommended.

Appendix E User behaviour modelling specifications

This appendix gives the elements required for modelling user behaviour, both in their vehicles and on foot.

E.1 Lines of cars

It is essential to have a model simulating the formation of lines of cars for evaluation of the number of cars in the tunnel, hence the number of users in the tunnel and the influence of the traffic on smoke movement (air displacement). The model suggested here has deliberately been much simplified so as not to conceal the numerous unknowns in this sort of problem.

E.1.1 Traffic flowing smoothly

When the traffic is flowing smoothly, continuously and evenly, then $I = V/D$ and $N = L/I$, and thus $N = (L*D)/V$, where:

I is the distance in metres between moving vehicles (front bumper to front bumper);

V is the speed in metres per second;

D is the flow for a given lane in vehicles per second;

N is the number of vehicles present in the tunnel in one lane;

L is the length of the tunnel in metres.

For safety, the interdistance should be $I > I^*$, the safe distance between vehicles, which in turn depends on average vehicle length and vehicle speed V. In France, the formula applied¹ is $I^* = 8 + 0.2 V + 0.003 V^2$, with V in km/hour. When $I < I^*$, congestion is considered likely.

It is important to note that the highest rate of traffic flow does not mean the greatest number of vehicles present in the tunnel. For example, in the case of a single-tube one-way tunnel (two lanes) having a length of 1200 metres, the figures per lane are as shown in the table below.

| | V (km/h) | I* (m) | I (m) | D (veh./h) | N (veh.) |
|------------------------------|----------|--------|-------|------------|----------|
| Traffic moving freely | 70 | 40 | 47 | 1500 | 30 |
| Heavily congested | 50 | 26 | 26 | 2000 | 46 |
| Heavily congested | 20 | 13 | 13 | 1500 | 92 |

¹ M. Cohen, INRETS. This formula is based on an average vehicle length of 8 metres. Strictly speaking, one could adjust average length to the composition of the traffic specific to the tunnel, but apart from special cases in regard to the flow and lengths of HGVs, this is unnecessary for a calculation which anyway is approximate (no account taken of the influence of the nuisance caused by HGVs, etc.).

E.1.2 Tailbacks

When a fire breaks out, it is assumed that the traffic is completely immobilised in the vicinity of the fire at the moment $t = 0$, at a distance d from the tunnel entrance (expressed in metres) and that tailback extends back at v metres per second. This speed will be calculated by the approximate formula $v = D/(1/I(0) - D/V)$, where $I(0)$ is the standardised interdistance when stationary, which will be taken as equal to 10 metres (average length of 8 metres + a gap of 2 metres between vehicles). The tailback extends back as far as the tunnel entrance in a time $T = d/v$. T is then compared with the time required to close the tunnel.

The speed at which the tailback extends back also determines the probability of a pile-up at the end of the line, so with the tailback moving back at a speed of more than 15 km/hour, it is generally felt that control by the patrol cars would be impracticable and the risks high.

In the previous example, two lanes theoretically at saturation point with 3000 vehicles an hour travelling at 70 km/hour, the tailback would be growing at the rate of 5.3 metres/second, or 20 km/h. With a fire occurring in the middle of the tunnel, the tailback would extend back to the entrance in less than 120 seconds – less than two minutes.

E.2 User evacuation

To simulate the movements of the users who leave their vehicles and walk to the emergency exits, the following highly simplified model is used:

- average time taken to evacuate a vehicle completely: 1.5 minutes for a car or HGV, 5 minutes for a coach;
- Walking speed:
 - 1 m/s with good visibility;
 - 0.5 m/s if visibility is seriously impaired;
 - 0.3 m/s if visibility is nil² (only applies to users who are walking in the right direction, because when visibility is nil some users may well be walking into danger without realising it. For practical purposes, it may be assumed that on average 50% of the users do in fact walk in the right direction).

To calculate the number of users, a single average vehicle occupation rate (excluding coaches) of 1.5 persons is applied for all tunnels.

² Walking blindfold, see PIARC (World Road Association) 1999

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At the request of the CESTR, the CETU set up a working party to put together a guide intended for all persons to whom road tunnel safety documentation applies.

The working party was made up of representatives from the CETU, the land transport department's dangerous goods transport unit (DDT-MTMD), the national industrial environment and hazards institute (INERIS), of owners and operators, some members also belonging to the CESTR. The scientific management centre of the École des Mines in Paris provided methodological and operational assistance to the working party.

The working party's activities were based chiefly on a detailed analysis, conducted by the Docalogic Inflow engineering and design office, of the methods of organising and the content of specific hazard investigations carried out on a number of typical road tunnels in France.

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Guide to road tunnel safety documentation:

Booklet 0: Safety documentation objectives

Booklet 1: Practical method of compiling the safety documentation

Booklet 2: Tunnels in operation: "From the existing condition to the reference condition"

Booklet 3: Comparative risk analyses

➤ **Booklet 4: Specific hazard surveys)**

Booklet 5: Emergency response plans

As a key document in the safety documentation, the specific hazard investigation views the tunnel as a comprehensive system comprising the users, the tunnel itself with its facilities and environment, the operator and the maintenance, repair and emergency services.

This booklet is designed to provide assistance with the specific hazard investigation, both to those directly involved in the decisions taken in regard to tunnel safety and to the relevant engineering and design offices.

The CETU (Centre d'Etudes des Tunnels / tunnel study centre) set up the working party which compiled this booklet in response to the express request of the CESTR (Comité d'Evaluation de la Sécurité des Tunnels Routiers / road tunnel safety assessment committee).