Safety in Tunnels

TRANSPORT OF DANGEROUS GOODS THROUGH ROAD TUNNELS

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LA SÉCURITÉ DANS LES TUNNELS
Transport de marchandises dangereuses dans les tunnels routiers

FOREWORD

Managing the risks involved with transporting dangerous goods through road tunnels has presented serious problems in many countries. Finding solutions to these complex problems required varied scientific experience and strong financial support that was not available in any single organisation or country. For these reasons, the OECD's Road Transport and Intermodal Linkages Research Programme and PIARC's Committee on Road Tunnels launched a joint research project based on terms of reference approved by both organisations. The European Commission also provided substantial contributions to the project.

The following tasks were carried out by the research group:

- Review current national and international regulations.
- Develop a system for international use as a common reference for harmonised tunnel regulations.
- Examine the risk assessment and decision processes in current use and develop tools to improve these processes.
- Review risk reduction measures and evaluate their effectiveness to improve safety according to tunnel and traffic characteristics.

ABSTRACT

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This report provides a comprehensive package covering both regulatory and technical issues concerning the transport of dangerous goods through road tunnels. The report proposes harmonised regulations to facilitate compliance by road transport operators and enforcement, thus improving safety. A quantitative risk assessment (QRA) model has been developed as part of the research which compares the risks of transporting dangerous goods through a tunnel to using an alternative route. A decision support model (DSM) was also developed as part of the research which allows decision makers to combine the results from the QRA with other relevant data (which are not of a scientific or technical nature but rather of a subjective or political nature). The DSM will help the decision-maker to determine the preferred route for the transport of dangerous goods or upgrades to existing tunnel infrastructure and other measures required to meet safety objectives. Finally, the report details the effectiveness of measures that can be taken to reduce the risks of incidents in tunnels.

Field classification:
Economics and administration, design of tunnels, traffic and transport planning, traffic control, road safety devices.

Field codes:
10, 25, 72, 73, 85

Keywords:
Accident, accident prevention, classification, cost, damage, danger, decision process, evaluation (assessment), fire, freight, infrastructure, legislation, planning, repair, risk assessment, safety, specification, transport, tunnel.

TABLE OF CONTENTS

Executive Summary and Recommendations 7

- Proposed regulations 7
- The quantitative risk assessment model (QRAM) 9
- The decision support model (DSM) 10
- Risk reduction measures 11
- Recommendations 12
- Expected benefits 14

Chapter 1 Introduction 15

- Objectives 15
- Organisation and funding of the project 15
- Structure of the report 16

Chapter 2 Information on Previous Large Tunnel Fires 19

- Findings 19
- Conclusions 21

Chapter 3 Review of Current National and International Regulations 23

Chapter 4 Harmonised Groupings of Dangerous Goods Loadings 27

- Objectives of harmonised regulations 27
- General principle of the groupings 27
- Proposed grouping system 28
- Conclusions concerning the grouping system for dangerous goods loadings 32

Chapter 5 The Quantitative Risk Assessment Model (QRAM) 33

- Problem description 33
- Purpose 33
- Indicators 34
- Accident scenarios 36
- Evaluation of accident probability 38
- Determination of physiological consequences, structural and environmental damage 40
- Evaluation of consequences in open sections and tunnel sections 43
- Escape/sheltering possibilities 45
- Sensitivity analysis 46
- Validation process 47

Chapter 6 The Decision Support Model (DSM) 49

Definition of the decision problem 50
DSM inputs 52
Survey and choice of decision support methodologies/tools 52
The DSM computer program 53
Recommendations 55

Chapter 7 Risk Reduction Measures 57

Objectives and contents 57
Identification of the risk reduction measures 58
The effectiveness of native risk reduction measures 67
Effectiveness of "non-native" risk reduction measures related to accident probabilities 72
Assessment of the "non-native" risk reduction measures related to response times 77
Concluding remarks 83

References 84

Glossary 85

Annex. List of Participants 86

EXECUTIVE SUMMARY AND RECOMMENDATIONS

Road traffic (especially heavy goods traffic) in tunnels has continually increased over many years. In addition, with improving construction techniques, tunnels are an increasingly cost-effective engineering solution in many countries, not simply to cross difficult geographic features, but also to traverse urban areas with minimum local environment impact. While most techniques concerning tunnel construction and safety have been steadily improving, the problems raised by dangerous goods have not yet been dealt with satisfactorily.

A serious incident involving dangerous goods in a tunnel can be very costly in terms of human lives, the environment, tunnel damage and transport disruption. On the other hand, needlessly banning dangerous goods from tunnels may create unjustified economic costs. Moreover, it may force operators to use more dangerous routes – such as through densely populated areas – and thus increase the overall risk.

The rules and regulations for the transport of dangerous goods in tunnels vary considerably among countries and even within countries. The definition of "local rules and regulations", decision taking, responsibility and enforcement are left to local or provincial authorities and politicians, the tunnel owners, or "expert" opinions. For the most part, there are no general rules or regulations that are applicable to all road tunnels at the national level.

The lack of systematic regulation is in part the result of limited tools to assess risks and make decisions. This project is a comprehensive package covering both regulatory and technical issues. A system for international regulations has been devised using a scientific approach. A number of tools have been developed which are needed to decide on the regulations for each specific tunnel.

Proposed regulations

Currently, planning the transport of dangerous goods requires reference to different regulations, each with different lists of loadings which are authorised or banned in various tunnels, assuming that the carrier is even aware of the existence of such restrictions. The regulations are not always well respected, a main reason being that they are difficult to understand and check.

Under the system proposed in this report, authorities are free to set the regulations that are suitable for the tunnel in question. However, the regulations will be expressed in the same way everywhere, referring to the same lists of dangerous goods loadings which are authorised or banned. These common "lists" are called "groupings of dangerous goods loadings" (or more simply "groupings").

The adoption of the proposed system would improve safety because harmonised regulations would be easier to comply with and easier to enforce. In addition, it would facilitate the organisation of international transport and thus eliminate technical barriers to trade and rationalise international transport operations.

Under the system proposed in this report, all dangerous goods loadings would be split into a small number of groupings. This should be done in such a way that all loadings referred to in the same grouping could be accepted together in the same tunnel. The number of groupings must remain reasonably low for the system to be practicable.

The proposed grouping system is based on the assumption that there are three major hazards in tunnels which may cause numerous victims and possibly serious damage to the structure:

- Explosions.
- Releases of toxic gas or volatile toxic liquid.
- Fires.

The main consequences of these hazards, and the efficiency of possible mitigating measures, are roughly as follows:

- *Large explosions.* Two levels of large explosions can be distinguished:
  - *"Very large" explosion*, typically the explosion of a full loading of LPG in bulk heated by a fire (Boiling Liquid Expanding Vapour Explosion – BLEVE – followed by a fireball, referred to as "hot BLEVE"), but other explosions can have similar consequences.
  - *"Large" explosion*, typically the explosion of a full loading of a non-flammable compressed gas in bulk heated by a fire (BLEVE with no fireball, referred to as "cold BLEVE").

  A "very large" explosion ("hot BLEVE" or equivalent) will kill all the people present in the whole tunnel or in an appreciable length of tunnel and cause serious damage to the tunnel equipment and possibly its structure. The consequences of a "large" explosion ("cold BLEVE" or equivalent) will be more limited, especially regarding damage to the tunnel structure. There are generally no possibilities to mitigate the consequences, particularly in the first case.

- *Large toxic gas releases.* A large release of toxic gas can be caused by leakage from a tank containing a toxic gas (compressed, liquefied, dissolved) or a volatile toxic liquid. It will kill all the people near the release and in the zone where the ventilation (either natural or mechanical) will push the gas. A part of the tunnel may be protected but it is not possible to protect the whole tunnel, especially in the first minutes after the incident.

- *Large fires.* Depending on the tunnel geometry, traffic and equipment, a large fire will have more or less important consequences, ranging from few victims and limited damage to several dozens of victims and serious damage to the tunnel.

The order of these hazards: explosion, toxic release (gas or volatile toxic liquid), fire, corresponds to the decreasing consequences of an incident and the increasing effectiveness of the possible mitigating measures. From the above assumptions, a system with five groupings can be derived, ranked A to E in order of increasing restrictions concerning goods permitted in tunnels:

Grouping A	All dangerous goods loadings authorised on open roads.
Grouping B	All loadings in grouping A except those which may lead to a very large explosion (“hot BLEVE” or equivalent).
Grouping C	All loadings in grouping B except those which may lead to a large explosion (“cold BLEVE” or equivalent) or a large toxic release (toxic gas or volatile toxic liquid).
Grouping D	All loadings in grouping C except those which may lead to a large fire.
Grouping E	No dangerous goods (except those which require no special marking on the vehicle).

Grouping A is the largest category; it contains all loadings which are authorised for road transport, including the most dangerous ones. Grouping E is the most restrictive one, containing only those loadings which do not require a special marking on the vehicle, *i.e.* the least dangerous ones. Further restrictions (such as banning dangerous goods in any quantities) are impossible for authorities to enforce: there is no way for authorities to differentiate loadings in Grouping E (which do not require exterior placards) from vehicles without dangerous goods short of stopping the vehicle for verification. All loadings in Grouping E are included in Grouping D, all loadings in Grouping D are in Grouping C, and so on. These groupings can be the basis for differentiated regulations, for example:

- *Grouping C (6:00 to 22:00) - Grouping A (22:00 to 6:00).* This means that loadings in grouping A and not in grouping C are authorised from 22:00 to 06:00 only, while loadings in Grouping C may be transported anytime.

- *Grouping C (free passage) - Grouping B (under escort).* Loadings in Grouping A and not in Grouping B are forbidden, loadings in Grouping B and not in Grouping C are authorised with an escort only, loadings in Grouping C can go through the tunnel freely.

For mixed loadings of dangerous goods on the same transport unit, the grouping for each type of dangerous goods is identified. For the whole loading, the first alphabetical grouping is used.

The quantitative risk assessment model (QRAM)

Quantification of risk is difficult because numerous factors and variables influence probabilities and consequences of incidents involving dangerous goods both within and outside tunnels. Even with expert knowledge, it is therefore difficult to assess risk for all circumstances, environments, weather conditions, etc. Computer calculations are an indispensable tool for developing a sound rational approach to the problem.

In order to rationally evaluate the risks and set regulations, a comprehensive model is needed to deal with both tunnels and the open road. Due to the complexity of developing such a model, the task was best carried out through international co-operation. The resulting quantitative risk assessment model (QRAM), developed as part of this project, is a unique tool which can be used in all countries.

A complete assessment of the risks involved in transporting dangerous goods would require the consideration of all kinds of dangerous materials, all possible meteorological conditions, all possible incidents, sizes of breaches, vehicles fully or partially loaded and many other variables. Since all circumstances are impossible to consider, simplifications have to be made. The model currently considers 13 accident scenarios which are representative of the groupings described in the proposed regulations. If the groupings permitted in a tunnel change, the possible accident scenarios change. The

QRAM can produce risk indicators for the various groupings and provide a scientific basis for the regulations. The 13 scenarios considered by the model are:

Scenarios representative of each grouping in the QRA model

Grouping E	Heavy Goods Vehicle fire with no dangerous goods (20 MW) Heavy Goods Vehicle fire with no dangerous goods (100 MW)
Grouping D	***In addition to scenarios for Grouping E:*** BLEVE* of Liquid Petroleum Gas (LPG) in cylinders Release of acrolein in cylinders
Grouping C	***In addition to scenarios for Grouping D:*** Pool fire of motor spirit in bulk Vapour Cloud Explosion (VCE) of motor spirit in bulk
Grouping B	***In addition to scenarios for Grouping C:*** Release of ammonia in bulk Release of chlorine** in bulk Release of acrolein in bulk BLEVE of carbon dioxide in bulk (not including toxic effects)
Grouping A	***In addition to scenarios for Grouping B:*** BLEVE of Liquid Petroleum Gas (LPG) in bulk Vapour Cloud Explosion (VCE) of LPG in bulk Torch fire of LPG in bulk

* Boiling Liquid Expanding Vapour Explosion.

** Chlorine is considered in countries where its transport is allowed in appreciable quantities on roads.

The decision support model (DSM)

Decision support methodologies have been studied theoretically for many years and are applied in various fields. A survey and evaluation of proven state-of-the-art decision support tools was carried out, and concluded that there are no shortcuts to making rational decisions for the safe transport of dangerous goods. The various, potentially conflicting, objectives must be subject to a mutual weighting – no matter how delicate it may seem to quantify these objectives and weights. In cases where no formalised decision support tool is used, the weighting is made instinctively.

When making decisions about which groupings are to be permitted in tunnels, decision makers must keep in mind that the goods prohibited in the tunnel must be transported on some alternative route. The risk and inconvenience on the alternative route will directly influence which grouping is the best from a societal point of view. This implies that it might not be rational to give the same grouping to two identical tunnels carrying the same traffic if the alternative routes differ significantly, *e.g.* in terms of length and population density along the route.

One of the primary objectives for the decision on which grouping to permit in a tunnel is to minimise the risk to human life. Apart from the risks to human life, there are several other factors that need to be taken into account when taking a decision on the routing of dangerous goods. The decision process is a complex procedure and a decision support model (DSM) is therefore required to ease and assist rational decision making. The attributes that are evaluated and weighted by the DSM include:

- Injury and fatality risks to road users and the local population using the indicators from the QRAM. The DSM helps the decision maker to weight his concerns (for example, a risk-adverse decision maker considers one incident with 100 fatalities less acceptable than 100 incidents with one fatality in each).

- Material damage due to possible incidents on tunnel or detour route.
- Environmental impact due to an incident on tunnel or detour route. The environmental output from the QRAM is limited, giving only approximate indicators for environmental risk. The DSM can be expanded to accept more detailed environmental information.
- Direct expenses (investment and operational cost of tunnel risk reduction measures as well as possible additional costs in the transport of dangerous goods).
- Inconvenience to road users due to a possible incident (time lost during repair works after an incident in the tunnel).
- Nuisance to local population (environmental impact of dangerous goods traffic, with the exclusion of possible incident consequences, but possibly including psychological impact).

Any other attribute found relevant by the decision maker can also be included in the decision problem. In order to make a decision, the decision maker must determine which attributes are relevant and how these should be weighted against each other. These choices must reflect the preferences of the decision maker.

A computerised tool has been developed, making it possible to take account of the above attributes in a rational manner. The DSM includes the option of choosing between the classical Bayesian decision methodology and multi-attribute methodologies. The DSM utilises the QRAM output directly. Other technical data is used as input, for example, reparation costs following an accident or additional costs for transporting dangerous goods by a longer route. The decision-maker thus has all the technical input and must provide only the policy-based preferences.

Risk reduction measures

There are several measures that can be implemented in tunnels which will reduce either the probability or the consequences of an incident in a tunnel. These will influence the regulations governing the restriction of dangerous goods transport through a tunnel. Extensive studies were carried out to determine the effectiveness of these measures as part of this project.

A number of these measures are included in the QRAM. The model can be used to examine the effects of introducing these measures into a tunnel. In addition, a number of other measures were examined and procedures described which would permit an extension of the existing QRAM to include safety measures that were not part of the original model specification.

Both qualitative and quantitative methods for the analysis of the effects of risk reduction measures are presented in this report. Using the QRAM together with these methods, it is possible to assess the effects of these measures for a given tunnel.

The effects of measures are unique to each tunnel, depending on the traffic characteristics and local circumstances. A general effect of the measures applicable to all tunnels could therefore not be generated. Likewise, the costs of measures vary for each type of tunnel. Costs will also differ considerably if the measures are incorporated during the initial design and building stage compared to the cost of retrofitted measures. The costs are therefore best estimated for each particular tunnel case so that the efficiency or cost effectiveness ratio of the measures can be properly evaluated for the specific case.

List of risk reduction measures classified according to their main purpose

MEASURES TO REDUCE THE PROBABILITY OF AN ACCIDENT		
Related to tunnel design and maintenance		
Tunnel cross section and visual design	Alignment Lighting (normal)	Maintenance Road surface (friction)
Related to traffic and vehicles		
Speed limit Prohibition to overtake	Escort Distance between vehicles	Vehicle checks
MEASURES TO REDUCE THE CONSEQUENCES OF AN ACCIDENT		
Alarm, information, communication of operator and rescue services		
Close-circuit television Automatic incident detection	Automatic fire detection Radio communication (services)	Automatic vehicle identification *Emergency telephone*
Communication with users		
Emergency telephones *Radio communication (users)*	Alarm signs/signals	Loudspeakers
Evacuation or protection of users		
Emergency exits Smoke control	*Lighting (emergency)* Fire-resistant equipment	Failure management
Reduction of accident importance		
Fire-fighting equipment Rescue teams	Drainage *Road surface (non-porous)*	Emergency action plan *Escort*
Reduction of the consequences on the tunnel		
Fire-resistant structure	Explosion-resistant structure	

Recommendations

Implementation of a consistent regulatory and technical framework

The results from this project are applicable in all countries with tunnels. The analysis of risks and the development of decision support tools achieved through this project provide road administrations with options to improve the transport of dangerous goods through road tunnels:

- It is strongly recommended that administrations which allow the transport of dangerous goods through road tunnels *implement the "groupings of dangerous loadings" system as the basis of regulations*. This system should be implemented at both the national and international levels.

- It is recommended that through the adoption of these regulations all tunnels are assigned a category. This will require new *sign-posting*, both at the tunnel approach and alternative routing signs.

- The adoption of the “groupings” system requires a systematic and scientific basis for decision making. To this end, *the QRAM and the DSM* developed as part of the project are currently the state of the art in the field and *are recommended for use in all countries to support the adoption of the proposed groupings system*.

International regulatory framework

As a global body, the United Nations Committee of Experts for the Transport of Dangerous Goods is the most appropriate body to act as the guardian, promoter and developer of this system of groupings. It is *recommended that the system be included in the UN’s Model Regulations and promoted in all regions of the world*. This represents an important mechanism to promote global transport efficiency through the implementation of a consistent and harmonised regulatory framework.

Recognising that the United Nations Committee of Experts for the Transport of Dangerous Goods deals with multimodal regulations, which are non-mandatory, the most viable road specific alternative is the United Nations Economic Commission for Europe Working Party No. 15 on the transport of dangerous goods. This Working Party is responsible for the European Agreement concerning the *International Carriage of Dangerous Goods by Road (ADR)*, which is applied throughout 34 contracting states and which is the basis for national legislation throughout the European Union. However, many non-European states are likely to wish to adopt these regulations and will therefore have a strong interest in how the regulations evolve in the future.

It is *recommended that the relevant United Nations Committee should be charged with developing the signs necessary for the implementation and enforcement of the regulations.*

Model application and development

The quantitative risk assessment and decision support models require extensive inputs and require a sound understanding of the models and their functions. To assist users, the following are recommended:

- A *database on applications* containing all experiences with the QRAM, accessible by Internet. This database should contain the results of all available national runs of the model.
- A *network of experienced model users* who can be contacted if problems cannot be solved by the users themselves.
- Meetings of new *user groups* to be arranged in order to develop further expertise in use of the models throughout the world.

This collection of experiences and results can form a basis for further improvements of the quantitative risk assessment software and the reference manual. The target is to improve the quantitative risk assessment software in a continuous process, involving all users and their experiences.

Expected benefits

This project has focused on the safe transport of dangerous goods by road. It is likely to generate the following benefits to road transport and infrastructure management flowing from the implementation of the recommendations and the adoption of the tools developed:

- Reduction in the cost of damage to road infrastructure arising from possible incidents in tunnels or on detour routes.
- Reduction in the environmental impact due to an incident in tunnels or on detour routes.
- Improvement in network efficiency by implementing consistent and harmonised regulations for the transport of dangerous goods through tunnels.
- Improvement in overall transport efficiency through reduction in the time costs to road users associated with a possible incident (time lost arising from the incident itself, detour routes and during repair works after an incident in the tunnel).
- Increased efficiency in the deployment of funds invested in upgrading/constructing tunnel infrastructure, management systems and risk reduction measures.
- Increased efficiency of road transport operations arising from compliance with regulations and correct routing of vehicles.

Chapter 1

INTRODUCTION

Road traffic (and especially heavy goods traffic) in existing tunnels has continually increased over many years. Also, due to population or environmental reasons, the actual number of road tunnels has grown in many countries. While most techniques concerning tunnel construction and safety have been steadily improving, the problems raised by the transport of dangerous goods have not yet been dealt with satisfactorily.

A serious incident involving dangerous goods in a tunnel can be very costly in terms of human lives, the environment, tunnel damage and transport disruption. On the other hand, needlessly banning dangerous goods from tunnels may create unjustified economic costs. Moreover, it may force operators to use more dangerous routes – such as through densely populated areas – and thus increase the overall risk.

Objectives

The purpose of this research is an overall improvement in the safety of transporting dangerous materials by road. Linked to this is facilitating the organisation of dangerous goods transport and thus preventing unnecessary excess costs and promoting economic development. The objectives are:

- To rationalise and harmonise the decision-making process leading to the authorisation or prohibition of dangerous goods transport in each road tunnel, and the regulations for implementing these decisions.
- To evaluate and improve the measures aimed at reducing the risks due to dangerous goods in road tunnels and optimise their implementation.

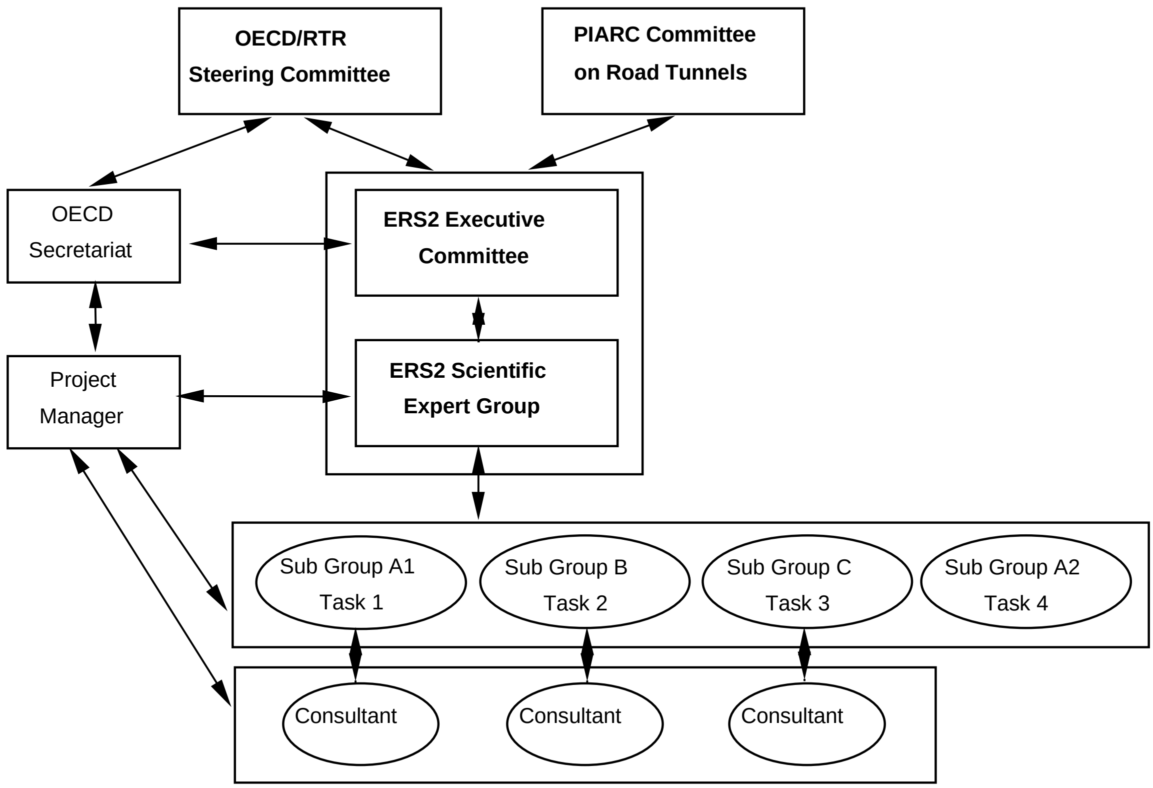
Organisation and funding of the project

Given the complex and extensive nature of this study, it could only be carried out through international co-operation. The project was jointly organised by the OECD and PIARC, with a significant contribution from the European Commission. Twelve countries participated in this study, funding the participation of their experts (see Annex). In addition, eleven countries and the European Commission contributed a total of FRF 5.5 million to fund several research contracts. These countries were Austria, Denmark, France, Japan, the Netherlands, Norway, Sweden, Switzerland, Spain, the United Kingdom and the United States.

Figure 1.1 shows the general structure of the project. The OECD RTR Steering Committee and the PIARC Committee on Road Tunnels (C5) take decisions at the executive level concerning the objectives, initiation, organisation, financing and follow-up of the project. They created an Executive

Committee to oversee the financial and policy issues. The Scientific Expert Group was responsible for the detailed objectives, budget, overseeing consultants work, the general advancement, results and quality control of the research. Four sub-groups were established to deal with the various tasks.

Figure 1.1. **Organisation of the project**



Structure of the report

In addition to the Executive Summary and Recommendations and this introductory chapter, the report has six other chapters:

Chapter 2: Information on previous large tunnel fires

Given the danger that can be caused by fires in tunnels even when they do not involve dangerous goods, a study of 33 large fires in tunnels was carried out and is summarised in this chapter.

Chapter 3: Review of current national and international regulations

Chapter 3 summarises the findings of a study that was carried out in two missions:

- Mission 1 consisted of a wide survey by mail to collect and analyse data from many countries.

- Mission 2 aimed at getting more precise data through in-depth interviews concerning a select number of countries, and examining application (and other) problems to draw a set of conclusions.

Chapter 4: Harmonised groupings of dangerous goods loadings

This chapter discusses proposals for a harmonised system for categories of goods that can pass through tunnels. Adopting such an international system would facilitate regulations for the authorisation or detouring of dangerous goods in road tunnels.

Chapter 5: Quantitative risk assessment model (QRAM)

This chapter presents an overview of a QRAM that was specifically developed to evaluate the risks involved in transporting dangerous goods through tunnels.

Chapter 6: Decision support models (DSM)

Chapter 6 discusses the different types of DSM and specifically presents a DSM which was developed to use the QRAM results and other inputs in order to decide which goods are suitable to pass through a tunnel.

Chapter 7: Risk reduction measures (including transport and tunnel operation)

This chapter examines measures that limit the risks involved in transporting dangerous goods through road tunnels. Measures that are well adapted for each specific case are recommended, with detailed specifications and an evaluation of the costs and effectiveness towards risks.

Chapter 2

INFORMATION ON PREVIOUS LARGE TUNNEL FIRES

Findings

As a part of this project, information on previous large tunnel fires was collected from the OECD countries and South Africa. The information was gathered from publications and through direct contact with tunnel officials. A number of fires took place some time ago (since 1949) and detailed information was therefore difficult to obtain. It was also difficult to obtain all the necessary or wanted information about some other fires.

The study consisted of 33 large tunnel fires involving heavy goods vehicles (HGVs) or multiple car fires. The fires were divided into four groups:

A. Fires involving gasoline (2 fires); gas (1 fire) and carbon bisulphate (1 fire) – 4 fires.

B. Fires involving plastic products and other oil-based products – 7 fires.

C. Fires causing personal injuries (but not A and B) – 11 fires.

D. Other fires involving HGVs, buses and multiple cars – 11 fires.

Details of the fires in groups A, B and C are summarised in Table 2.1. Only four fires of type A were found. They were the fires in the *Isola delle Femmine* tunnel, Italy (gas road tank vehicle), the *Caldecott* tunnel, United States (33 000 litres of gasoline), the *Holland* tunnel, United States (11 tons of carbon bisulphate) and the *Chesapeake Bay* tunnel, United States (2 000 litres of gasoline). Two of the fires started after collisions, one was started by a burning tyre and the fourth was caused by a tank shell falling off a HGV in the tunnel. Twelve persons were killed in the fires and 23 injured (a further 66 suffered damage through smoke inhalation). The fires lasted for more than four hours.

Seven fires of type B were found. Two of these fires were caused by collisions, four were caused by motor problems and one was caused by a burning tyre. In the fires, 12 persons were killed, five were injured and 73 suffered smoke inhalation. Most of the fires lasted for more than one hour.

Eleven fires of type C were documented. Nine were caused by collisions and two by engine problems. Many of the reported injuries were caused by the initial collision before the fire was ignited. In the eleven fires, 77 people were killed and 73 were injured.

In the 33 fires covered by this study (types A to D), 103 persons were killed, 101 persons were injured and 139 persons suffered from smoke inhalation. Eight buses, approximately 200 HGVs, about 150 private cars and 15 other vehicles were destroyed by fire. The following goods burned in the fires, most of which are not classified as goods dangerous in transport or goods causing special problems:

- Bread, margarine and flour, paper (two cases), fish, cycles in carton and plastic bags, soft drinks (two cases), private cars (eight cases), refrigeration truck, cotton.
- Paint (two cases), plastic dust bins, fish oil, polyethylene (two cases), pine resin, polyester fibres.
- Carbon bisulphate, gasoline road tank vehicle (two cases), gas road tank vehicle.

Table 2.1. **Summary of the fires studied**

Fire type	Tunnel name	Country	Tunnel length (m)	Date of fire	Cause of fire	Duration of fire	Goods burned	People killed	People injured
A	Holland	United States	2 567	13.05.1949	Goods	4 hrs	Carbon bisulphate	0	0
A	Chesapeake Bay	United States		03.04.1974	Tyre	4 hrs	Gasoline	0	1
A	Caldecott	United States	1 083	07.04.1982	Collision	3 hrs	33 000 l gasoline	7	2
A	Isola delle Femmine	Italy	148	1993	Collision		Gas road tank vehicle	5	20
B	Tauern	Austria	6 400	29.05.1999	Collision	15 hrs	Paint	12	0
B	Frejus	France	12 870	05.05.1993	Motor	2 hrs	Plastics	0	0
B	Porte d'Italie	France	425	11.08.1976	Motor	45 mins	Polyester	0	0
B	Moorfleet	Germany	243	31.08.1969	Tyre	2 hrs	Polyethylene	0	0
B	Hovden	Norway	1 283	13.06.1993	Collision	2 hrs	Polyethylene	0	5
B	Guadarrama	Spain	2 870	14.08.1975	Gearbox	3 hrs	Pine resin	0	0
B	Blue Mountain	US	1 302	1965	Motor		Fish oil	0	0
C	Pfänder	Austria	6 719	10.09.1995	Collision	1 hrs	Bread	3	0
C	Mt Blanc	France	11 600	24.03.1999	Motor	53 hrs	Margarine, flour	39	0
C	L'Arme	France	1 100	09.09.1986	Collision			3	5
C	Peccorila Galleria	Italy	662	1983	Collision		Fish	9	20
C	Serra Ripoli	Italy	442	1993	Collision	3 hrs	Paper	4	4
C	Kajiwara	Japan	740	17.04.1980	Collision	2 hrs	Paint	1	0
C	Nihonzaka	Japan	2 045	11.07.1979	Collision	4 days		7	3
C	Sakai	Japan	459	15.07.1980	Collision	3 hrs		5	5
C	Velser	Netherlands	768	11.08.1978	Collision	2 hrs	Flowers, soft drinks	5	5
C	Huguenot	South Africa	4 000	27.02.1994	Gearbox	1 hrs		1	28
C	Gumefens	Switzerland	343	1987	Collision	2 hrs		2	3

Of the 33 fires, traffic incidents were the reported cause in 13 cases, all involving more than one vehicle. A vehicle related problem was listed as the primary cause in 18 cases (motor defects: 12, faulty brakes: one, gear box: two, tyres: three). In one case, a tank shell fell off a vehicle and one fire had an unknown cause.

In 20 cases, the fire started in a lorry/HGV/truck, four cases in a bus, three cases in a private car, two cases in a van/camper and in one case, a mobile crane. The fires resulted in the loss of 147 private cars, 200 lorries/HGV/truck/trailer combinations, eight buses, three vans/campers, two road tank vehicles, two fire vehicles and two motorcycles.

The majority of the fires lasted between one and five hours. One fire lasted for more than 53 hours (Mount Blanc, France/Italy) and one for four days (Nihonzaka, Japan).

Of the 33 fires, 18 had taken place before 1990 and 15 in 1990 or later. However, as reporting is likely to have improved during the last ten years, it cannot be said that the number of tunnel fires has increased in recent years. The number of fires in the first and second half of the 1990s was also the same. Of the 22 fires where time of the day was given, 12 occurred between midday and midnight. Ten of the fires took place after 18:00 but before 08:00 in the morning. This is usually counted as a period with low traffic volumes.

Conclusions

It is difficult to draw any clear conclusions with statistical significance based on 33 large tunnel fires. The high proportion of fatalities to injuries compared with other traffic incidents is consistent with the view that fires in tunnels are a specific and serious problem. It should, however, be noted that collisions or traffic accidents cause less than 50% of these fires. Most fires are caused by some kind of technical or electrical problem within the vehicle.

To reduce the number of fires in tunnels, the potential for incidents and accidents needs to be reduced and, where incidents do occur, they should be handled with high expertise as quickly as possible. Many vehicle problems appear to be caused by driving on steep and long slopes often in high altitudes. Three significant measures could be to require all HGVs to be installed with an automatic self-extinguishing device, require regular inspection and to construct resting places at intervals along the road so that drivers could rest their vehicle and allow the engine to cool down.

Many fire reports noted that clear responsibilities and short response times are essential to reduce the consequences of incidents and fires. An emergency plan and training of personnel were advocated in many reports.

It appears that many drivers do not know what to do in case of a fire. Even though most tunnels are equipped with fire extinguishing equipment (extinguishers and fire hydrants), drivers do not know how to use them. Information or education programmes directed at drivers of heavy goods vehicles could be a very effective measure.

The study found that the fire brigades were warned in most cases and the response appears to have been rapid for the most part. The fire fighters also managed to put out most of the fires, even where dangerous goods were involved. An American study of large tunnel fires (Egilsrud, 1984) commented on the use of sprinklers. In the OECD study, only one of the operators asked replied that sprinklers would have been helpful. Only in one case, the Nihonzaka fire, is it documented that sprinklers had been useful; however, in this case the fire re-started after initially being contained.

The Egilsrud report also discusses whether the fire brigade should attempt to extinguish fires of unknown or dangerous goods, given the danger this could pose to fire fighters. Many of the largest fires studied as part of this project involved the burning of goods that are not classified as dangerous. It was expected that fires involving dangerous goods would be more of a problem than this study shows. In the study undertaken as part of this project, only four fires involved fuel oil, gas or other dangerous goods. Other oil-based products such as plastic were involved in seven fires. The remaining fires consumed ordinary products such as paper, flour, flowers, soft drinks, etc. It is important to note that HGVs carry large tanks of diesel fuel, oil and often small propane gas cylinders.

Chapter 3

REVIEW OF CURRENT NATIONAL AND INTERNATIONAL REGULATIONS

One of the first tasks of this project was to review current national and international regulations regarding the transport of dangerous goods through road tunnels. Consultants were employed to systemise the information collected in questionnaires submitted to 24 countries, clarify answers and make recommendations for further analysis work. A total of 22 countries responded, one of which does not have any road tunnels; the analysis was therefore based on information from 21 countries.

Complementary and more detailed information was then collected from nine countries using questionnaires and interviews. These countries included Austria, France, Germany, the Netherlands, Japan, Norway, Switzerland, the United Kingdom, and the United States (State of California). The objective was to examine existing road tunnels and the rules, regulations and policies for transporting dangerous goods through those tunnels. Problems arising from the existing regulations with respect to decision making, enforcement, operation and transport were identified.

This chapter summarises the findings of the two studies, the full reports (OECD and PIARC, 1996, 1997) are available on the Internet and include a database to assist in further analysis of the questionnaire replies.

Definitions of dangerous goods transport by road are almost standardised within many OECD regions. For example, in Europe, the ADR codes (European Agreement on the Transport of Dangerous Goods by Road) are commonly used (or are the basis) for defining the transport of dangerous goods by road. Most states in the United States and provinces in Canada follow codes in compliance with the United Nations Model Regulations. Australia and Japan have their own codes for defining dangerous goods, although Australia is currently aligning with the United Nations system.

In contrast, the rules and regulations for the transport of dangerous goods in tunnels vary considerably among countries and even within countries. Rules and regulations applying to specific tunnels have been devised in a number of countries. The definition, decision making, responsibility and enforcement are left to local or provincial authorities and politicians, the tunnel owners, or “expert” opinions. For the most part, there are no general rules or regulations that are applicable to all road tunnels at the national level.

Frequently, rules and regulations are defined and enforced for tunnels with special characteristics such as underwater tunnels, urban tunnels, those with high traffic density or aged tunnels. The restrictions imposed vary considerably. Among these are: inter-vehicle distance, speed limit, hourly/daily limitations, escorting requirements, mandatory notification of cargo, amount and type of substances, requirements in terms of vehicle and tunnel provisions, etc.

It is notable that countries and/or regions with few tunnels often have more and stricter rules and regulations for the transport of dangerous goods in tunnels than do tunnel-rich countries. For example, in Europe, the Netherlands and the Flemish region of Belgium have strict regulations on all or some dangerous substances, while Norway (575 km of tunnels) and Italy (600 km of tunnels), have few or no restrictions.

In most countries, decisions on whether a tunnel should have restrictions on the transport of dangerous goods, are *not* based on detailed quantitative risk assessments for comparison of risks. However, a number of countries intend to implement this approach in future regulations.

A number of problems arise from existing regulations with respect to decision making, enforcement, operation and transport.

- The practice of authorising many tunnels for the transport of dangerous goods is in contradiction with the rules that prescribe the contrary as a principle.
- The new tendency to base decision making on risk studies is not planned for in present regulations.
- Existing regulations apply only to state-owned tunnels; no regulations exist for tunnels owned by local communities.
- Large variations in restrictions for the various tunnels cause problems for drivers since it is difficult to be aware of the current regulations of each and every tunnel on their route.
- Lack of advanced notification through proper information boards or road signs for dangerous goods traffic is a problem in many countries.
- There is no strict requirement to signal diversion routes if a tunnel is banned/restricted for dangerous goods.
- Some carriers or drivers, in particular from outside the country, are not familiar with restrictions in the tunnels. Information about current restrictions is not systematically submitted at border crossings or found in federal newsletters.
- The restrictions cause heavy vehicles to use streets and roads that are less suited to this kind of traffic.

Many of the problems identified could be dealt with by introducing standardised international road signs, both for dangerous goods restrictions as well as for available diversion routes.

In addition, it is essential that carriers are made aware of the various regulations, for example through broad distribution of the information in official gazettes or newsletters. For foreign carriers, relevant material should be handed over at the border crossings or at toll stations.

There is little or very limited information on how existing regulations are complied with, but infringements are known at least in tunnels with no permanent control. With the exception of tunnels crossing borders, where permanent controls are performed by customs personnel, the level of control is in most cases limited to spot checks (if at all). The problem of infringements or evasions, however, is not considered a serious problem in any of the countries surveyed.

Some countries have identified plans for improvements and modifications of their rules and regulations as follows:

- Transfer of responsibility with respect to decision making and enforcement from a federal to a local level.

- Stricter requirements for proper signing of current regulations at each tunnel and on possible diversion routes.

- Adjusting current regulations so as not to conflict with the regulations for open roads.

- Decisions on restricting or authorising dangerous goods in tunnels should be based on a quantitative comparison of risks using QRA methodology.

- Introduction of more/new requirements in terms of safety provisions and equipment in tunnels which authorise the transport of dangerous goods.

- The regulations should be of a uniform character, *e.g.* they should apply throughout the country, region, county, etc.

- The soaring number and increasing complexity of products manufactured by the chemical industry make it more difficult to decide whether a material is covered by the restrictions or not. This increases the work required for advising carriers and manufacturers of chemicals and enforcing regulations.

This review emphasised the need for this project and provided a useful synthesis of the regulatory system and practices regarding the transport of dangerous goods through tunnels. It is likely that many of these regulations will evolve in the coming years based on the recommendations of this study and other work that emerges.

Chapter 4

HARMONISED GROUPINGS OF DANGEROUS GOODS LOADINGS

Objectives of harmonised regulations

As discussed in the previous chapter, current regulations concerning dangerous goods transport in road tunnels vary from one country to another, and often from one tunnel to another within the same country. This leads to difficulties for carriers. Planning transport journeys requires reference to different regulations, each with different lists of loadings which are authorised or banned in various tunnels, assuming that the carrier is even aware of the existence of such restrictions. The regulations are not always well complied with, a main reason being that they are difficult to understand and check.

Harmonising regulations would meet the following objectives:

- Facilitate the organisation of international transport and thus eliminate technical barriers to trade and rationalise national transport operations.
- Improve safety because harmonised regulations would be easier to comply with and easier to enforce.

This chapter builds on a discussion paper, which was submitted to the interested bodies in charge of international regulations for the transport of dangerous goods. In addition to the OECD and PIARC Committee members, it was circulated among the United Nations Sub-Committee of Experts on Transport of Dangerous Goods, United Nations Economic Commission for Europe Working Party No. 15 on Road Transport of Dangerous Goods and the European Commission Technical Committee on the Transport of Dangerous Goods.

General principle of the groupings

Harmonised regulations do not mean that the same regulation should apply to all tunnels, nor even that two similar tunnels in two different places should have the same regulation. The only indispensable point is that the regulations should be expressed in the same way everywhere, *i.e.* they should refer to the same lists of dangerous goods loadings which are authorised or banned.

These common “lists” are here called “groupings of dangerous goods loadings” (or more simply “groupings”). “Loading” refers not only to the nature of the transported goods, but also whether they are transported in bulk or packaged form and the possible presence of different dangerous goods in the same vehicle (“transport unit” in regulatory terms).

The basis of the proposed system is that the definition of the groupings of dangerous goods loadings should be the same for all tunnels in all countries. The decision-making process would be unaffected by these regulations and would remain the responsibility of the authority in charge of the tunnel (recommendations for the decision process are contained in Chapter 7). However, the decision should result in a regulation based on the dangerous goods groupings decided internationally.

The general idea of the system is to split all dangerous goods loadings into a small number of groupings. This should be done in such a way that all loadings referred to in the grouping could be accepted together in the same tunnel. The number of groupings must remain reasonably low for the system to be practicable.

A system with five groupings (A, B, C, D and E) is proposed, ranked in order of increasing restrictions regarding goods that are permitted in the tunnel. Grouping A is the largest category; it contains all loadings which are authorised for road transport, including the most dangerous ones. Grouping E is the most restrictive one, containing only those loadings which do not require a special marking on the vehicle, *i.e.* the least dangerous ones. Further restrictions (such as banning dangerous goods in any quantities) are impossible for authorities to enforce: there is no way for authorities to differentiate loadings in Grouping E (which do not require exterior placards) from vehicles without dangerous goods short of stopping the vehicle for verification. All loadings in Grouping E are included in Grouping D, all loadings in Grouping D are in Grouping C, and so on. These groupings can be the basis for differentiated regulations, for example:

These groupings can be the basis for more complex regulations, for example:

- Grouping C (06:00 to 22:00) – Grouping A (22:00 to 06:00)

  Grouping C is allowed from 06:00 to 22:00 and grouping A from 10:00 to 18:00, which means that loadings in grouping A and not in grouping C are authorised from 22:00 to 06:00 only, and loadings in grouping C anytime.

- Grouping C (free passage) **-** Grouping B (under escort)

  Loadings in Grouping A and not in Grouping B are forbidden, loadings in Grouping B and not in Grouping C are authorised with an escort only, loadings in Grouping C can go through the tunnel freely.

Proposed grouping system

Main risks in a tunnel

Banning dangerous goods from a tunnel that are authorised in the open can only be justified where the risk of serious accidents (for example, involving numerous victims or unacceptable damage to the tunnel) is greater in the tunnel than in the open. This means that dangerous goods which cannot cause numerous victims nor serious damage to the structure should not be considered for such a decision (for example, liquids which are dangerous by contact only).

The proposed grouping system is based on the assumption that in tunnels there are three major hazards which may cause numerous victims and possibly serious damage to the structure:

- Explosions.
- Releases of toxic gas or volatile toxic liquid.
- Fires.

The main consequences of these hazards, and the efficiency of possible mitigating measures, are roughly as follows:

- *Large explosions.* Two levels of large explosions can be distinguished:
    - *"Very large" explosion*, typically the explosion of a full loading of LPG in bulk heated by a fire (Boiling Liquid Expanding Vapour Explosion – BLEVE – followed by a fireball, referred to as "hot BLEVE"), but other explosions can have similar consequences.
    - *"Large" explosion*, typically the explosion of a full loading of a non-flammable compressed gas in bulk heated by a fire (BLEVE with no fireball, referred to as "cold BLEVE").

  A "very large" explosion ("hot BLEVE" or equivalent) will kill all people present in the whole tunnel or in an appreciable length of tunnel and cause serious damage to the tunnel equipment and possibly its structure. The consequences of a "large" explosion ("cold BLEVE" or equivalent) will be more limited, especially regarding damage to the tunnel structure. There are generally no possibilities to mitigate the consequences, particularly in the first case.

- *Large toxic gas releases.* A large release of toxic gas can be caused by a leakage from a tank containing a toxic gas (compressed, liquefied, dissolved) or a volatile toxic liquid. It will kill all people near the release and in the zone where the ventilation (either natural or mechanical) will push the gas. A part of the tunnel may be protected but it is not possible to protect the whole tunnel, especially in the first minutes after the accident.

- *Large fires.* Depending on the tunnel geometry, traffic and equipment, a large fire will have more or less important consequences ranging from few victims and limited damage to several dozens of victims and serious damage to the tunnel.

The order of these hazards: explosion, toxic release (gas or volatile toxic liquid), fire, corresponds to the decreasing consequences of an accident and the increasing efficiency of the possible mitigating measures.

Description of the system

From the above assumptions, a system with five groupings can be derived:

Grouping A	All dangerous goods loadings authorised on open roads.
Grouping B	All loadings in grouping A except those which may lead to a very large explosion ("hot BLEVE" or equivalent).
Grouping C	All loadings in grouping B except those which may lead to a large explosion ("cold BLEVE" or equivalent) or a large toxic release (toxic gas or volatile toxic liquid).
Grouping D	All loadings in grouping C except those which may lead to a large fire.
Grouping E	No dangerous goods (except those which require no special marking on the vehicle).

In fact, a system with six groupings could be chosen to differentiate between the risks of a large explosion and a large toxic release. However, cold BLEVEs can happen with any non-flammable compressed or liquefied gas transported in bulk, including those which are toxic. For this reason, and in order to limit the number of groupings, it was deemed appropriate to deal with large toxic releases and large (cold BLEVE) explosions in the same grouping.

There are several ways of describing the proposed groupings which would correspond to the above definitions. The most widely recognised, and global, transport classification system is that of the United Nations Committee of Experts Recommendations on the Transport of Dangerous Goods. However, as its Model Regulations are intended to be multimodal, it is easier to utilise the most widely used regional road specific transport regulations, which are based on the UN Model Regulations. This is the European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR). The proposed system of groupings is set out in Table 4.1.

The table shows the proposed permitted dangerous goods, by class, in each grouping of loadings, whether in bulk (tanks/tank containers) or packaging (packages, intermediate bulk containers, large packaging). It is based on the 1999 Annexes to ADR which will remain in use up to 1 January 2003. It uses ADR item numbers (which in due course will be replaced by the four-digit UN substance identification numbers) and utilises ADR "limited quantity" provisions of marginal 10 011 which are mode specific and thus a little different from the limited quantity thresholds in UN Model Regulation Chapter 3.4.

For mixed loadings of dangerous goods on the same transport unit, the grouping for each type of dangerous goods is identified. For the whole loading, the first alphabetical grouping is used.

Consistency with the quantitative risk assessment model (QRAM) and decision support model (DSM)

It is important to ensure consistency between the grouping system and the QRAM and DSM:

- The QRAM must incorporate accident scenarios representative of each of the groupings; if the groupings allowed in a tunnel change, the scenarios taken into account must be different, so that the risk indicators produced by the QRAM may be different and make it possible to discriminate between groupings.

- The DSM must process the results from the QRAM (and other data) in order to propose decisions expressed as the optimal grouping of loadings to be allowed in a tunnel.

Table 4.2 lists the loadings chosen for the development of the QRAM (see Chapter 5). They are representative of the five groupings described above. The DSM considers the various groupings which may be allowed in the tunnel (see Chapter 6).

Table 4.1. **Groupings of dangerous goods loadings to be used in harmonised regulations for road tunnel**

Class	Grouping A	Grouping B	Grouping C	Grouping D	Grouping E
	All dangerous goods permitted to be transported by ADR.	All dangerous goods except those with very large explosion hazard.	All dangerous goods except those with very large explosion, large release of toxic gas or liquid or risk of cold BLEVE hazard.	All dangerous goods except those with very large explosion, large release of toxic gas or liquid or risk of cold BLEVE and large fire hazard.	No dangerous goods above ADR 10 011 threshold.
1	All	Below ADR 10 011 threshold only.	Below ADR 10 011 threshold only.	Below ADR 10 011 threshold only.	Below ADR 10 011 threshold only.
2	All	A, O, T, TC, TO, TOC gases in tanks and cylinders. F, TF, TFC gases in cylinders only.	A, O and F gases in cylinders only.	A, O, F gases in cylinders only.	Below ADR 10 011 threshold only.
3	All	All except 6°, 7°.	All except 6° and 7° and 1°-5°, 31°-34° in tanks/tank containers.	All except 6° and 7° and substances in tanks/tank containers.	Below ADR 10 011 threshold only.
4.1	All	All except 21°-25°, 31°, 32°, 41°, 42°.	All except 21°-25°, 31°, 32°, 41°, 42°.	All PG II and III substances except 21°-25°, 31°-50°.	Below ADR 10 011 threshold only.
4.2	All	All PG II and III substances in tanks/ tank containers. All substances in packages.	All PG II and III substances in tanks/ tank containers. All substances in packages.	All PG II and III substances in tanks/ tank containers. All substances in packages.	Below ADR 10 011 threshold only.
4.3	All	All PG II and III substances in tanks/ tank containers. All substances in packages.	All PG II and III substances in tanks/ tank containers. All substances in packages.	All PG II and III substances in tanks/ tank containers. All substances in packages.	Below ADR 10 011 threshold only.
5.1	All	All PG II and III substances in tanks/ tank containers. All substances in packages.	All PG II and III substances in tanks/ tank containers. All substances in packages.	All PG II and III substances in tanks/ tank containers. All substances in packages.	Below ADR 10 011 threshold only.
5.2	All	All except 1°, 2°, 11° and 12°.	All except 1°, 2°, 11° and 12°.	Below ADR 10 011 threshold only.	Below ADR 10 011 threshold only.
6.1	All	ADR items 11°-28°, 31°-36°, 41°-44°, 51°-68°, 71°-73° and 90° in tanks/tank containers and packaging.	All ADR items in Grouping B in packaging, PG II and III in tanks/tank containers.	All ADR items in Grouping B in packaging PG II and III in tanks/tank containers.	Below ADR 10 011 threshold only.
6.2	All	Items 3°, 4°.	Items 3°, 4°.	Items 2°, 3°, 4°.	Below ADR 10 011 threshold only.
7	All	All.	All except UN Nos. 2977 and 2978.	All except UN Nos. 2977 and 2978.	Below ADR 10 011 threshold only.
	All dangerous goods permitted to be transported by ADR.	All dangerous goods except those with large explosion hazard.	All dangerous goods except those with large explosion, large release of toxic gas or liquid or risk of cold BLEVE hazard.	All dangerous goods except those with large explosion, large release of toxic gas or liquid or risk of cold BLEVE and large fire hazard.	No Dangerous Goods above ADR 10 011 threshold.
8	All.	All.	PG II and III substances in tanks/tank containers. All substances in packages.	PG II and III substances in tanks/tank containers. All substances in packages.	Below ADR 10 011 threshold only.
9	All.	All.	All.	All except item 4 in tanks/tank containers.	Below ADR 10 011 threshold only.

Key: PG = Packing Group; A = Asphyxiant; C= Corrosive; F = Flammable; O = Oxidising; T = Toxic.
Note: Empty uncleaned tanks/tank containers and packaging shall be treated as if full or part-full.

Table 4.2. **Loadings representative of each grouping in the QRAM**

Groupings of loadings	Representative loadings for QRA
Grouping A	LPG in bulk and in cylinders; carbon dioxide in bulk; Ammonia/chlorine[1] in bulk; acrolein in bulk and cylinders; motor spirit in bulk; HGV without dangerous goods.
Grouping B	Carbon dioxide in bulk; ammonia/chlorine[1] in bulk; acrolein in bulk and cylinders; motor spirit in bulk; LPG in cylinders; HGV without dangerous goods.
Grouping C	Motor spirit in bulk; LPG in cylinders; acrolein in cylinders; HGV without dangerous goods.
Grouping D	LPG in cylinders; acrolein in cylinders; HGV without dangerous goods.
Grouping E	HGV without dangerous goods.

1. Chlorine is considered in countries where its transport is allowed in appreciable quantities on roads.

Conclusions concerning the grouping system for dangerous goods loadings

The review of current national and international regulations has clearly identified the need for harmonised regulations concerning transport of dangerous goods through road tunnels. The aim of the proposed system is not to classify tunnels but to provide common lists of dangerous goods loadings (called “groupings”) to which all tunnel regulations would refer. The choice of which grouping should be allowed in a particular tunnel would be left to the authority in charge of the tunnel.

The proposed groupings are based on a rational approach to the risks which can be created by dangerous goods in tunnels. They are consistent with the QRAMs and DSMs developed under the project, so that these models can provide data and make proposals on the choice of the optimal grouping to be allowed in a given tunnel.

It is recommended that this grouping system should be integrated into the international agreements and national legislation dealing with road transport of dangerous goods in order to regulate the transport of dangerous goods in road tunnels. The principles of the groupings should be respected in order to maintain the integrity of the QRAM and the DSM. However, it is envisaged that the United Nations would become the guardians of the system. Regular reviews of the assignment of substances should be carried out in order that minor adjustments might be made in the light of additional QRA studies that may be undertaken. It would be necessary, however, to ensure that any modification of the grouping system was adopted universally and concurrently.

It is an essential element of the system that it is transparent and widely recognised. To this end, each road tunnel should be categorised on the basis of the grouping of loadings permitted through the tunnel. In addition to regulatory notices, toll by-laws, etc., it is recommended that each tunnel be signed to indicate which grouping is permitted to be transported through the tunnel. Establishing such signs is within the competence of the bodies in charge of international conventions on road signage (for example, the United Nations ECE for Europe) who should be charged with developing these signs. Once such a system were adopted, it is anticipated that road maps and other driver information systems might also indicate the groupings of loadings authorised in the road tunnel, thus enhancing journey planning for the carrier.

Regulating road tunnels using a system of groupings of loadings as developed above would also ensure a greater level of compliance. Not only will tunnel operators and carriers be able to utilise a simple and straightforward regime which is accessible and easily understood, enforcement bodies will also be able to carry out random checks on the approaches to tunnels without having to familiarise themselves with complex international agreements or tunnel by-laws.

Chapter 5

THE QUANTITATIVE RISK ASSESSMENT MODEL (QRAM)

The transport of dangerous goods through tunnels implies special risks to road users, physical structures, environment and people residing near tunnels or detour roads. Transport authorities have to decide whether dangerous goods transport is permitted on certain routes or not. If permitted, the safest and most practical manner for transporting these dangerous goods has to be decided. QRAMs can assist decision makers by providing risk estimates that are both accurate and objective for different types of dangerous goods, tunnels and transport scenarios.

Problem description

Risk is characterised by two aspects:

- Occurrence probability of an event.
- Consequences of an occurring event.

Quantification of risk is difficult due to the fact that probabilities for traffic accidents are low (the probability of an accident with dangerous goods is even lower). However, the consequences of such an accident can be enormous. Numerous factors and variables influence the probabilities and consequences of accidents involving dangerous goods both within and outside tunnels. Even with expert knowledge, it is therefore difficult to assess risk for all circumstances, environments, weather conditions, etc. Computer calculations are an indispensable tool to develop a sound rational approach to the problem.

QRAMs have been used for many years to estimate the risk of dangerous good movements for different transport conditions on the open road. Some OECD Member countries (the Netherlands, Norway and, to a certain extent, France), also developed QRAMs for road tunnels. There was a need, however, for a comprehensive model to deal with both tunnels and the open road. Due to the complexity of such a model, this was best carried out through international co-operation. The result is a unique tool which can be used in all countries.

Purpose

The purpose of the QRAM is to quantify the risks due to transport of dangerous goods on given routes of the road system. A comparison of one route including a tunnel with an alternative route in the open can be made. The QRA model was developed based on the following components:

- Indicators.
- Accident scenarios.

- Evaluation of accident probability.
- Determination of physical consequences, structural and environmental damage.
- Evaluation of consequences on humans (open and tunnel sections).
- Uncertainty/sensitivity analysis.
- Validation.

The QRAM methodology is as follows:

- Choose a small number of representative goods.
- Select a small number of representative accident scenarios involving these goods.
- Determine the physical effects of these scenarios (for open road and tunnel sections).
- Determine the physiological effects of these scenarios on road users and local population (fatalities and injuries).
- Take into account the possibilities of escape and sheltering.
- Determine the associated probabilities of occurrence.

Indicators

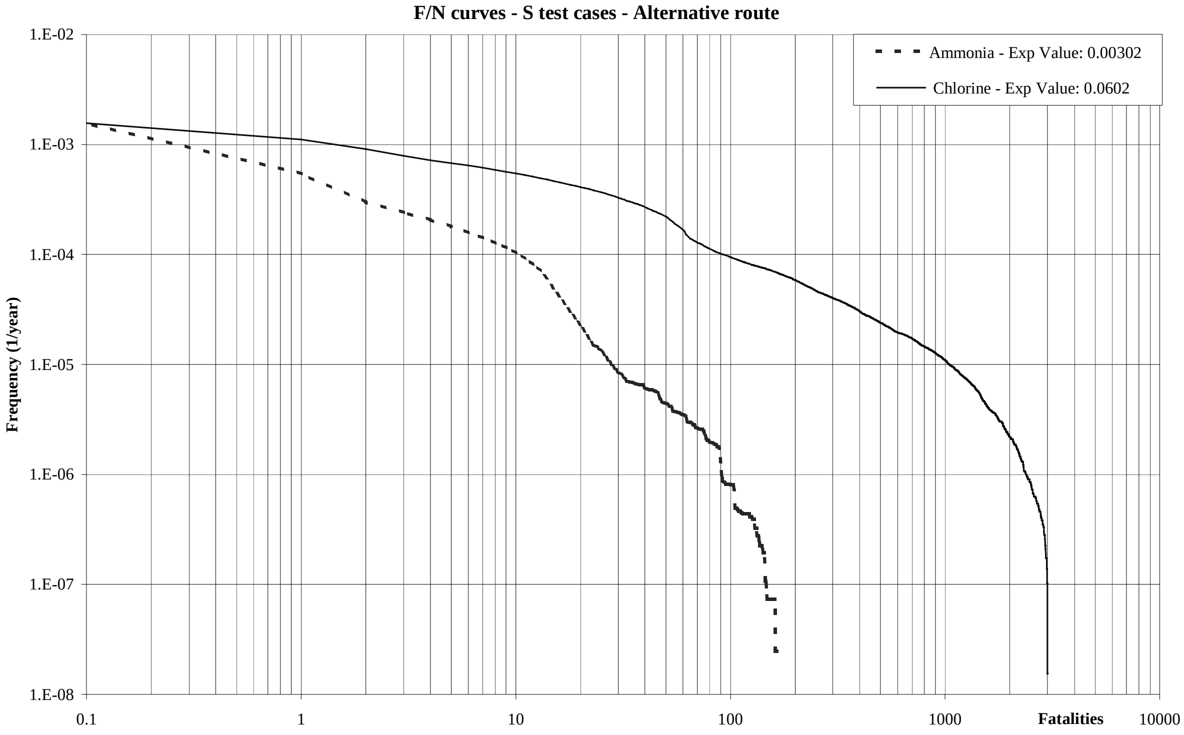
The consequences of an accident are fatalities, injuries, destruction of buildings and structures and damage to the environment. As in every modelling process, simplifying indicators are necessary to describe the effects of the system behaviour. The QRAM produces indicators which characterise the following risk aspects::

- Societal risk.
- Individual risk.
- Structural damage (rough estimation).
- Environmental damage (rough estimation).

Societal risk

A common way to describe societal risk is to calculate F/N curves. F/N curves illustrate the relationship between accident frequency and accident severity. On the abscissa, the number of victims x (fatalities, injured people) is shown in logarithmic scale. On the ordinate, the corresponding yearly frequencies F(x) for the occurrence of accidents with x or more victims are shown. For each given situation (population, traffic, dangerous goods traffic, route, weather, etc.), one F/N curve represents the societal risk. As an illustration, F/N curves calculated in the S tunnel test case are shown in Figure 5.1.

Figure 5.1. **S test case: application of ammonia and chlorine release consequences to the same frequencies**



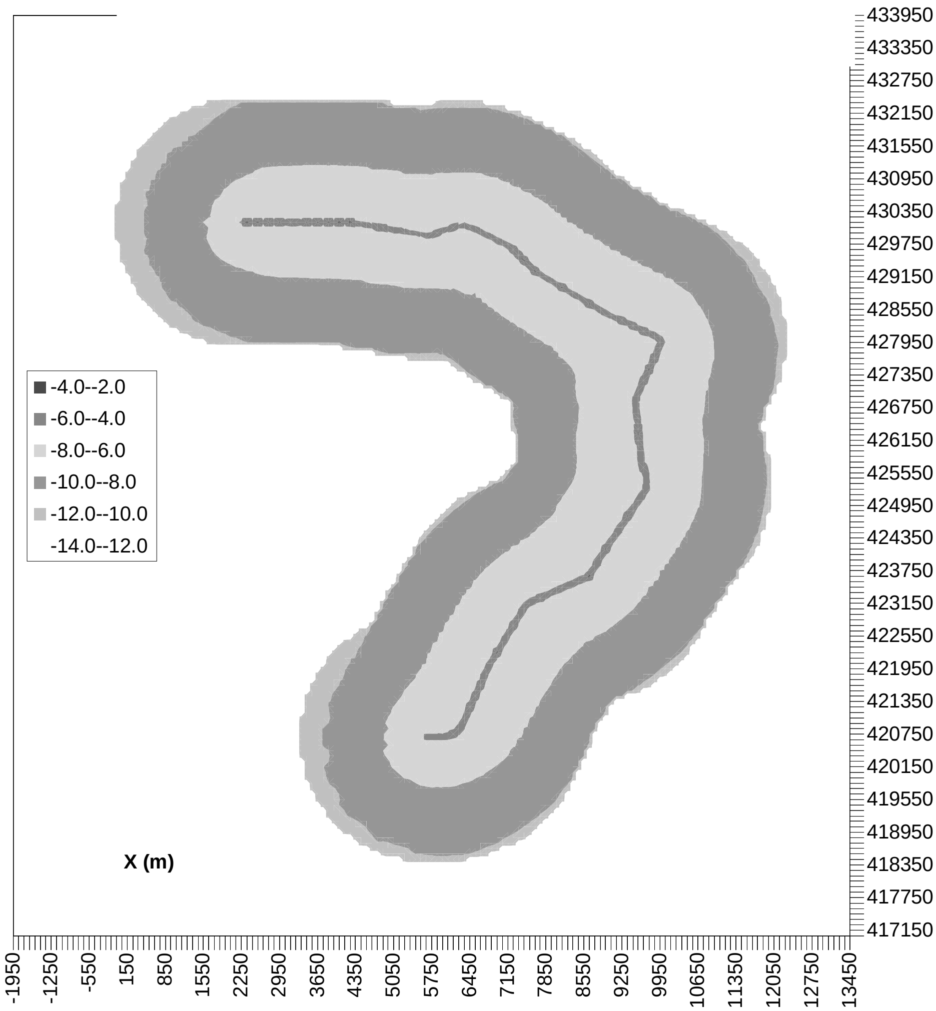
One F/N curve (the lower one) considers the consequences of an ammonia release through a 50 mm diameter breach. The other F/N curve considers the consequences of chlorine release through a 50 mm diameter breach. In both examples, the same frequencies for the occurrence of an incident are used. There is a great difference between the two curves and the corresponding expected value differs by a factor of 20. Due to its huge toxic effects, transport of chlorine by road is prohibited in some countries (*e.g.* Austria) or is only permitted in small quantities (*e.g.* France, Canada).

Individual risk

The individual risk indicator refers to the risk of fatalities or injuries to the local population due to an incident occurring. Individual risk is expressed as a frequency per year. It could also be expressed in terms of recurrence time, *i.e.* average number of years between two accidents with the considered consequence (fatality, injury). The QRAM calculates the spatial allocation of risk. Two-dimensional maps containing the individual risk for the surroundings of the analysed route can be drawn as shown in Figure 5.2. The individual risk can be calculated for the residents or the workday population.

Figure 5.2. **D test case: individual risk due to dangerous goods transport**

Individual risk – D test case – alternative route – all scenarios



Note: The values in the legend represent powers of 10 values of individual risk frequencies: For example, -6 to -4 represents the areas where the fatality frequency (if remaining permanently in this place) is between 10^{-4} and 10^{-6} per year.

Further indicators

In addition, the QRAM calculates rough estimates of structural and environmental damage.

Accident scenarios

A complete assessment of the risks involved in transporting dangerous goods would require the consideration of all kinds of dangerous materials, all possible meteorological conditions, all possible accidents, sizes of breaches, vehicles fully or partially loaded, and many other variables. Since all circumstances are impossible to consider, simplifications have to be made.

As shown in Table 5.1, only a limited number of scenarios are taken into account. Two scenarios relate to fires of medium and important intensity involving heavy goods vehicles without dangerous goods. These scenarios represent a serious risk in tunnels. The other scenarios involve dangerous goods. The scenarios are selected to represent the various groupings of dangerous goods (see Chapter 4) and were chosen to examine different severe effects: overpressure, thermal effect and toxicity.

Table 5.1. **Main characteristics of the 13 selected scenarios**

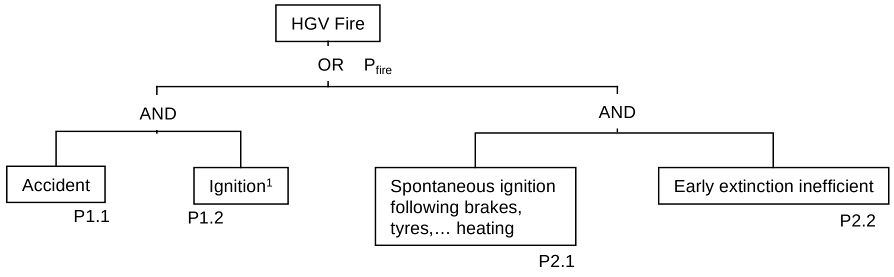
Scenario No.	Description	Capacity of tank	Size of breach (mm)	Mass flow rate (kg/s)
1	HGV fire 20 MW	-	-	
2	HGV fire 100 MW	-	-	
3	BLEVE of LPG in cylinder	50 kg	-	
4	Motor spirit pool fire	28 tonnes	100	20.6
5	VCE of motor spirit	28 tonnes	100	20.6
6	Chlorine release	20 tonnes	50	45
7	BLEVE of LPG in bulk	18 tonnes	-	
8	VCE of LPG in bulk	18 tonnes	50	36
9	Torch fire of LPG in bulk	18 tonnes	50	36
10	Ammonia release	20 tonnes	50	36
11	Acrolein in bulk release	25 tonnes	100	24.8
12	Acrolein in cylinders release	100 litres	4	0.02
13	BLEVE of carbon dioxide in bulk (not including toxic effects)	20 tonnes	-	-

Key: BLEVE = Boiling liquid expanding vapour explosion; HGV = Heavy goods vehicle; LPG = Liquid petroleum gas; VCE = Vapour cloud explosion.

Each scenario is based on a different event tree. Figure 5.3 shows the event tree for scenarios 1 and 2, heavy good vehicle fire without dangerous goods. From this event tree, the following probability equation could be derived:

$$P_{fire} = P_1 + P_2 = (P_{1.1} + P_{1.2}) + (P_{2.1} + P_{2.2})$$

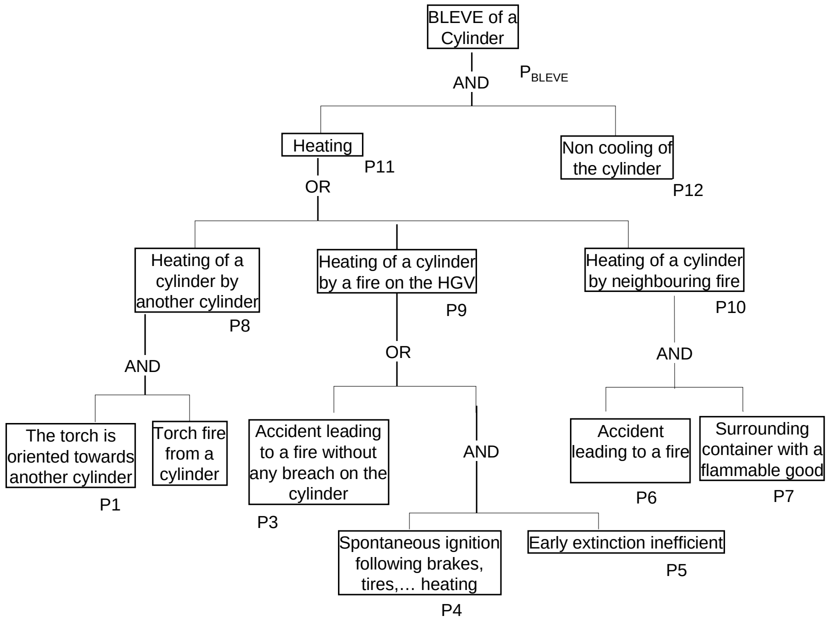
Figure 5.3. **Event tree for the scenario HGV without dangerous goods**



1. Ignition in case of an accident may start on the HGV transporting the dangerous goods or on other vehicles involved in the accident.

Figure 5.4 shows the event tree for the scenario of a BLEVE of LPG in cylinder (50 kg). Such event trees and corresponding probability equations are produced for all considered scenarios.

Figure 5.4. **Event tree for a BLEVE of 50 kg LPG cylinders**



Evaluation of accident probability

The purpose is to determine frequencies of occurrence of the chosen scenarios depending on the section of the route considered. For this purpose, the route has to be subdivided into homogenous sections in terms of road elements, traffic, dangerous goods transported, environment and weather conditions. This must be done by the user of the model, who also has to provide and prepare the necessary input data.

Scenario related calculations are divided into four steps:

1. Determination of accident involvement rates for heavy goods vehicles (with and without dangerous goods) per million vehicle kilometres for various countries, urban/non urban areas, bi-directional/separated roads, surface/tunnel routes, adverse/favourable surface route conditions.

2. Determination of heavy goods vehicle and dangerous heavy goods vehicle traffic on the different sections of the route considered. The traffic entered by the user is translated into a number of yearly vehicle kilometres.

3. Proportion of heavy goods vehicle accidents that can lead to 20 MW and 100 MW fires. Proportion of dangerous heavy goods vehicles of each type that can lead to one scenario or more.

4. Scenario rates once an accident has taken place.

Steps 1, 3 and 4 are carried out by the model. Values for step 2 are to be entered by the user. Values for step 3 can be entered also by the user, but default values are defined in the model.

It is possible that scenarios can occur without an accident in the true sense of the word, *e.g.* due to overheating of brakes. Such incidents, together with accidents, are called "events". Care has to be taken since there can be different databases for events and accidents. For the model, scenarios involving dangerous heavy goods vehicles were taken as a part of dangerous heavy goods vehicle events (see Figure 5.5). Results of the calculations are shown in Table 5.2.

Figure 5.5. **Possible repartition of different types of accidents/events**

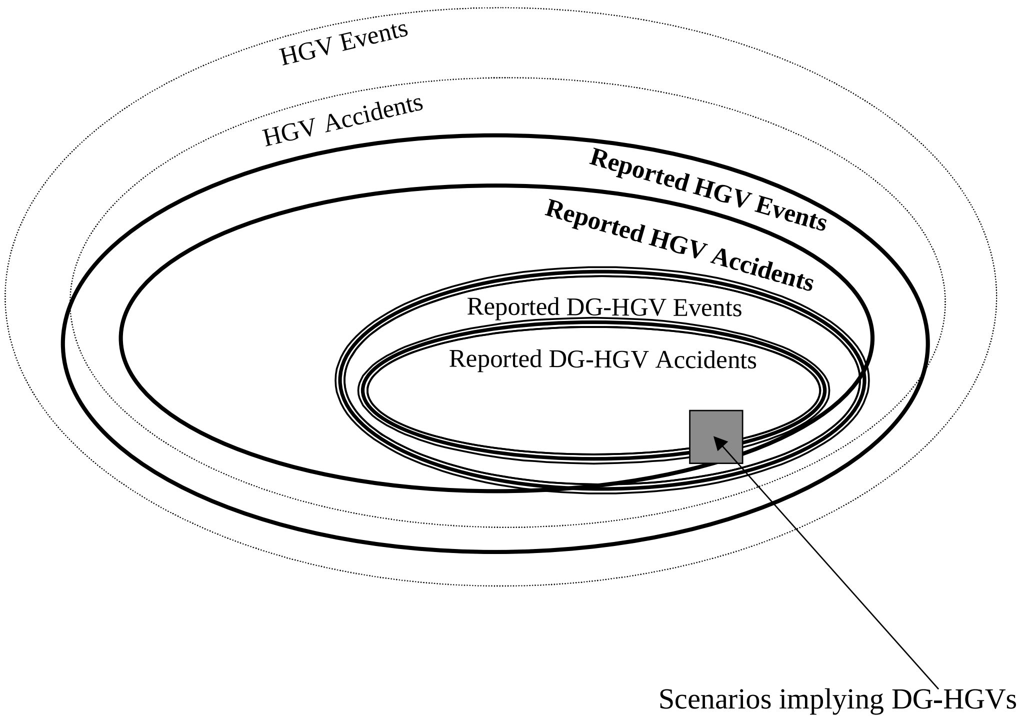


Table 5.2. **DG-HGV scenarios rates once an event has occurred**

	Scenario	DG type	Load	Urban open	Rural open	Urban tunnel	Rural tunnel
Scenario	Scenario characteristics			Scenario rates			
BLEVE of propane in cylinder	3	2	Small	4.3E-04	8.0E-04	1.7E-03	5.1E-03
Pool fire of motor spirit	4	3	Large	2.7E-03	4.5E-03	2.8E-03	2.0E-02
VCE of motor spirit	5	3	Large	2.7E-04	4.5E-04	2.8E-04	2.0E-03
Chlorine release	6	1	Large	3.1E-02	5.4E-02	3.1E-02	5.4E-02
BLEVE of propane in bulk	7	2	Large	2.3E-04	4.2E-04	2.8E-04	2.0E-03
VCE of propane in bulk	8	2	Large	2.3E-04	4.2E-04	2.8E-04	2.0E-03
Torch fire of propane in bulk	9	2	Large	2.3E-03	4.2E-03	2.8E-03	2.0E-02
Ammonia release	10	1	Large	3.1E-02	5.4E-02	3.1E-02	5.4E-02

Determination of physiological consequences, structural and environmental damage

Apart from scenarios in which fragments are in some cases liable to be thrown great distances, the translation of the physical consequences into physiological ones is generally performed by means of probit functions.

For toxic releases in the open, the physical effects are assessed with a dense gas dispersion model. In tunnels, the pre-conditioner calculates the drift of a toxic plug along the tunnel as a function of the incident location and the tunnel characteristic.

Vapour cloud explosions in the open air are evaluated by calculating the geometry of the cloud when it is initiated and the flammable mass it represents compared to the total released mass. In tunnels, a simple model is used, that allows the calculation of the level of overpressure generated by the ignition of the flammable cloud.

Pool fire calculations in the open are based on the effects of radiation from large pool fires. In tunnels, after assessing the smoke movements from the fire, it is possible to calculate distances of effects considering the toxicity of fumes and the thermal radiation of the smoke layer.

A BLEVE corresponds to two phases: a physical expansion once a vessel is ruptured (overpressure and missile effects), and a chemical reaction if the dangerous good is flammable. Both consequences are covered in the calculations.

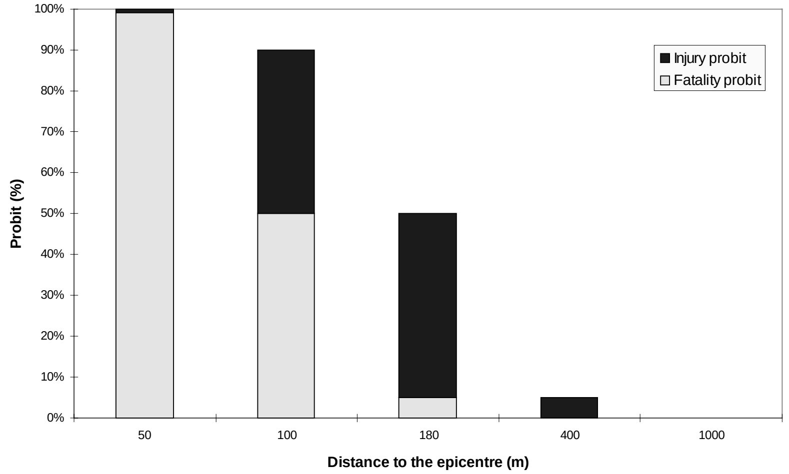
Determination of injuries

Due to the fact that injury percentages do not necessarily decrease with growing distance, as is the case for fatalities (Figure 5.6), it was decided to produce F/N curves for:

- Fatalities only.
- Fatalities plus injuries.

Expected values for injuries only can be calculated from these two F/N curves. This is done for fires, explosions and toxic releases.

Figure 5.6. **Example of evolution of percentages *vs.* distance for fatalities and injuries**



Structural damage

In general, structures are load-bearing constructions and their failure is likely to cause serious problems to the integrity of the tunnel. In a driven tunnel, this is simply the tunnel lining. For a cut-and-cover tunnel, the general structure includes support members such as lateral walls and roofs.

Table 5.3 identifies four damage categories which are considered in the QRAM.

Table 5.3. **Categories of damage**

	Damage scenario
1	Tunnel structure (collapse or structural integrity problems).
2	Internal civil structures including roadway (general integrity is not an issue).
3	Damage to protected equipment
4	Damage to unprotected equipment, *e.g.* lighting.

Table 5.4 summarises the characteristics of commonly used material with regard to the temperatures at which temporary and permanent reduction in strength occurs.

Table 5.4. **Summary of strength loss characteristics of common structural material**

Material	Temporary reduction in strength	Permanent reduction in strength
Dense concrete	Reduction becomes significant at 300°C and 50% strength remains at 600°C.	Loss in residual strength becomes significant at 300°C.
Light concrete	Reduction becomes significant at 500°C and 50% strength remains at 750°C.	Loss in residual strength becomes significant at 500°C.
Reinforced and pre-stressed steel	Strength begins to decrease at 150°C and drops to 50% at 450°C.	Residual strength begins to decrease at 150°C and drops to 50% at 400°C.
Steel structures	Strength begins to decrease at 200°C and drops to 50% at 500~600°C.	Residual strength begins to decrease at 300°C.

Table 5.5 summarises critical criteria for thermal failure of various materials used for tunnel equipment.

Table 5.5. **Representative failure temperatures for tunnel ancillary equipment**

Equipment item	"Failure" temperature (°C)
Thermoplastic (boxes, switch covers, cable sheath)	Melting point 180°C
"MODAR" cable tray	Approx. max. service temp 100°C
Aluminium alloy (light fittings)	Significant property reduction at 300°C
Steel (support brackets and fittings)	Significant property reduction at 500°C
Cables	250°C for sub-main and final circuit lighting cables and communications cables, 1 000°C for emergency lighting cables
Lighting	Temperature must not exceed 40°C

Estimation of re-instatement costs

The re-instatement costs depend on the tunnel type, size, location, construction features and level of damage caused by the accident. In addition, labour and material costs will vary from country to country. To avoid uncertainties in the methodology, the reinstatement cost is presented as a percentage of the estimated capital cost of building a new tunnel with similar specifications (Table 5.6).

Table 5.6. **Reported cost breakdowns for driven and cut-and-cover tunnels**

Cost items	Driven tunnel	Cut-and-cover
Civil cost	***77.5%***	***81%***
Excavation	40.5%	10%
Tunnel lining	24%	52.5%
Tunnel civil	5%	10.5%
Others	5%	5%
M&E cost	***22.5%***	***19%***
Lighting fittings	4.5%	4.0%
Ventilation	2%	2%
Power	4.5%	7%
Tunnel system	15.2%	13%
Other	8%	8%

For the QRA software, it was decided to use a different breakdown of costs, based on a similar set of cost items.

Table 5.7. **Assumed default percentage cost breakdowns for driven and cut-and-cover tunnels**

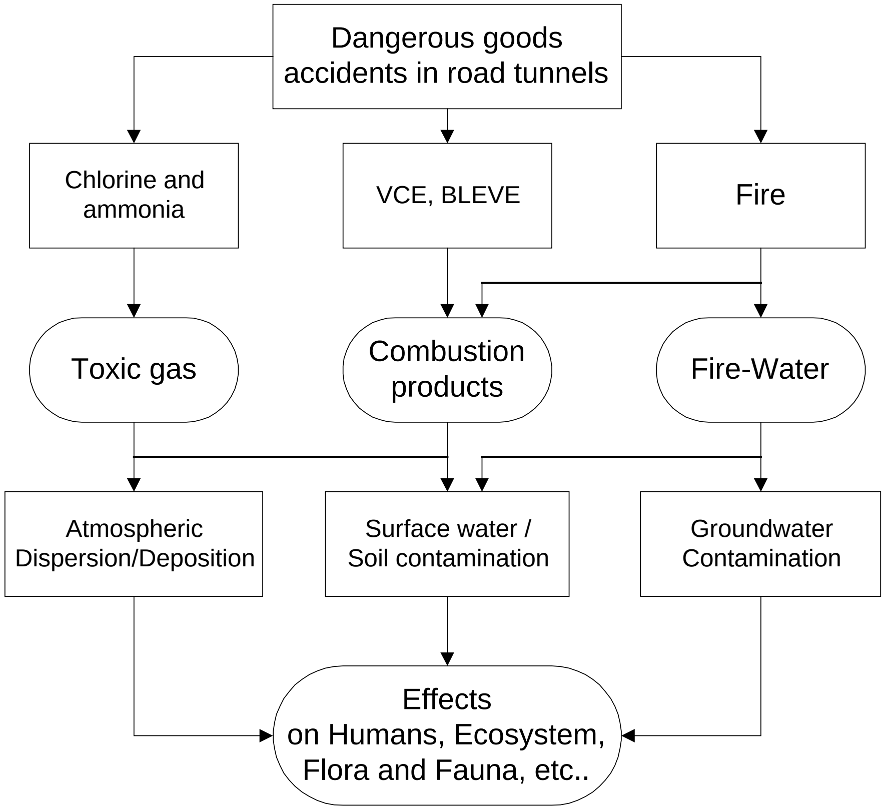
Cost items	Damage category	Driven tunnel %	Cut-and-cover %
Excavation	4	50	15
Tunnel lining	4	25	60
Internal civil structures, including roadway	3	12.5	12.5
Ventilation	2	6.5	6.5
Safety equipment	2	2	2
Lighting	1	3	3
Traffic equipment	1	1	1

The estimated total re-instatement cost is obtained by summing up the damage cost for each affected item. The damage cost for each affected item is calculated by multiplying the cost factors given in Table 5.7 by a weighting factor based on the proportion of tunnel length affected within each damage category.

Environmental effects

The main environmental impacts of dangerous goods accidents in road tunnels in terms of atmosphere, water and ground contamination are shown in Figure 5.7.

Figure 5.7. **Component of environmental pollution**



While the model considers environmental impacts, the indicators used are more qualitative than other indicators used in the model. A full assessment of environmental impacts is outside the scope of this model. The classification of dangerous goods is not generally done on the basis of environmental hazards (for example, a significant spill of milk could have serious environmental consequences in certain environments). A full quantitative assessment of the environmental consequences of incidents involving dangerous goods would be extremely complex and of limited value. The environmental impact indicators are summarised in Table 5.8.

Evaluation of consequences in open sections and tunnel sections

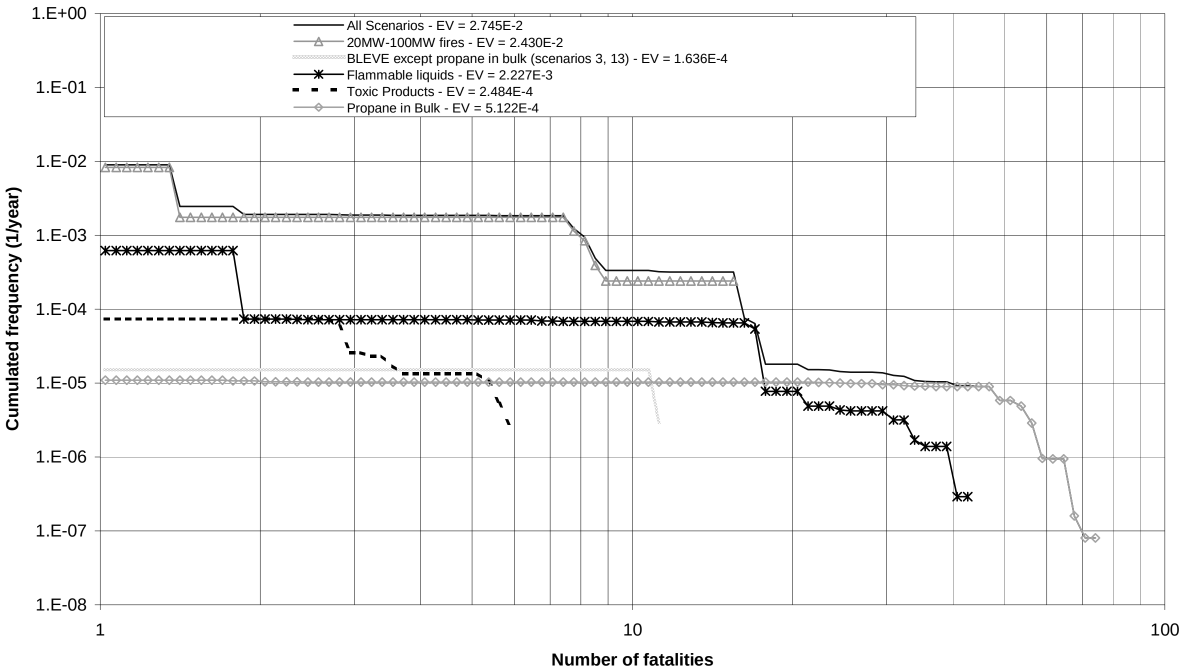
Extensive calculations provide individual risk data and F/N curves for selected scenarios and for different types of transport. As an example, results from the C test case are shown (Figures 5.8 and 5.9).

Table 5.8. **Environmental impact indicators (severity: negligible, low, medium, high)**

Scenario	Key factors affecting severity: None	Drainage retention system[1]	Fire water control[2]	Limited adjacent flora, fauna or aquatic systems
HGV fire, 20 MW	Low - Large quantity of combustion products dispersed in air.	-	Negligible	negligible
HGV fire, 100 MW	Medium - Large quantity of combustion products dispersed in air. - Large quantity of fire water.	-	Low	Negligible
LPG cylinder BLEVE	Negligible - Small quantity of combustion products dispersed in air.	-	-	Negligible
Motor spirit pool fire	High - Large quantity of combustion products dispersed in air. - Harmful liquid hydrocarbon spill. - Large quantity of fire water.	Low	Low	Negligible
Motor spirit VCE	Medium - Large quantity of combustion products dispersed in air. - Harmful liquid hydrocarbon spill.	Low	-	Negligible
Chlorine release	High - Large quantity. - Very harmful liquid spill.	Low	-	Negligible
LPG tank BLEVE	Low - Large quantity of combustion products dispersed in air.	-	-	Negligible
LPG tank VCE	Low - Large quantity of combustion products dispersed in air.	Low	-	Negligible
LPG torch fire	Medium - Large quantity of combustion products dispersed in air. - Large quantity of fire water.	-	Low	Negligible
Ammonia release	High - Large quantity. - Very harmful liquid spill.	Low	-	Negligible

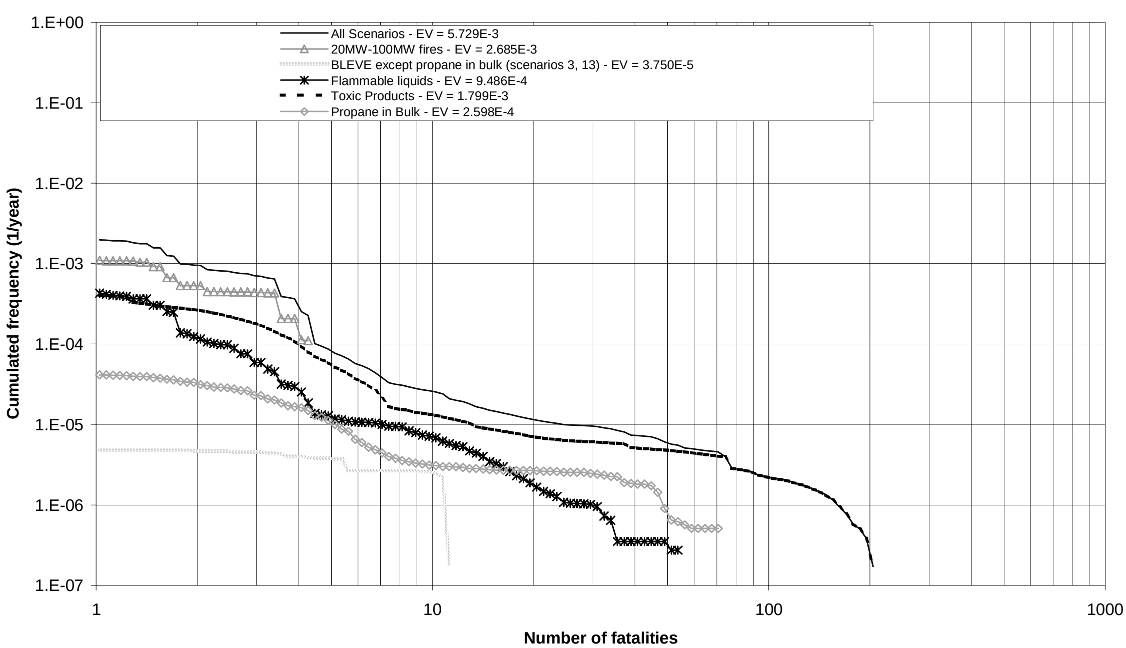
1. It is assumed that drainage systems will generally not be able to retain all fire-fighting water in the event of a major fire.
2. It is assumed that control measures for minimising discharge of fire-fighting water (*i.e.* rapid response of emergency services, use of bunds, etc.) are effective.

Figure 5.8. **F/N curves C tunnel test case**



EV = Expected value = fatalities (+ injuries) / year.

Figure 5.9. **F/N curves C alternative route test case**

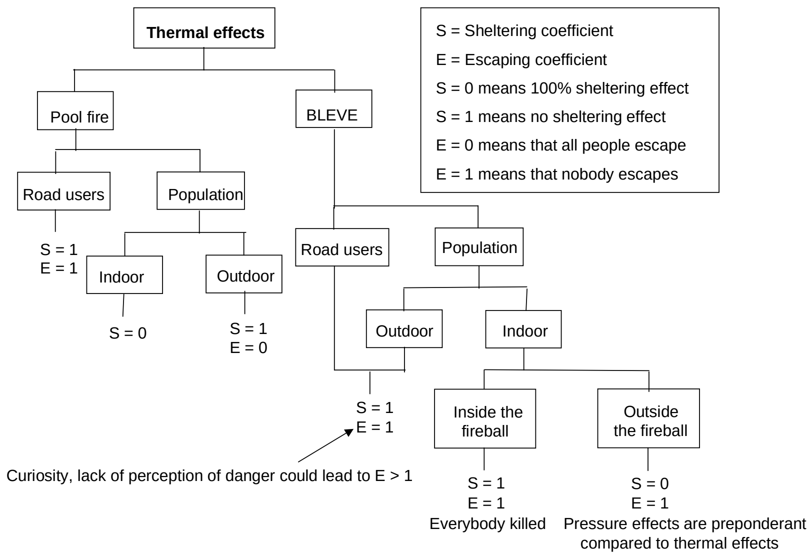


EV = Expected value = fatalities (+ injuries) / year.

Escape/sheltering possibilities

For both the open road and tunnel situations, escape/sheltering calculations are performed in the model. Figure 5.10 summarises the kind of cases that can be encountered. For the tunnel evacuation principles, pre-movement time (this concept is explained in Chapter 7) and occupant response times are taken into account.

Figure 5.10. **Sheltering effects and escaping possibilities for thermal effects outside of a tunnel**



Sensitivity analysis

Deterministic analysis involves uncertainties. Various parameters have been tested to assess their influences. The results of these tests are shown in Figures 5.11 to 5.13.

Figure 5.11. **Results of sensitivity analysis (variation in travel speed)**

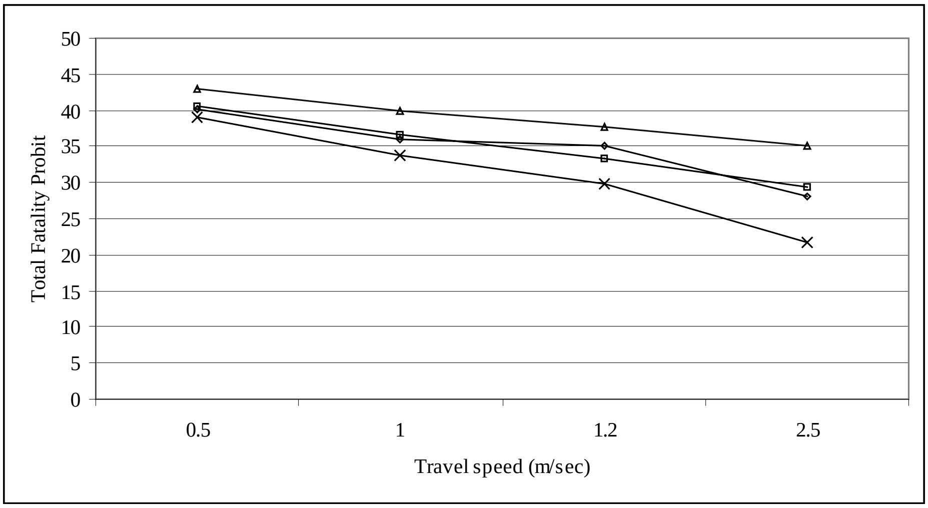


Figure 5.12. **Results of sensitivity analysis (variation in warning systems bps)**

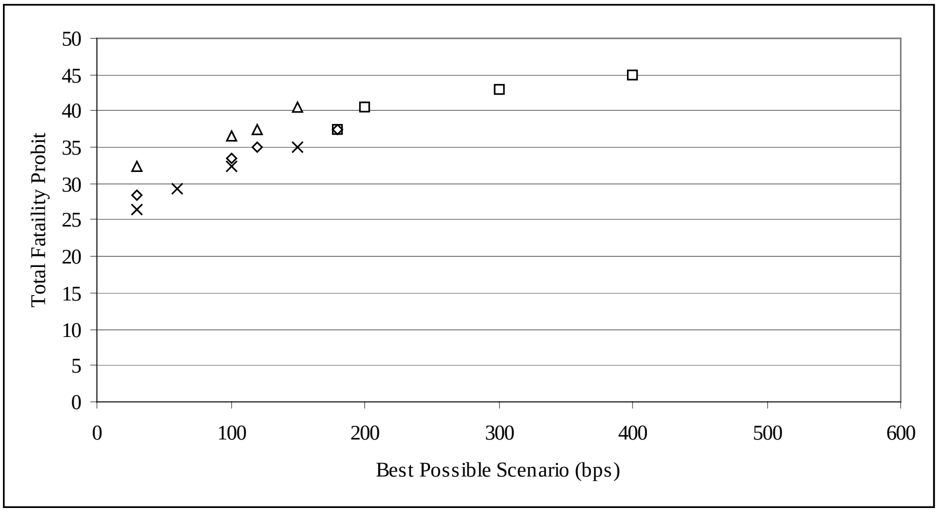
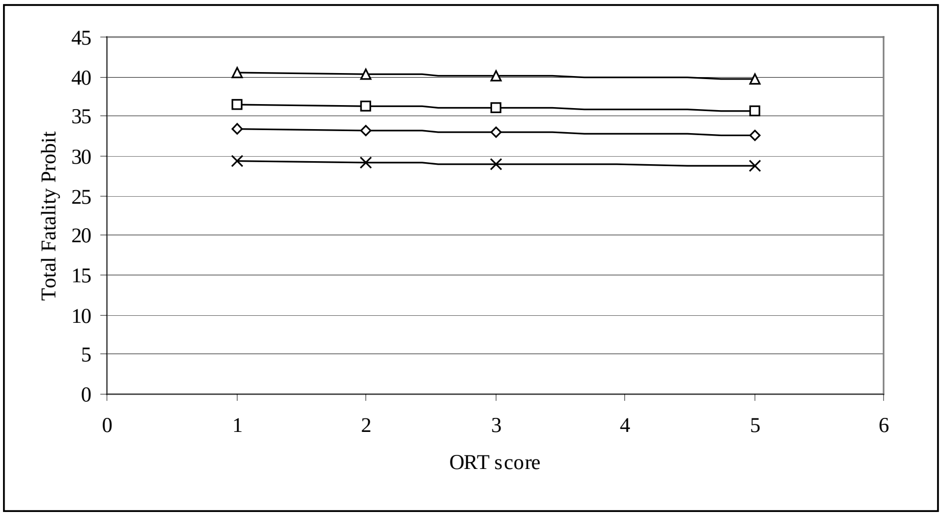


Figure 5.13. **Results of sensitivity (variation in individual occupant response time, ORT score)**



Validation process

This step in the development of the QRAM was necessary to test the developed model by persons not involved in the model-building process, but familiar with system behaviour, risk assessment and computer models. The following countries were involved in the validation process: Austria, France, the Netherlands, Norway, Sweden and Switzerland. Test cases were chosen for urban, rural, one-bore, twin-bore, rock, cut-and-cover tunnels, different road environments, different ventilation systems and a wide variety of traffic conditions.

Five validation group meetings were held where experiences were exchanged and documented. After each meeting, the model was revised by the model developers, eliminating bugs and solving the problems identified in the validation process. Sensitivity analysis with the latest versions of the model were carried out to check the results of model calculations with expert knowledge. The validation phase is only the first step in the ongoing process of practical use of the model developed, which should continue in the future. The validation group approved the model with some additional conditions:

The QRA software should be recommended in OECD Member countries for the calculation of risk for a single tunnel, the calculation and comparison of societal risks of tunnel and detour routes and the calculation of the 2D distribution of individual risks along a route.

To overcome problems for new users, online help should be provided. It was recommended:

- To establish a database, containing all experiences with the QRAM, accessible by Internet. This database should contain the results of all available national runs of the model.

- To establish a network of experienced model users who can be contacted if problems cannot be solved by the users themselves.

This collection of experiences and results can form a basis for further improvements of the QRA software and the reference manual. The target is to improve the QRA software in a continuous process, involving all users and their experiences.

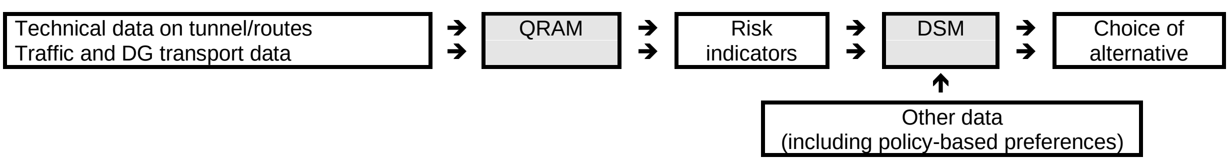
Chapter 6

THE DECISION SUPPORT MODEL (DSM)

The role of the DSM is to give decision makers assistance in deciding which groupings of dangerous goods should be allowed through a given tunnel. The decision must be made based on the results of the QRAM described in the previous chapter. A precondition for the DSM is that the decision maker acts in consideration of the safety of road users and local population along both the tunnel route and the alternative routes being considered.

The DSM uses the output from the QRAM and other information supplied by the decision maker as shown in Figure 6.1. The policy-based input contains data which are not of a scientific or technical nature but rather of a subjective, political nature. The data could include weighting of the importance of fatalities to the decision maker compared to injuries either in monetary terms or as pure weights. It could also be monetary values for lost time of road users or losses due to tunnel closure following an incident.

Figure 6.1. **Structure of the study and decision process**



Key: QRAM: quantitative risk assessment model; DSM: decision support model.

In order to provide the best possible basis for decisions concerning transport of dangerous goods in road tunnels, two different guides to decisions are presented in this chapter. These are:

- A *computerised tool* developed specially for the purpose of supporting decisions concerning groupings of dangerous goods loadings authorised in tunnels. The DSM provides the user with the choice of three different methodologies requiring, to some extent, different preference inputs.

- *Recommendations*. These sum up the various attributes that should be considered when making a decision and make recommendations on how to evaluate the alternative groupings against these attributes (using the QRAM output among others). In order to reach a decision, the attributes must be weighted against one another. The way to reach a decision once all necessary data are available is left to the decision maker.

Definition of the decision problem

The decision problem must be defined in terms of: *i)* overall objective; *ii)* who is to decide and what is the point of view of the decision maker; *iii)* description of decision problems in terms of possible alternatives; and *iv)* which decision process should be used .

The overall objective is to set up a framework to evaluate risks and decide on the regulations for the routing of dangerous goods through road tunnels or otherwise. The regulations are based on the groupings proposed in Chapter 4.

The formulation of the decision problem depends on the point of view of the decision maker. In this case, the decision maker should be an authority capable of taking the entire objective into account. That is, the decision maker should act in consideration of the entire geographical area including tunnel, alternative route(s) and the area influenced by the consequence of traffic on these routes.

In order to make a DSM, it is necessary to clearly define the decision problem. For a given tunnel, the primary decision is the choice of which groupings of dangerous goods loadings should be allowed in the tunnel. This choice will force prohibited traffic to use a detour route (the alternative route). Consequently, the decision must take into account the risks on the tunnel route due to the dangerous goods loadings allowed on it and the risks on the detour route due to the loadings banned from the tunnel.

A second decision concerns the choice of possible risk reduction measures to be implemented in the tunnel. Clearly, this second decision is linked to the first one: risk reduction measures can influence which loadings can be accepted in the tunnel; conversely, permitted dangerous goods affect the choice of the measures. Combining all choices of regulation with all optimised risk reduction measures in one single analysis would be quite complex (numerous QRA runs would be required) and, thus, for practical purposes, inexpedient. Figure 6.2 sketches the decision process:

- The QRAM is run for the tunnel route and the alternative route applying standard risk reduction measures. Separate QRAM runs are required for each of the time periods considered, for road users and local population and for fatalities and fatalities plus injuries. This amounts to a maximum of 24 QRAM runs.

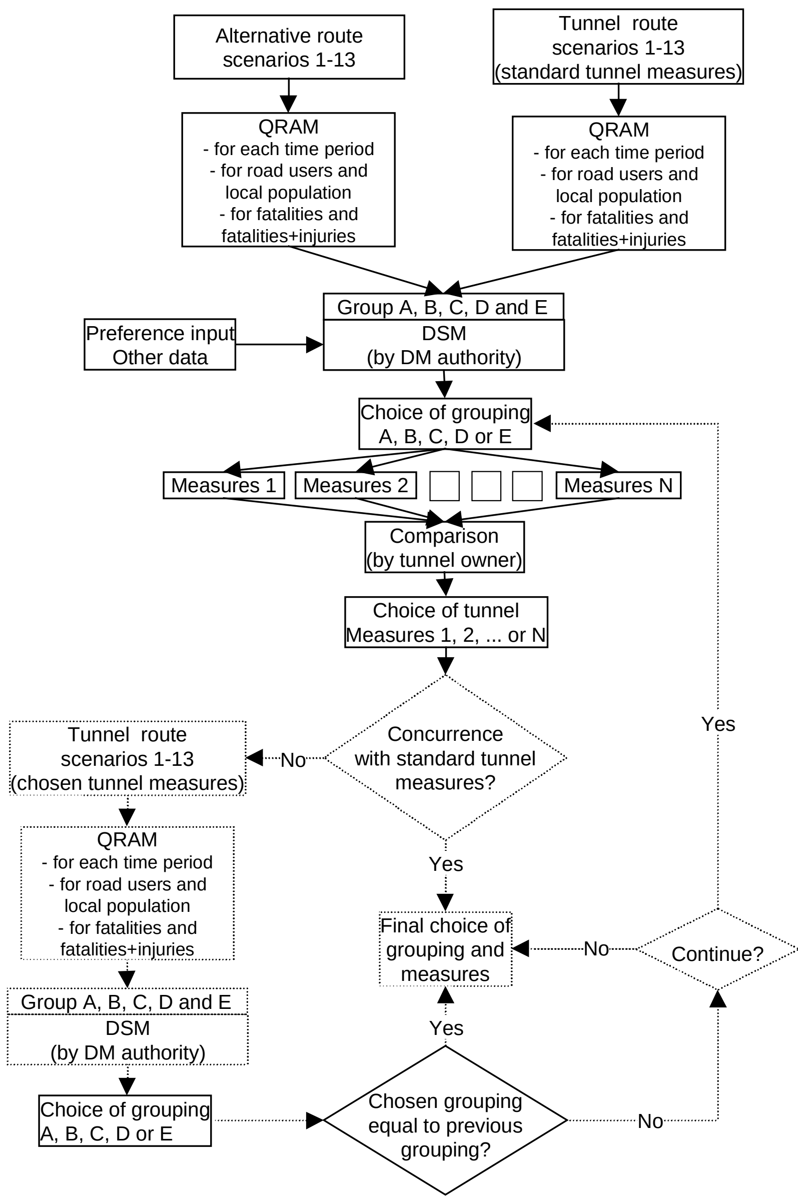
- The results of these QRAM runs are combined with Groupings A to E by the DSM tool. Then the decision-making authority chooses the regulation with the help of the DSM, taking into account also the political preference input and other necessary information provided by the decision maker.

- In a next step, the risk reduction measures are optimised by the tunnel owner, taking into account the chosen regulation. If the optimised measures differ significantly from those used in the first run of the QRAM, a new run of the QRAM and DSM may prove necessary to check the choice of the regulation. If there is not found to be sufficient congruence between the optimised measures and the standard measures used, the QRAM is run for the optimised set of measures and the optimal grouping of the tunnel determined. A final decision has been reached if the optimal grouping is found equal to the previously chosen grouping.

- If not, the optimisation of measures must be repeated on the basis of the latest selected grouping. There is no guarantee that the proposed decision process converges towards an overall optimal decision if the decision problem is found to be very sensitive (overall optimal decision means a decision which is optimal with respect to both tunnel measures and grouping). Aiming at an overall optimisation would require initial QRAM runs for all sets of tunnel measures and that the decision of mitigating measures is included directly in the DSM, taking into account also the price of implementing the measure.

In general, the DSM should only consider attributes for the tunnel if the same attributes are also considered for the alternative route and vice versa. For example: material damage to the tunnel should be considered only if it is possible to evaluate material damage in the open too. In such cases, damage to road users and local population property should also be taken into account.

Figure 6.2. **Proposed decision process**



DSM inputs

The QRAM risk indicators provide important input for the various attributes that might be considered in the DSM. However, other inputs may also be considered in order to evaluate the various regulation alternatives *vis-à-vis* the decision maker's objectives. Possible objectives included in the DSM are listed below:

- Safety (includes fatalities and fatalities plus injuries due to possible accidents on both tunnel and detour routes, with a distinction between road users and the local population).
- Direct expenses (includes investment and operational cost of tunnel risk reduction measures as well as possible additional costs in the transport of dangerous goods).
- Inconvenience to road users (time lost during repair works after an accident in the tunnel).
- Environmental impact (due to an accident on tunnel or detour route, if appreciable).
- Nuisance to local population (environmental impact of dangerous goods traffic, with the exclusion of possible accident consequences, but possibly including psychological impact).
- Material damage (due to possible accidents).

In addition to the direct information on the attributes describing each objective above, some policy-based input is necessary in the DSM so that decisions are consistent with the values that are important to the decision maker. A necessary preference input is the weighting of the various attributes taken into account by the DSM. This weighting is done in different ways according to the type of DSM chosen. Another important, but optional, preference input could be risk aversion; that is, for example where one accident with 100 fatalities is considered less acceptable than 100 accidents with one fatality in each.

Survey and choice of decision support methodologies/tools

Decision support methodologies have been studied theoretically for many years and are applied in various fields. Computerised tools are available, consequently a survey and evaluation of proven state-of-the-art decision support tools was carried out. Three main categories were examined, all of which deal with multiple and possibly conflicting objectives:

- *Bayesian decision analysis* is a transparent procedure based on rationally defined axioms. It can be modelled using decision trees or Bayesian networks (influence diagrams). The multiple objectives are weighted into a common utility function. The decision alternative which maximises the expected value of this function (*i.e.* the expected utility) is selected.
- *Multi-attribute (also called multi-criteria) decision analysis* evaluates the alternatives for each of the objectives. Various methods require direct or indirect weighting of these objectives to obtain an overall score of the alternatives. These methods are, among others: the analytic hierarchy process (AHP); the simple multi-attribute rating technique (SMART); and the weighted product method. The method called the simple multi-attribute rating technique (SMART) uses a weighted summation. The alternative with the largest score is selected.

- *Cost-benefit analysis* covers two different approaches. One is very similar to the Bayesian analysis and, thus, weights expected costs vs. expected benefits. The other, classical one, values alternatives in a purely economic non-probabilistic way and compares the net present value of the benefits and costs of the alternatives.

The survey concluded that there are no shortcuts to rational decision making. The various, potentially conflicting, objectives must be subject to a mutual weighting no matter how delicate it may seem to quantify these objectives and weights. In cases where no formalised decision support tool is used, the weighting is made instinctively. The choice of methodology is mostly a question of whether the transformation of objectives to a single scale is to be made implicit or explicit. Furthermore, important information regarding the various individual objectives might be lost in the aim to make implicit transformations. Thus, it was concluded that the direct transformations used in the Bayesian approach should be applied as far as possible.

The DSM computer program

The DSM uses the following elements – denoted attributes – in the assessment of the dangerous goods traffic:

- Consequences from dangerous goods accidents on the tunnel route:
  - Fatalities and injuries of road users.
  - Fatalities and injuries of population.
  - Damage to the tunnel.
  - Additional user time and mileage from diversion of all traffic after a dangerous goods accident.
  - Loss of operational income while the tunnel route is closed.
  - Damage to the environment.
- Consequences from dangerous goods accidents on the open route:
  - Fatalities and injuries of road users.
  - Fatalities and injuries of population.
  - Damage to the environment.
- Consequences of diverting dangerous goods traffic to the open route:
  - Additional time and mileage for the transport of dangerous goods due to the diversion.
  - Loss in operational income due to the diversion.

The attributes are of a very different nature and will normally be measured in different units. However, to determine the most beneficial grouping to be authorised in the tunnel, the DSM facilitates a quantitative comparison of the changes in attributes.

Three approaches have been implemented in the DSM (COWI, 2000):

- Bayesian approach.
- SMART approach.
- Aggregated SMART approach.

Bayesian DSM

The Bayesian approach is essentially based on capitalisation of all attributes. Hence, human fatalities and injuries, tunnel damage, inconvenience to users, and damage to the environment, are converted into a monetary unit. Summing up the expected capitalisation of all attributes gives a figure which measures the overall consequence of the grouping selected. The resulting figures for each grouping provides a simple basis for deciding the optimal grouping, *i.e.* the grouping leading to the smallest total expected cost.

Conversion of attributes to monetary units requires that prices are determined. These are denoted *preferences* and include the equivalent cost of human fatality or injury, of traffic diversions (intentional or due to accidents) and of environmental damage. Obviously, the preferences can be quite delicate to decide, but direct quantification provides transparency in the decision making.

SMART DSM

The SMART approach is based on individual comparison of each of the attributes. The attribute is transformed into a non-dimensional figure (rank) from 0 to 1.0 by dividing the attribute value by the smallest value obtained for that attribute when considering all grouping alternatives. An inverse relationship is used such that the smallest value of the attribute will give the rank 1.0 and higher values of the attribute will give a rank below 1.0. The ranks are multiplied by user-specified weights, and summing up for all attributes gives a combined score for the grouping. The grouping with the maximal score is considered the optimal grouping.

The only user input in the SMART approach is then relative weights to apply to the non-dimensional rank for the individual attributes.

Aggregated SMART DSM

To reduce the number of weights to be specified in the SMART methodology, an aggregated version of the SMART methodology has been introduced. Relevant combinations of attributes are used (*e.g.* fatalities and injuries are combined into “human consequences”) and it is these aggregated attributes that are ranked.

Combination of the individual attributes into the aggregated attributes is based on capitalisation (*i.e.* the preferences introduced for the Bayesian methodology); the method thus represents a hybrid between the Bayesian and the SMART methodologies.

DSM constraint on individual risk

The average number of fatalities per year represents the fatality risk and the associated attributes are included in the optimisation problem. The Bayesian, SMART and Aggregated SMART approaches are furthermore based on comparison of the expected utility or the score of the considered alternatives and thus only relate to the relative levels of risk. By measuring the individual risk, the number of fatalities is related to the people exposed to the risk. In order to secure that the level of risk acceptable for the individual is not violated, the individual risk is also calculated and it is checked whether these individual risk values exceed specified maximum levels. These levels are regarded as constraints to the optimisation problem.

Recommendations

The decision process is a complex procedure, evaluating several factors. A DSM is therefore required in order to support rational decision making. However, should a decision maker decide not to use the DSM, the following recommendations provide a guideline of what to take into account.

The most important recommendation is that the decision maker should compare the risk of transporting a given substance through the tunnel with that of transporting the same substance on the alternative route when deciding on restrictions to traffic through a tunnel. Without this comparison, the decision on the grouping of a given tunnel will not be optimal from a societal point of view since the traffic that is restricted from the tunnel will be transported on an alternative route.

The relevant attributes do not differ from those on which the computerised DSM tool is based. These are represent by the QRAM outputs with respect to:

- F/N curves for fatalities and injuries for road users and third party, *i.e.* local population.
- Expected number of fatalities and injuries for road users and third party, *i.e.* local population.
- Material damage due to possible accidents.
- Environmental impact due to an accident on tunnel or detour route (the environmental output from the QRAM is limited, see Chapter 5).

Evaluations by the decision maker with respect to:

- Direct expenses (includes investment and operational cost of tunnel risk reduction measures as well as possible additional costs in the transport of dangerous goods).
- Inconvenience to road users due to a possible accident (time lost during repair works after an accident in the tunnel).
- Nuisance to local population (environmental impact of dangerous goods traffic, with the exclusion of possible accident consequences, but possibly including psychological impact).

Any other attribute found relevant by the decision maker can also be included in the decision problem. In order to make a decision, the decision maker must determine which attributes are relevant and how these should be weighted against each other. These choices must reflect the preferences of the decision maker.

If risk aversion is a concern of the decision maker, the decision takes into account not only the expected number of fatalities. The full F/N curves provides information on the scale of the accidents, *i.e.* knowledge of how frequent accidents with N or more fatalities are. As an example, a risk adverse decision maker considers one accident with 100 fatalities less acceptable than 100 accidents with one fatality in each. The information necessary for accounting risk aversion is in the shape of the F/N curves, the steeper the F/N curve the better.

Finally, it is important to secure that the level of risk acceptable for the individual is not violated. The QRAM provides the individual risk levels for the local population, which should be held against some acceptance criteria.

Chapter 7

RISK REDUCTION MEASURES

Objectives and contents

When vehicles carrying dangerous goods are allowed in a tunnel, a number of measures can be used to reduce the probability and consequences of an accident. At the outset of this project, it appeared that:

- No systematic description of the measures was readily available.
- Many measures are costly during either construction or operation, or both, while their effectiveness is most often not well known.
- It is very difficult to decide whether and in which case each measure should be implemented.

For these reasons, a significant part of this project was devoted to examining risk reduction measures with the following objectives:

- *Phase I.* To review all possible risk reduction measures, make a detailed description and analyse their advantages and disadvantages.
- *Phase II.* To objectively analyse the effectiveness of the measures and thus provide the basis for an assessment of their cost-effectiveness, taking advantage of the QRAM described in Chapter 5.

No systematic cost-effectiveness analysis has ever been reported for measures to reduce the risks of dangerous goods transport in road tunnels. The main reason is that the effects of measures on risks are very difficult to assess. To develop a methodology for such an assessment has been a major issue for the project. It is not worth developing tools to estimate the cost of measures since reasonably accurate cost estimations can be performed by specialised consultants for tunnel construction or refurbishment. Nevertheless, some data on costs of measures have been collected (Van der Sluis *et al*., 1998).

A general report (PIARC, to be published) gives a synthesis of all the work performed on risk reduction measures. The main findings are outlined below.

Phase I: Review of the risk reduction measures

This study (Van der Sluis *et al*., 1998) included a literature survey, a questionnaire sent to several tunnel operators and a tentative ranking of the measures. In addition, complementary information is available on a number of measures related to fire and smoke control (PIARC, 1999). The results of these two studies are outlined below.

Phase II: Assessment of the effectiveness of the measures towards risk

By the time Phase I was finalised, a first version of the QRAM was available. The intention was to use it to make an objective assessment of the effectiveness of the measures: to compare the effects on fatalities and damage of two runs of the model for a given tunnel with and without a measure.

However, quantitative data concerning the effects on the probability and consequences of all accident scenarios are lacking for a number of measures. Therefore all measures examined under Phase I were not taken into account in the QRAM.

For those measures which were fully taken into account in the QRAM (termed *native* measures), the assessment of the effectiveness could be successfully performed on six example tunnels using the method described above. The results are synthesised below.

To assess the effectiveness of the measures that are not taken into account in the QRAM (termed *non-native* measures), expert judgement is necessary. A useful approach is to obtain expert opinions on the effectiveness of each measure (or set of measures) in improving safety with respect to dangerous goods transport for a specific tunnel. However, this approach does not give quantitative results which can be used in a detailed cost effectiveness analysis. For this reason, most activities concerning the "non-native" measures were devoted to developing methodologies to take their effects into account as far as possible when using the QRAM. Two complementary methods were investigated:

- For those measures which have an influence on the probability of an accident, or on the probability of a scenario given an accident, a methodology was outlined to adjust the probabilities used in the QRAM.
- A number of measures have an effect on the response times of the users, operator or emergency teams in case of an accident. A methodology was developed to take such measures into account in a probabilistic way when using the QRAM and was applied to a few examples to provide insights into the effectiveness of some of these measures.

The conclusions describe how to use these results to assess the cost-effectiveness of specific measures in a given tunnel.

Identification of the risk reduction measures

Measures restricting the transport of dangerous goods (such as prohibition, limitation of quantities transported, or restriction of transit times) are not considered here. These measures require the consideration of alternative routes as well as the tunnel. Decisions on these measures require the use of the QRAMs and DSMs described in Chapters 5 and 6.

Table 7.1 lists the 27 measures examined. As many measures have several purposes, the classification is somewhat arbitrary and is based on their main purpose. It takes into account the fact that most fatalities generally occur before the arrival of the emergency services. Some measures appear a second time in italics, to indicate a second important purpose. The measures to ensure communication and/or information mainly aim at reducing the consequences of an accident, but can also have an effect on its probability by informing users that a first incident has occurred. A short summary of each of these measures is provided below.

Table 7.1. **List of risk reduction measures classified according to their main purpose**

MEASURES TO REDUCE THE PROBABILITY OF AN ACCIDENT		
Related to tunnel design and maintenance		
Tunnel cross section and visual design	Alignment Lighting (normal)	Maintenance Road surface (friction)
Related to traffic and vehicles		
Speed limit Prohibition to overtake	Escort Distance between vehicles	Vehicle checks
MEASURES TO REDUCE THE CONSEQUENCES OF AN ACCIDENT		
Alarm, information, communication of operator and rescue services		
Close-circuit television Automatic incident detection	Automatic fire detection Radio communication (services)	Automatic vehicle identification *Emergency telephone*
Communication with users		
Emergency telephones *Radio communication (users)*	Alarm signs/signals	Loudspeakers
Evacuation or protection of users		
Emergency exits Smoke control	*Lighting (emergency)* Fire-resistant equipment	Failure management
Reduction of accident importance		
Fire-fighting equipment Rescue teams	Drainage *Road surface (non-porous)*	Emergency action plan *Escort*
Reduction of the consequences on the tunnel		
Fire-resistant structure	Explosion-resistant structure	

Measures to reduce the probability of an accident

Tunnels cross-section and visual design

Many elements of the tunnel cross-section have an important influence on safety. The number of tubes and the number of lanes per tube have a clear effect on the frequency and the consequences of accidents. The width of the lanes can affect accident rates. The camber influences drainage efficiency and thus the consequences of a dangerous liquid spill. Hard shoulders can have an effect on accident frequencies but they are especially useful for the access of the emergency teams to mitigate the consequences. Safety barriers between the carriageway and the footpath may have some positive impact on accident severity, although they have a very negative effect on escape and rescue. Lay-bys for emergency parking in case of vehicle breakdown will reduce the probability of collision. The visual perception of the driver determines to a high degree the comfort and the driving speed, which in turn will reflect on the safety. Alignment and lighting (see below) are key elements; the picture is, however, not complete without a design that takes the shapes and colours of the tunnel cross section into account.

Alignment

Ascending gradients (ramps) can have an unfavourable impact on accident rates because of very slow vehicles. Descending gradients increase the risk of accidents. Horizontal curves can have an unfavourable effect on accident rates, usually in combination with other factors such as speed or descending gradient. Clearly, the design of the vertical and horizontal alignment is an important factor in limiting the frequency of accidents.

Lighting (normal and emergency)

Accident rates are higher in the entrance zone of tunnels, due to visibility problems, particularly when driving from a very luminous outside environment into the much darker tunnel environment. For this reason, to limit the frequency of accidents, sufficient lighting is necessary during the daytime in the threshold zone; it should be gradually reduced inside the tunnel. National or international recommendations ensure appropriate lighting levels; higher levels do not improve safety. Marker lights can be installed at a height of one metre above the footpath. This facilitates evacuation in cases where smoke obscures normal lighting.

Maintenance

Poor maintenance, for instance in the form of defects in the pavement, equipment and lighting failures or inferior cleaning in the tunnel, results in reduced safety for drivers. A reliable maintenance operation is therefore vital for reducing the probability of an accident.

Road surface

The pavement within the tunnel must have the same qualities as that in the open in terms of friction and evenness. However, porous surfaces should be avoided when dangerous goods are authorised as such surfaces can increase the consequences of a liquid spill and of a subsequent fire.

Speed limit

A lower speed limit imposed either at the entrance of or inside a tunnel can have drawbacks, such as creating congestion on roads with heavy traffic. If it concerns only part of the traffic, for instance vehicles carrying dangerous goods or all heavy vehicles, it tends to increase the difference in speed between vehicles, which may create extra collision risks. Another difficulty is to enforce this measure. However, reducing speeds globally decreases the frequency and severity of accidents. Speed reductions are considered to be one of the most cost-effective measures, provided that the aforementioned difficulties can be overcome.

Prohibition to overtake

Overtaking is generally prohibited in two-way tunnels with one lane in each direction. In one-way tubes, overtaking is generally allowed for passenger cars; it is recommended to prohibit it for all heavy vehicles. There is no reason that this measure should apply only to vehicles carrying dangerous goods.

Escort

Escort consists in stopping vehicles transporting dangerous goods before they enter a tunnel, performing a visual check, then taking small groups (with sufficient distances between the vehicles) through the tunnel accompanied by vehicles carrying fire-fighting and other safety equipment. Escort vehicles can be provided behind the dangerous goods vehicles, or both in front and behind. Other vehicles may or may not be allowed in the tunnel during the escort. This measure is expensive but is expected to reduce the frequency of accidents as well as their consequences, since a fire will be detected and fought very quickly and fewer people will be present near the burning vehicle. A less expensive (and less effective) measure is to make dangerous goods vehicles stop and give notice before they enter so that the operator can give them permission to enter once all useful precautions have been taken (for example, avoiding the simultaneous presence of coaches).

Distance between vehicles

A sufficient distance between vehicles in motion reduces the frequency of nose-to-tail accidents. A drawback is that it also reduces the traffic capacity of the tunnel and can lead to congestion if the traffic is high. A sufficient distance between vehicles stopped inside a tunnel because of an accident can reduce the consequences because fewer people are near the accident and a possible fire will not be able to spread as easily. However, distances between vehicles, either in motion or stopped, are very difficult to enforce.

Vehicle checks

Another measure, which is less expensive than escort, is to stop vehicles carrying dangerous goods (or all heavy goods vehicles) before they enter the tunnel and perform a visual check before they can enter. Leakages and/or over-heated parts can be detected in this way. Automatic equipment to detect over-heated vehicle parts is currently being tested.

Measures to mitigate the consequences of an accident

Close-circuit television (CCTV)

Major tunnels are equipped with a close-circuit television (CCTV) which covers the whole length of the tunnel and the areas around the portals. The purpose is two-fold:

- To monitor the traffic flow, and possibly also dangerous goods vehicles if they must give prior notice or are escorted.
- To detect, or at least identify, any incident or accident and obtain the information necessary to take the appropriate actions.

Generally the operator does not monitor the whole tunnel permanently, but any alarm (automatic traffic incident detection, lifting of a telephone or an extinguisher, etc.), will draw the operator's attention to a screen which is automatically trained on the part of the tunnel where the alarm comes from.

Automatic traffic incident detection

An automatic traffic incident detection system is able to detect a change in traffic conditions, such as stopping or a significant reduction in speed. Used in combination with CCTV, the operator is able to receive information quickly on the cause of the changes in traffic condition. This can result in effective action to lessen the possibility of an accident at the end of a queue (reducing the accident frequency) or, in case of an accident, facilitate the evacuation of road users and alert the emergency teams (reducing the accident consequences). Such a system is a useful complement to CCTV (since the operator does not permanently watch the whole tunnel) and other alarm systems such as emergency telephones.

Automatic fire detection

Automatic fire detection facilitates rapid action in case of a fire. Carbon monoxide and opacity sensors are implemented in ventilated tunnels: they will detect the products of the fire, but cannot differentiate them from pollutants normally emitted by vehicles. A specific fire detection system is especially useful in unmanned tunnels when the ventilation regime in case of a fire is different from the regime that will be triggered automatically in case of pollution (for instance, smoke exhaust instead of fresh air blowing). In manned tunnels, automatic fire detection can reduce detection time and aid in localising the fire. However, indirect fire detection can be obtained through an incident detection system used in combination with a CCTV.

Radio communication (services and users)

Radio signals cannot be received underground. More and more tunnels are now equipped with re-broadcasting systems, which may aim at all or part of the following users:

- Emergency services, allowing them to communicate with their control centres and with the tunnel control centre.
- Motorists, so that one or several public radio stations can be re-broadcast; in case of an emergency, the tunnel operator can break in on these radio frequencies and provide information and safety instructions; mobile phones can also be re-broadcast and used to alert users or enable people in difficulty to call for help if needed.
- Tunnel personnel, to improve the safety and efficiency of maintenance and safety teams.

Automatic vehicle identification

An automatic vehicle identification system would provide the operator with information on vehicles carrying dangerous goods that enter the tunnel. In case of an accident, the appropriate actions would be initiated since the properties of the goods involved would be known. It would also facilitate the enforcement of restrictions, provided that the detection is fully automated and takes place at some distance ahead of the tunnel. Such a system is technically feasible but would require standardisation of the onboard equipment as well as internationally enforceable regulation.

Emergency telephones

Most tunnels are equipped with emergency telephones at regular intervals. This equipment is important for safety:

- It can be used by motorists to inform the tunnel operator or the police about the situation in the tunnel and thus give the alarm in case of an accident.
- Users can be informed of the steps to be taken in a given situation.
- It can also be used by emergency services in the tunnel if no other means of communication is available.

Alarm signs/signals

Fixed signs are used to indicate safety facilities that can be used by motorists, such as extinguishers, emergency telephones and exits. In addition, traffic lights are used in most tunnels to prevent vehicles from entering the tunnel in case of an accident; traffic lights are also implemented inside long tunnels to stop vehicles in the case of an accident instead of letting them conglomerate at the site of the accident. The main problem is the compliance of drivers with such signals. Therefore, in manned tunnels, it is recommended that variable message signs be installed to provide explanations to drivers. Several countries install barriers at tunnel portals.

Loudspeakers

Several countries install loudspeakers in road tunnels. These can be used to provide instructions to an individual motorist who has left his vehicle or to all tunnel users in case of an emergency. However, a number of problems have been encountered with the use of loudspeakers due to the poor acoustic properties of most tunnels, the ambient noise created by road traffic and ventilation, and the number of languages which need to be used to allow the majority of users to understand the message.

Emergency exits

The following evacuation possibilities exist:

- Exit the tunnel tube on foot (or by car in low traffic two-way tunnels).
- Direct communication with the outside (in shallow tunnels).
- Cross-connections between tunnel tubes (in tunnels with two or more tubes).
- Special escape corridors (in cut-and-cover or immersed structures) or galleries (in deep tunnels).
- Shelters (in deep one-tube tunnels, safe ventilated fireproof rooms with telephone, often connected with the outside, through a fresh air ventilation duct for instance).

Emergency exits are very useful to limit the exposure of users to a hazardous environment in the case of an accident involving dangerous goods.

Smoke control

Smoke control (evacuation) is generally carried out through the tunnel ventilation equipment. Due to a significant decrease in vehicle pollutant emissions, the choice and design of the ventilation system is increasingly determined by the needs in case of a fire. Longitudinal ventilation aims at creating a uniform airflow along the tunnel, most often using jet fans. In case of a fire, smoke is pushed to a portal. This system is well suited for one-way tubes with no congestion. In other cases, semi-transverse or transverse ventilation can be used. Under normal operating conditions, air ducts bring fresh air inside the tunnel while other ducts may be used to exhaust polluted air. In case of a fire, the equipment is operated so as to limit the longitudinal airflow in order to facilitate smoke stratification at the ceiling and leave a layer of clear air below. At the same time, smoke is extracted through openings in the ceiling. This extraction is usually dimensioned for a lorry fire, not for a very serious dangerous goods fire.

Fire-resistant equipment

Not all pieces of equipment need to be fire-resistant; for instance, lighting or video cameras at the ceiling will anyway be obscured by smoke in hot zones. However, it is necessary that the apparatus on both sides of a fire continues to function. This means that the power supply and telecommunication networks must be protected. Ventilation equipment must also meet fire-resistance requirements in order to ensure appropriate smoke control under high temperatures.

Failure management

During an accident, some structural components and pieces of equipment may fail due to high temperatures or other reasons. Consequently, the various systems must be designed in such a way that this failure has limited effects. The following failure management methods can be used:

- *Redundancy:* for instance, when the normal power supply fails, an emergency power supply will take over.
- *Fail-safe system:* for instance, loss of power supply will leave emergency doors unlocked.
- *Partitioning:* this is used, for instance, for leaky feeders or emergency lighting – if one section is lost, other sections will continue to function.

Fire-fighting equipment

All tunnels provide fire-fighting equipment to be used by motorists: extinguishers are placed at regular intervals and some countries also provide fire hoses. This equipment has proved to be effective in extinguishing starting fires. All important tunnels include fire hydrants, some also provide hoses for use by firemen. These are generally supplied by specific water reservoirs or the local water distribution network. Automatic extinguishing systems (sprinklers) are not recommended as safety equipment in tunnels because of the hazards they may create for people present in the fire and smoke zone. However, they can be used to protect the tunnel once evacuation is completed.

Rescue teams

Public rescue services are called in case of an emergency in a tunnel. Their access to the tunnel may be hindered by long distances or traffic congestion (which may be caused by the accident itself). Once at the tunnel, access to the accident site depends on the specific case (through the tube with the accident, a second tube, direct accesses from the open, etc.). Although their action is very important in mastering a fire or evacuating injured people, in most cases a fire will have reached full intensity and fatalities will have occurred before their arrival. For this reason, in tunnels with high risks (long one-tube tunnels with heavy traffic, or shorter very heavily trafficked tunnels), rescue teams can be stationed at the tunnel portals so that they are able to intervene within a few minutes.

Drainage

A drainage system is usually built in tunnels to evacuate polluted water from the carriageway surface and (often separately) clear water from the ground. This system is also very useful for evacuating an accidental spill of a dangerous liquid. In order to increase its efficiency in case of a sudden and significant release, the distance between inlets can be reduced or a slot gutter used. Siphons can be built to avoid flame propagation and explosions in the underground system in case of a flammable liquid spill.

Emergency or action plan

An emergency or action plan is indispensable to quickly start all necessary actions and ensure co-ordination between the many intervening parties in case of a serious accident. It must describe the actions to be taken by the operator and emergency services and the communication between them. Its preparation must involve all parties and be based on a number of accident scenarios. The emergency plan must be regularly updated to take into account all changes in the tunnel, traffic and environment. Training, including exercises at regular intervals, is necessary for the plan to be effective when an emergency occurs.

Fire-resistant structure

In the absence of any special provision, tunnel structures may collapse, at least locally, in the event of a serious fire. This may endanger the safety of users and emergency services and require costly repairs and a long traffic disruption. The need for fire-resistance provisions depends on the type of tunnel and the role of the specific structure. The main structure of rock tunnels does not generally require any special fire resistance; in contrast, immersed tunnels need sufficient protection to prevent the tunnel flooding due to a local failure during a fire. Where they are provided, shelters must be fire-resistant. Depending on their role, ventilation ducts may also require some level of fire resistance to maintain an efficient smoke control.

Explosion-resistant structure

An explosion-resistant structure is not needed for safety reasons because an explosion capable of damaging the tunnel will not leave any survivors. However, when Grouping A (see Chapter 4) is allowed, the stability of the possible second tube in case of an explosion in the first one should be checked. Apart from this specific point, explosion resistance is only aimed at protecting the tunnel itself. Its high cost generally prevents it from being cost-effective if protection against very serious explosions is sought.

Ranking of the measures

A number of tunnel operators representing 14 European tunnels were asked to complete a questionnaire (Van der Sluis *et al*., 1998). The first part of the questionnaire requested general information about the tunnel, the second part requested information about the measures being investigated, and the third part concerned the ranking of the measures. The requested information included the cost of the measure, its effect on reducing the number of victims and the potential reduction in damage to the tunnel.

Based on this information, each measure was given one of the following three rankings:

1. Low effect.
2. Medium effect.
3. High effect.

The measures were then divided into three effect-groups: the 25% of the measures with the highest score forms the group of measures with a high effect. The following 50% are defined as the group having a medium effect. The remaining measures are grouped in the low-effect group.

Cost information was difficult to come by since the questionnaire responses were incomplete. To resolve this problem, measures were categorised as low-, medium- or high-cost.

The three categories for both the effect on victim reduction and the cost of the measures are best visualised in a 3×3 matrix showing the efficiency of each measure (Table 7.2). In the 3×3 matrix, three sections can be distinguished. The cell (low cost) × (high effect) indicates measures that are very efficient. The cell (high cost) × (low effect) indicates measures that are considered inefficient. The remaining seven cells contain measures with less pronounced efficiency levels. These seven cells together form the so-called “grey area”.

Table 7.2. **Ranking of the measures for their efficiency on victim or damage reduction**

	High effect	Medium effect	Low effect
Low cost	**VERY EFFICIENT**		
Medium cost			
High cost			**NOT EFFICIENT**

The same 3×3 matrix can be used to visualise the efficiency of the measures in terms of reduction to the damage of the tunnel structure.

The study showed that measures score differently when regarding their effect on reducing the number of victims compared to their effect on reducing the damage to the tunnel structure.

Conclusions

The main conclusions of the study are:

- The method presented to rank measures on efficiency should be performed for a specific tunnel, since every tunnel is unique.
- The method is a qualitative one and can be used to select the most promising measures for a specific tunnel in order to reduce the risk of the transport of dangerous goods.
- When measures are ranked, the effect on the reduction of victims and the damage to the tunnel structure must be distinguished since these rankings can be very different.
- The ranking used in this study consists of three groups:

  1. Measures with low cost and high effect and therefore very efficient and recommended.
  2. Measures with high cost and low effect and therefore not efficient and not recommended.
  3. Measures in the "grey area".

It is recommended that a low-cost measure should always be investigated, even if this measure has only a medium or low effect.

The effectiveness of native risk reduction measures

Introduction

Native measures are those already included in the QRAM described in Chapter 5. A number of sensitivity tests were performed to examine how the results of the QRAM are affected by changes in the risk reduction measures (Pons, 2000). The "native" measures include fire resistance, explosion resistance, smoke control, drainage, emergency exits, delay to close the tunnel and delay to activate ventilation. The cross-section (number of lanes, camber) and gradient were also examined. Although a total of nine parameters were considered in this study, the cross-section, gradient and fire and explosion resistance parameters are tunnel specific and therefore were not varied within the scope of this study. An earlier version of the QRAM was used which considered only the first ten scenarios detailed in Table 5.1.

Methodology

A sensitivity study was undertaken in order to examine how the results of the QRAM are affected by changes in "native" risk reduction measures. This study was undertaken for the following tunnels:

- V Tunnel (2 kilometres, 2 tubes, longitudinal ventilation).
- H Tunnel (3 kilometres, 1 tube, longitudinal ventilation).
- W Tunnel (6.7 kilometres, 2 tubes, longitudinal ventilation).
- S Tunnel (8.6 kilometres, 1 tube, semi-transverse ventilation).

- C Tunnel (1 kilometre, 2 tubes, longitudinal ventilation).
- O Tunnel (3.3 kilometres, 1 tube, 3 lanes, semi-transverse ventilation).

The tunnels considered in this study were used as examples only and it is possible that the data do not correspond to the actual measures/devices/characteristics of those tunnels. The basic characteristics of the tunnels were reported by the relevant authorities; however, the accuracy of this data was not verified. The tunnels are therefore not named.

The sensitivity study was carried out on the same basis for all tunnels: A base case was defined corresponding, as far as practicable, to the actual definition of the tunnel being considered. The "native" risk reduction parameters were varied as follows:

- *Emergency exits:* none, every 100 metres, 250 metres, and 500 metres.
- *Drainage:* none, 0.1 m^2 at 100 metres intervals, 0.3 m^2 at 20 metres intervals, 5 centimetres wide continuous slot, and a 9 centimetres wide continuous slot.
- *Smoke control:* For longitudinal systems, normal ventilation = 0, 6 m/s or corresponding to the base case; emergency ventilation = 0, 2, 3, 4, and 5 m/s. For transverse systems, the extraction rate and the longitudinal air flow are modified.
- *Time taken to have emergency ventilation fully functional:* 5, 10, 12 and 15 minutes.
- *Delay for stopping tunnel access:* 1, 6, 8 and 11 minutes.

The time taken to activate emergency ventilation and the delay for stopping access to the tunnel was not considered independently. For example, a one-minute delay for stopping tunnel access corresponded to a five-minute delay for emergency ventilation to become operational (the actions of starting ventilation and stopping traffic being taken simultaneously).

The "base conditions" for each tunnel are presented in Table 7.3. For the O and S tunnels, a semi-transverse ventilation system is used. In normal use, fresh air is blown in at a 30% rate of maximum capacity, where the total capacity is 516 m^3/s for the O tunnel and 554 m^3/s for the S tunnel and no extraction is performed. In an emergency situation, the extraction is changed to 110 m^3/s in the area of the incident for both tunnels. In every situation (normal and emergency), a pressure gradient of 6 Pa exists between the two portals for the O tunnel and 50 Pa for the S tunnel.

The following parameters were modified: emergency exits, drainage interval and opening area, ventilation delay, access delay and ventilation conditions. Each parameter was modified in turn, while the others were maintained at their base values.

Table 7.3. **Base case values for the six tunnels**

Base case	Unit	C Tunnel	H Tunnel	O Tunnel	S Tunnel	V Tunnel	W Tunnel
Length	m	1075	1855	3681	8602	2020	6700
Number of tubes	-	2	1	1	1	2	2
Direction	-	1-way	2-way	2-way	2-way	1-way	1-way
Emergency exits interval	m	200	-	400	200[4]	100	250
Drainage (interval)	M	20	50	Cont[1]	Cont	100	20
Drainage (opening)	m^2	0.075	0.09	0.07	0.09	0.3	0.06
Emergency ventilation delay	min	5	1[5]	1[5]	1[5]	1[5]	3
Forbidding access delay	min	15	5	15	15	1	1
Ventilation system	-	Long[2]	Long	Semi[3]	Semi	Long	Long
Normal ventilation air velocity	m/s	1	3.3	-	-	3.4	1
Emergency ventilation air velocity	m/s	4.5	2.2		-	3	4
Blowing air rate	%	-	-	30	30	-	-
Extraction	m^3/s	-	-	110	110	-	-
Pressure difference	Pa	-	-	6	50	-	-

1. Cont: Continuous drainage.
2. Long: Longitudinal ventilation.
3. Semi: Semi-transverse ventilation.
4. In reality, 800 metres.
5. In reality, the time to start the ventilation + the time for the ventilation to reach its full capacity (a minimum of three minutes) has to be used.

Results

In interpreting the results, account should be taken of the uncertainties related to the model itself and the description of the considered case (*e.g.* route, road users, local population and meteorological conditions). In the case of a sensitivity study, the uncertainties that must be considered relate only to the parameter that is varied (all other parameters remain constant). This can lead to slight differences being interpreted as significant, differences that otherwise would need to be neglected.

Average distance between two emergency exits

Emergency exits were considered to be gates/ways leading to a safe gallery (second tube, fresh air duct, etc.) that allow evacuation towards the tunnel portals *a priori* safely. Therefore, shelters distributed inside the tunnel (without access to a safe gallery) were not considered as emergency exits.

The average distance between two emergency exits is expected to have an effect on evacuation, and therefore has an effect on the number of victims occurring for a given incident. No effect on the scenario frequencies is expected, but the probability of fatalities could possibly be reduced when the emergency exits are closer.

The sensitivity study showed that when the average distance between two emergency exits is decreased from the tunnel length to 100 metres, both the *expected number of fatalities* and the *calculated maximum number of victims* decrease for the 20 MW fire and motor spirit vapour cloud explosion (VCE) scenarios. Sometimes a decrease is observed for the 100 MW fire, motor spirit pool fire and liquefied petroleum gas (LPG), boiling liquid expanding vapour explosion (BLEVE), VCE and torch and ammonia scenarios. Decreasing distances between emergency exits results in a decrease of the *probability to have a given number of victims*.

Drainage system

Regarding the ten scenarios in the version of the quantitative risk assessment model used for the sensitivity study, the only scenarios that can be affected by the drainage system are the motor spirit pool fire and the motor spirit VCE.

The drainage system is expected to have an effect on the pool spread, and therefore on the number of victims calculated for a given incident. No effect on the scenario frequencies is expected, but the probability of fatalities could possibly be effected when the open area of the drainage system is larger.

The sensitivity study showed that when the open area of the drainage system is increased from no drainage to a continuous slot with a 0.09 metre opening, both the *expected value of fatalities* and the *maximum number of victims* always decrease for the motor spirit VCE scenario and sometimes decrease for the motor spirit pool fire scenario. The drainage system does not affect any of the other scenarios nor is there a noticeable (overall) effect on the *probability to have a given number of victims*.

Delay to activate the emergency procedures

The delays to activate the emergency procedures are expected to have an effect on the number of people present in the dangerous zone when the scenario is initiated (access forbidden after a short while) and the physical consequences of the scenarios. This effect on the physical consequences is expected to result in a risk reduction as delays are decreased, if the considered scenario is a fire or a toxic release. In case of a VCE, the modification of the ventilation (from normal to emergency) leads to a modification of the flammable mass (between the upper and lower flammability limits). It is not possible to say *a priori* if this flammable mass is lower or higher after the ventilation modification has occurred. So the modification of the delay in activating the emergency ventilation could lead to no clear tendency or even to tendencies which are reversed compared to those observed for the other scenarios.

No effect on the scenario frequencies is expected, but the probability of fatalities could possibly be effected when the emergency procedures are activated faster.

The sensitivity study showed that when the time to activate the emergency procedures is decreased, both the *expected number of fatalities* and the *maximum number of victims* decrease for all scenarios, except for the motor spirit VCE scenario. This scenario shows both increases and decreases, depending on the case. The largest effects are observed for the LPG scenarios. When the delay decreases, this also results in an (overall) decrease of the *probability to have a given number of victims*.

Emergency ventilation

For this parameter, the presentation and interpretation of the results have been separated for the tunnels with a semi-transverse ventilation system (O tunnel and S tunnel) and the tunnels with longitudinal ventilation (C tunnel, H tunnel, V tunnel and W tunnel).

The emergency ventilation parameter is expected to affect the physical consequences of the considered scenarios. No effect on the scenario frequencies is expected, but the probability of one or more fatalities could possibly be reduced when the flow rate of the ventilation increases.

Transverse ventilation

Regarding the emergency ventilation applied to semi-transverse systems, a set of four calculations was performed with a moderate fresh air supply blown all along the considered tunnels (30% of the capacity) and an extraction of respectively 0, 50, 110, 200 m^3/s in the segment where the accident takes place. A fifth calculation was performed with a 110 m^3/s extraction but with no fresh air blown all along the tunnel (the effect of atmospheric conditions on longitudinal flows remains constant from the normal to the emergency situation).

The sensitivity study showed that when the extraction of air in the segment where the accident takes place increases, the *expected number of fatalities* and the *maximum number of victims* decrease for the 20 MW fire scenarios. In addition, an increase in victims for the ammonia scenario and slight decrease in victims for the 100 MW fire and motor spirit pool fire scenarios are observed. There is no effect on the VCE and BLEVE scenarios.

Longitudinal ventilation

For tunnels with longitudinal ventilation, the sensitivity studies show that when the emergency ventilation is increased in tunnels with an initial ventilation not sufficient to avoid back-layering, the *expected number of fatalities* and the *maximum number of victims* decrease for all but the LPG BLEVE scenario. These effects are only observed when the emergency ventilation is increased from 0 to 3 m/s. Furthermore, it is noted that this decrease also depends on the delay to activate the emergency procedures; the effect is greater when the delays are shorter.

For the tunnels with a sufficient initial air velocity to avoid back-layering, the sensitivity study shows that an increase of the emergency ventilation leads to a significant decrease of the *expected number of fatalities* and *the maximum number of victims* of the fire and ammonia scenarios. This effect is much smaller in the H tunnel. These decreases in the expected number of fatalities are especially observed for high emergency velocities (3 m/s and faster). The effect of the BLEVE scenario, which is after all a sudden phenomenon, does not vary when the emergency ventilation is modified.

Conclusions

As a conclusion to this part of the study, the main observations/interpretations obtained from the tunnels studied are summarised. Generally, two main indicators have been used: the expected number of fatalities and the maximum number of victims. It appears that even if in some cases the expected number of fatalities is subject to limited variations when one of the examined parameters is modified, substantial decreases of the maximum number of victims can be observed.

Regarding the studied tunnels, it can be concluded that:

- The average distance between emergency exits is most important for the 20 MW fire and motor spirit VCE scenarios in all tunnels, but can also have an important effect on the 100 MW fire, motor spirit pool fire, LPG BLEVE and ammonia scenarios in some tunnels.
- The drainage system is most important for the motor spirit VCE scenario in all tunnels and motor spirit pool fire in some tunnels.
- The delay to activate the emergency procedures is important for all scenarios except the motor spirit VCE scenario. The largest effects are observed for the LPG scenarios.
- The emergency ventilation is most important for the 20 MW fire scenario in tunnels with a semi-transverse ventilation system. No effect is observed on the VCE and BLEVE scenarios.
- In tunnels with a longitudinal ventilation, the effect of the emergency ventilation depends on the initial air velocity:
  - In cases where the initial ventilation is not sufficient to avoid back-layering, the emergency ventilation will have an effect on all but the LPG BLEVE scenario, when the emergency ventilation is increased from 0 to 3 m/s. These effects are more pronounced in tunnels with short delays to activate emergency procedures.
  - In cases where the initial ventilation is sufficient to avoid back-layering, the emergency ventilation will have a huge effect on the fire and ammonia scenarios in unidirectional tunnels. The effect on the remaining scenarios in unidirectional and all scenarios in bi-directional tunnels are less pronounced and non-existent for the BLEVE scenario.

Effectiveness of "non-native" risk reduction measures related to accident probabilities

Introduction

This section is based on the assessment of a number of the "non-native" risk reduction measures in terms of their effect on risk (Saccomanno *et al.*, 2000). However, the influence of changes in the "non-native" safety measures can only be inferred by introducing external adjustment to the base model estimates. In the absence of a thorough and objective procedure for introducing such changes, the application of the model to the "non-native" safety measures is somewhat speculative in nature.

In this section, the objective is to develop a method to introduce these "non-native" safety measures into the existing QRAM in such a way that they can be objectively evaluated.

Methodology

Figure 7.1 illustrates the framework of the approach for considering "native" and "non-native" safety measures in the existing QRAM. The framework consists of six modules:

1. Definition of a base case for the analysis (assumptions, conditions and risk inputs).

2. Estimation of the risks (probability and consequences) using the QRAM (based on “native” input measures).

3. Development of a list of “non-native” measures of interest to tunnel authorities and decision makers.

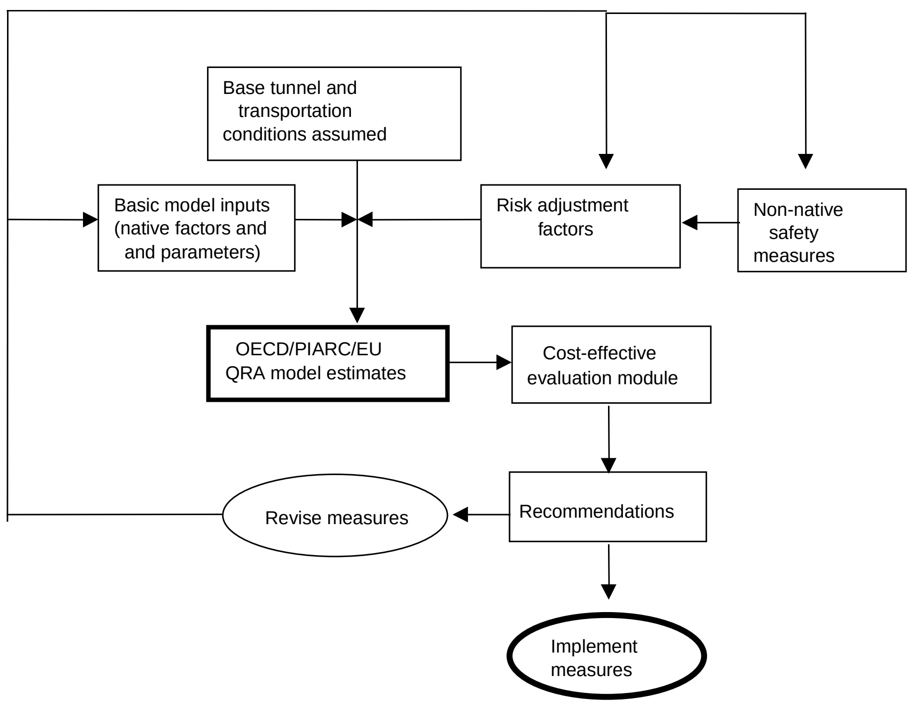
4. Provision of a link between the “non-native” measures and their influence on the risk components in the model; obtaining the risk adjustment factors for the different components of the risk.

5. Considering the uncertainty in the adjustment factor values.

6. Obtaining the revised estimates of the risk and evaluation of the cost-effectiveness of these measures.

This framework provides a formal link between the adjusted risk estimates for different safety measures and a decision module. The decision module considers the cost-effectiveness of each safety measure and makes the recommendations for the implementation and revisions.

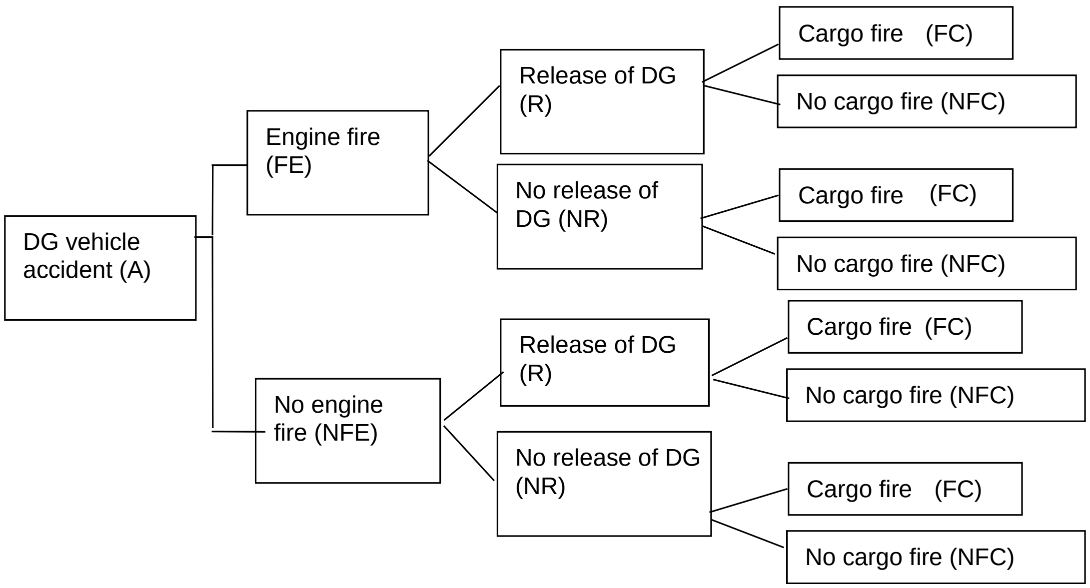
Figure 7.1. **Modifying the quantitative risk assessment model for “non-native” measures**



The combined effect on each risk component of the uncertainty in the adjustment factors is obtained by applying Monte Carlo methods to generate a random sample of values for each factor based on its underlying log-normal distribution. A joint probability expression for the risk is used to combine the input samples of the adjustment factors to yield a sample of values for each component of risk. These values are fitted with a distribution using empirical methods. In this section, the analysis has been limited to the transport of flammable liquids in bulk through a single tube tunnel with one lane in each direction. The risks are estimated for the “in-tunnel section”, such that differences in the risk at the tunnel transition zones (entrance and exit) have been ignored. While recognising that the risk for the transport of dangerous goods is a complex process, with a wide spectrum of probability and consequences, the treatment of a few major probability risk components or outputs in this section has been simplified. This is illustrated in Figure 7.2.

Figure 7.2. **Event tree of the basic risk components considered in this section**

The tree considers a dangerous goods accident to be the initiating event



A similar event tree was developed for the non-accident-initiating event, for which all subsequent events are repeated, and the base probabilities estimated.

The risk component probabilities along each branch in Figure 7.2 are expressed as joint probabilities of all preceding branches, calculated from the base case probabilities which serve as the basis for comparing the adjusted risks following the introduction of specific safety measures.

The study in Phase I had established the list of "non-native" safety measures of Table 7.1, which reflects five broad types of controls, *i.e.* tunnel design, incident detection, traffic control, traffic regulation and emergency response. Five representative safety measures from the original working group list are considered in this section:

- Change from nothing to an adequate fire-resistant tunnel structure.
- Change of the speed limit (reduction of 20 km/hour).
- Change from no escort to escort behind dangerous goods vehicles.
- Change from no CCTV to CCTV.
- Change from nothing to adequate fire-resistant equipment.

Risk component estimates and adjustment factors

For the risk reduction measures, tunnel case and accident scenarios, the adjustment factor for each of the 15 risk components inputs considered was estimated.

The adjustment factors are assigned a unique log normal distribution, with the mean being equal to the estimates and a standard deviation assumed in each case to be 10% of the mean. The speed control is an exception since the variation in opinions indicated a larger (20%) uncertainty. To reflect the uncertainty in the adjustment factor estimates, a sample of 20 000 random numbers was generated. The samples were combined using the joint probability relationship associated with each risk component. This yielded a combined risk estimate and corresponding distribution for each of the components considered.

For each risk component, a number of useful statistics were obtained. Table 7.4 summarises the risk component estimates of the means, 10th and 90th percentile for each safety measure and the base case. Also included is an estimate of the probability that the base case estimate will be exceeded by values from the distribution of the risk following the introduction of each safety measure and its adjustments.

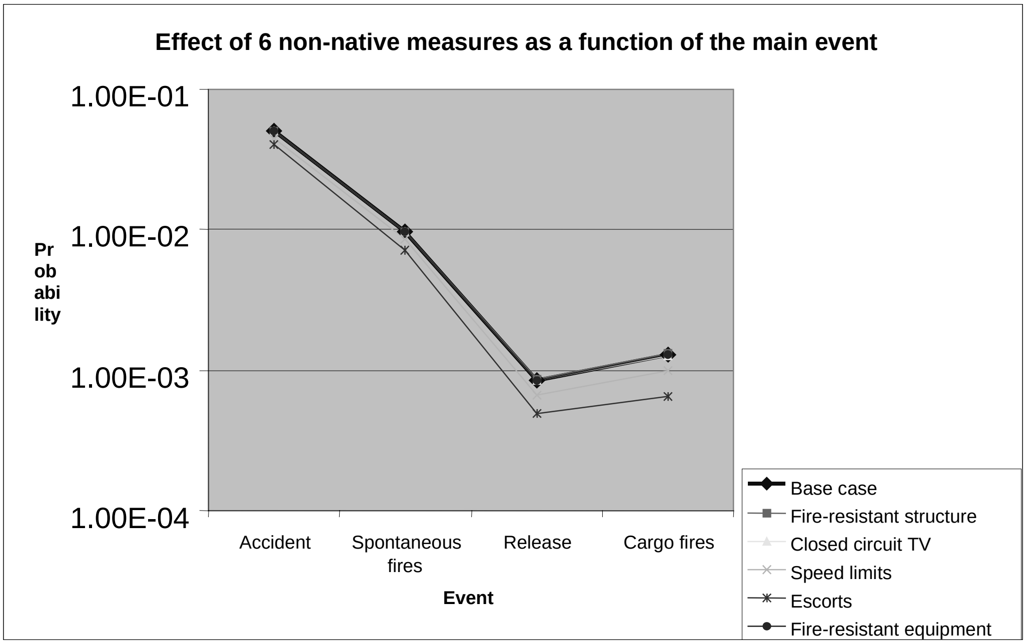
The relative merits of introducing each safety measure can be compared graphically with the risk estimates for the base case. This is illustrated in Figure 7.3 for the means of each measure considered in this section. A similar graph can be obtained for each of the statistical indicators generated by the simulation.

Table 7.4. **Risk component estimates means, 10th and 90th percentiles and the probability of exceeding the base case**

	Unit	Base case			Fire-resistant structure				CCTV			
	Per X years	Mean	10%	90%	Mean	10%	90%	P X>base	Mean	10%	90%	P X>base
Accident	100	5.0	4.4	5.7	5.0	4.4	5.7	45%	5.0	4.4	5.6	45%
Spontaneous fires	1 000	9.7	8.3	11.3	9.7	8.3	11.3	45%	9.8	8.4	11.2	45%
Release	10 000	8.4	6.9	10.0	8.5	7.0	10.0	55%	8.4	6.9	9.9	45%
Cargo fires	1 000	1.3	1.0	1.6	1.3	1.1	1.6	50%	1.3	1.0	1.5	40%

	Unit	Speed limit reduction				Escort dangerous goods				Fire-fighting equipment			
	Per X years	Mean	10%	90%	P X>base	Mean	10%	90%	P X>base	Mean	10%	90%	P X>base
Accident	100	4.5	3.4	5.7	25%	4.0	3.5	4.5	5%	5.0	4.4	5.6	45%
Spontaneous fires	1 000	8.5	6.4	11.0	25%	7.2	6.1	8.3	5%	9.7	8.3	11.3	45%
Release	10 000	6.6	4.8	8.5	10%	4.9	4.1	5.8	0%	8.4	6.9	10.2	45%
Cargo fires	1 000	1.0	0.7	1.3	10%	0.6	0.5	0.8	5%	1.3	1.0	1.6	45%

Figure 7.3. **Risk component means for the different safety measures and base case**



Results

The results developed in this section suggest that introducing a fire-resistant structure and access to fire-resistant equipment has little or no influence on the risk probabilities compared to the base case (no change). This result was expected since these measures are designed to reduce the damages associated with dangerous goods and fire events rather than reduce their likelihood of occurrence. Introducing a CCTV system along the tunnel has a negligible reduction effect on the chance of a cargo fire. The largest risk reduction effects are those resulting from the reduction of the speed limit and the introduction of an escort vehicle behind the dangerous goods being transported. The use of escorts has the most desirable effect on reducing all components of risk, *i.e.* accident, engine fire, release and cargo fire.

From a separate analysis for the same base case, it was concluded that the following safety measures have little, if any, influence on the risk probability:

- Change from nothing to adequate explosion resistance.
- Change from standard lighting to maximum lighting for emergencies.
- Change from standard lighting to marker lights for evacuation.
- Change of distance between stopped vehicles from 1 to 50 metres.
- Change from normal emergency services to special teams at portals.

The analysis in this section applies to flammable liquids. For toxic, corrosive and non-combustible liquids, the focus of the analysis is on the probability of release and engine fires.

Conclusions

The procedure outlined in this section permits an extension of an existing comprehensive QRAM to include risk reduction measures that were not part of the original model specification. This was done without obtaining new data or involving a re-specification of the major parts of the existing model. This initial application of the procedure to a specific tunnel and type of dangerous goods has produced some promising results which provide useful information to decision makers on the relative merits of the considered safety measures.

Assessment of the "non-native" risk reduction measures related to response times

Introduction

In order to develop and expand the capability of the QRAM, a study was undertaken by Hall *et al.* (2000) to assess the cost effectiveness of a range of risk reduction measures currently employed in road tunnels.

The objectives were:

- To develop a methodology for the analysis of time-related risk reduction measures.
- To estimate the effects of "non-native' risk reduction measures.
- To estimate the approximate costs of "native" and "non-native" measures.

The effectiveness of some risk reduction measures is related to the way in which they reduce delays for occupants, tunnel operators and emergency services in response to an emergency. For example, evacuation might be initiated within a few minutes in a tunnel with CCTV or automatic traffic incident detection, but without such systems there may be a significant delay before evacuation gets underway. In this way, such systems can have an effect on the pre-movement times for the evacuation and consequently an effect on the injuries and fatalities. If the appropriate time intervals are identified, the QRAM can be used to quantify the effects by modifying the default pre-movement times.

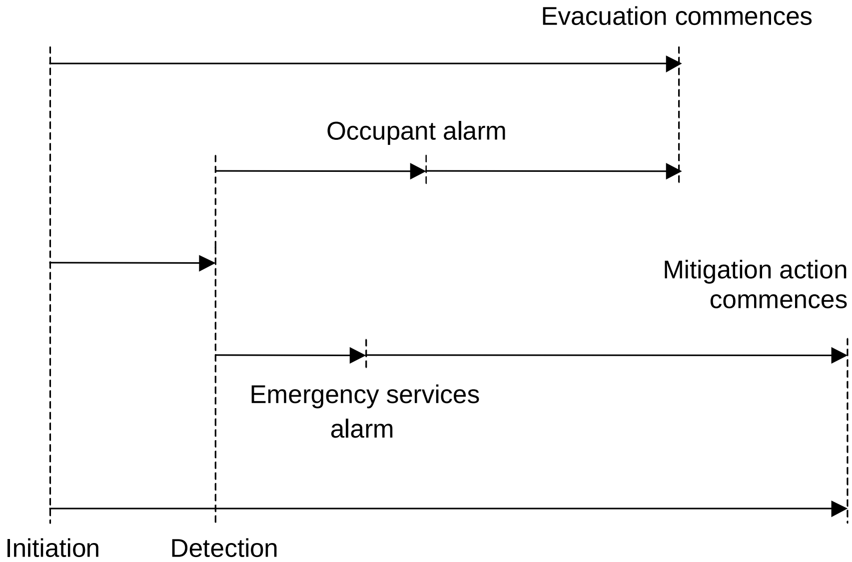
Methodology

The sequence of events following a tunnel incident can be represented as shown in Figure 7.4 by a number of distinct phases.

First, there is a detection phase with a finite time interval between initiation of the incident and the detection. Subsequently, it is appropriate to consider two separate timelines. One timeline concerns the response of the occupants and their implications for life and safety. After an incident is detected, there is an alarm phase during which the tunnel occupants at some distance from the incident become aware of the need to evacuate. In this respect, it might be appropriate to consider tunnel users located at least 100 metres away from the incident. At this distance, the nature of the incident and the potential risk would probably not be apparent. Once tunnel users are aware of the need to evacuate, a further time interval will generally elapse before they actually start to move. This is called the "pre-movement phase" and depends on a wide range of factors.

The second timeline deals with the emergency mitigation response and the effects of risk reduction measures on the severity of the hazard. Once an incident is detected, there will be a finite time interval before the emergency services will become aware of the need to respond. This has been referred to below as the "mitigation alarm phase". A further time interval will then elapse before the mitigation actions, such as fire fighting, can actually commence at the scene of the incident. This is important because it may take the nearest fire brigade several minutes to mobilise, travel to the tunnel portal and reach the scene of the incident.

Figure 7.4. **Sequence of events**



Reported incident data was used to obtain the likely time intervals for the alarm, detection, pre-movement and mitigation action times.

Methodology principles

The approach involves considering the response time intervals for each phase. Different categories of response, such as "fast", "average" and "slow", can be used, as illustrated below for detection:

Category	Detection time
Fast	$\Delta t_d \leq 1$ min
Average	1 min < $\Delta t_d \leq 5$ min
Slow	5 min < $\Delta t_d \leq 10$ min

The probability of the response corresponding to each of these categories has to be estimated using "expert" judgement (assuming no data is available). For this purpose, it may be easier to consider the cumulative probabilities as follows:

Category	Cumulative detection time	Cumulative probability of detection
Fast	$\Delta t_d \leq 1$ min	50%
Average or better	$\Delta t_d \leq 5$ min	90%
Slow or better	$\Delta t_d \leq 10$ min	100%

The discrete probability for each category can be derived from the cumulative values:

Category	Detection time	Probability of detection
Fast	$\Delta t_d \leq 1$ min	50%
Average	1 min < $\Delta t_d \leq 5$ min	40%
Slow	5 min < $\Delta t_d \leq 10$ min	10%

The number of time intervals is not limited to three, but depends on the precise knowledge of the performance.

Having determined different response categories, time intervals and probabilities, these can then be combined to determine the overall occupant and mitigation response times and the overall probabilities. This is achieved using the concept of the time-event trees. These are similar to the conventional event trees; the only difference is that they relate to the time intervals rather than the consequences directly.

In summary, the approach comprises the following basic steps:

- Select the appropriate response categories, time intervals and probabilities for each of the detection, occupant and mitigation alarm, pre-movement and mitigation pre-action time intervals.
- Combine the time intervals and their associated probabilities to determine the overall occupant and mitigation response times and their probabilities.

In addition to these basic steps, the effect of the mitigation response needs to be considered. This will be different for fires, BLEVEs, VCEs and toxic releases:

- For fires, the rate of the fire growth and the time taken to reach certain key fire sizes (*e.g.* 0.25, 3, 20 and 100 MW fires) need to be considered in order to estimate the probability that the fire can be controlled by fire fighting (mitigation action).
- For BLEVEs, it is assumed that if the fire reaches a certain threshold such as 3 MW, then a BLEVE will occur. The time taken to reach this fire size needs to be considered in order to estimate the probability that the BLEVE can be prevented by fire fighting (mitigation action).
- For VCEs, the mitigation actions relate to the prevention of ignition.

This method allows the assessment of combinations of the risk reduction measures in tunnels. The most effective combination of measures should minimise the detection, alarm, pre-movement and mitigation pre-action phases.

Estimates of the effects on the QRAM

Questionnaires were prepared and sent to several tunnel operators in Europe to gain information on the effectiveness and cost of the various risk reduction measures. Table 7.5 presents a summary of the measures present in a number of European tunnels.

Table 7.5. **Summary of the “non-native” risk reduction measures implemented in tunnels**

Risk reduction measure	V Tunnel	H Tunnel	W Tunnel	S Tunnel	O Tunnel	C Tunnel	T Tunnel
Emergency telephones	Y	Y	Y	Y	Y	Y	Y
Radio communications	Y	Y	Y	Y	Y	Y	Y
Traffic incident detection			Y	Y	Y	Y	Y
Closed circuit television	Y		Y	Y	Y	Y	Y
Fire detection	Y			Y			
Fire fighting equipment	Y	Y	Y	Y	Y	Y	Y
Fire-resistant equipment			Y	Y	Y	Y	Y
Fire-resistant structure	Y	Y	Y		Y		Y
Explosion-resistant structure	Y						
Prohibition to overtake			Y	Y			Y
Speed limit			Y				
Distance between vehicles					Y		Y
Vehicle identification system							
Escorting							Y
Rescue teams							Y
Lighting	Y	Y	Y	Y	Y	Y	Y
Alarm signs	Y	Y	Y	Y	Y	Y	Y
Action plan	Y	Y	Y	Y	Y	Y	Y

As a result of the survey, no quantitative information was obtained on the effects of these risk reduction measures.

The QRAM currently predicts the effects of drainage, emergency exits and ventilation. The effect of time-related risk reduction measures may be incorporated into the QRAM by specifying certain input parameters, which are dependent on the detection, alarm and pre-movement times. In particular, the QRAM requires the user to input the time to start the emergency ventilation and, in the absence of smoke control ventilation, this corresponds directly to the detection and alarm time. In addition, the user must specify the type of the emergency communication system and this is closely related to the calculation of the occupant pre-movement times.

Table 7.6 presents the assumed probabilities for the detection, alarm and pre-movement times for four tunnel variants, T1 to T4. Table 7.7 gives the corresponding response times: the best, average and worst estimates relate to the range of the outcomes of the time-event tree. The best, average and worst estimates correspond to cumulative probabilities of 10%, 50% and 90% respectively.

Table 7.6. **Estimated probabilities for the tunnel categories**

	Detection			Alarm			Pre-movement			
	Pd1	Pd2	Pd3	Pa1	Pa2	Pa3	Pp1	Pp2	Pp3	Pp4
T1	0.50	0.50	0.00	0.50	0.50	0.00	0.40	0.30	0.20	0.10
T2	0.40	0.50	0.10	0.30	0.50	0.20	0.20	0.30	0.30	0.20
T3	0.30	0.60	0.10	0.05	0.45	0.50	0.10	0.20	0.30	0.40
T4	0.05	0.45	0.50	0.05	0.45	0.50	0.00	0.20	0.30	0.50

Table 7.7. **Predicted detection, alarm and pre-movement times**

	Detection and alarm (minutes)			Pre-movement (minutes)		
	Best	Average	Worst	Best	Average	Worst
T1	0.8	4.0	5.2	1.5	4.7	15.0
T2	1.7	4.2	11.0	2.0	8.0	20.0
T3	4.0	9.0	11.0	3.0	12.7	22.5
T4	4.5	10.8	14.0	5.5	15.0	23.0

As noted above, in the QRAM the pre-movement times are related to the type of warning system. The types of warning system are as follows: W0 = no warning system, W1 = alarm bell, siren or similar, W2 = public address system providing pre-recorded messages, W3 = public address system and CCTV. Table 7.8 shows the key quantitative risk assessment input parameters relating to the response times for each of the tunnel categories. The QRAM was used to predict the distances over which the fatalities would occur in the event of fires; the results are summarised in Table 7.9.

Table 7.8. **Quantitative risk assessment model input parameters**

Quantitative risk assessment input parameters		T1	T2	T3	T4
Detection and alarm time (minutes)	tE	1	2	5	10
Type of warning system	Ecoms	W3	W2	W1	W0
Best estimate of pre-movement time (minutes)		1	2	3	5

Table 7.9. **Predicted distances over which fatalities occur in the event of a fire**

Metres

		T1	T2	T3	T4
Heavy goods vehicle 20 MW fire	≥ 90% fatalities	19	34	45	64
	≥ 50% fatalities	36	53	68	99
	≥ 10% fatalities	55	79	104	146
Heavy goods vehicle 100 MW fire	≥ 90% fatalities	160	186	204	222
	≥ 50% fatalities	189	212	239	279
	≥ 10% fatalities	216	260	287	333
Motor spirit pool fire	≥ 90% fatalities	218	252	273	305
	≥ 50% fatalities	256	287	315	370
	≥ 10% fatalities	287	336	373	489

This indicates, for example, that there would be a 19 metre section of the T1 tunnel in which 90% or more of the occupants would be killed and a 34 metre section in which 50% or more would be killed (this includes the 90% fatality zone). The actual number of fatalities depends on how many people are in each zone. The main observations are:

- For the 100 MW and pool fire scenarios, the fatality ranges are about 15%-20% greater for T2 compared to T1, about 25%-30% greater for T3 compared to T1, and about 40%-70% greater for T4 compared to T1.
- For the 20 MW fire, the increases in fatality ranges are higher; however, the resolution of the QRAM predictions is relatively poor for very small fatality ranges.

In conclusion, it can be seen that the methodology provides a means of distinguishing between the effects of the different response times and thus of the different time-related risk reduction measures. If the costs associated with each measure are known, the QRAM can be used to assess the cost effectiveness.

A methodology has been presented which enables an expert user of the QRAM to make estimates of the effects of the risk reduction measures on the time evolution of an incident involving dangerous goods. In addition, the steps involved in this methodology can help to identify important relationships between the risk reduction measures and the response time intervals, *e.g.* detection, alarm, pre-movement and mitigation.

Discussion

The flexibility of the methodology allows users to define their own time interval parameters, thus rendering the methodology tunnel-specific. This provides a means for comparing the effects of possible improvements, replacements and removals of existing risk reduction measures in a given tunnel. The application of the methodology with the QRAM has been illustrated for a set of hypothetical tunnel cases.

It is not possible to make general recommendations on the ranking of the risk reduction measures, since their effectiveness is tunnel-dependent.

The amount of cost data obtained through the questionnaire and literature search is either too limited or too variable to draw any conclusions on the cost-effectiveness of the measures in terms of life safety or structural damage reduction.

Concluding remarks

The objective of this work was to recommend the risk reduction measures which are specific to individual tunnels, where detailed specifications and cost-effective evaluations could be conducted to account for the risks involved.

In Phase I, the list of risk reduction measures (Table 7.1) aimed at reducing the probabilities and consequences of accidents was developed. A literature study was performed, in addition to which information was gathered by means of a questionnaire which was completed by the operators of 14 European tunnels. To compare the different measures, the effect and cost of each measure were categorised as low, medium or high. The outcome was a simple approach (the 3×3 matrix of Table 7.2) that can be used to provide preliminary qualitative indications of the costs and victim or damage reduction effects of different measures. Phase II comprised three studies concerned with more detailed quantitative approaches to assist the evaluation of the cost-effectiveness.

In the first study, a number of sensitivity tests were undertaken in order to investigate how the results of the QRAM are affected by changes to a set of "native" risk reduction measures. The results illustrate the sensitivity of the physical effects to adjustments in the "native" measures.

The second study aimed at designing a procedure to introduce "non-native" safety measures directly into the existing QRAM, in such a way that they could be objectively evaluated. The procedure permits an extension of an existing comprehensive QRAM to include safety measures that were not part of the original model specification. The initial application of the procedure to a specific tunnel and dangerous goods type has produced some promising results which provide useful information to decision makers on the relative merits of the safety measures considered.

The third study aimed at the development of a methodology to enable an expert user of the QRAM to make estimates of the effects of the risk reduction measures on the time evolution of an incident. The methodology provides a means of quantitatively comparing the effects of different risk reduction measures or combinations of measures. In addition, the steps involved in this methodology can help to identify important relationships between the risk reduction measures and the response time intervals, *e.g.* detection, alarm, tunnel occupant pre-movement and mitigation pre-action. This provides a means for comparing the effects of possible improvements, replacements and removals of existing risk reduction measures in a tunnel.

Overall, the studies conducted have provided qualitative and quantitative methods for the analysis of the effects of risk reduction measures. Using the QRAM together with these approaches, it is possible to assess the effects of both "native" and "non-native" measures for a specific tunnel. A general effect of the measures applicable to all tunnels could not be generated, since the measures can have different effects in each (type of) tunnel.

The cost data gathered during the studies was either too limited or too variable to draw any general conclusions on the cost-effectiveness of measures in terms of life safety or structural damage reduction. However, if cost data of the measures concerned are available, an evaluation of cost-effectiveness may be conducted using the QRAM together with the methodologies outlined above.

REFERENCES

Hall, R.C. and Y. Luong (2000), "Assessment of Risk Reduction Measures Related to Response Times", WS Atkins Consultants Ltd, Ref. CL3002-R1, May.

COWI (2000), Decision Support Model (DSM), by COWI for OECD ERS2 Group, Report No. 42069-006 Issue No. 2, April.

OECD and PIARC (1996), *Transport of Dangerous Goods through Road Tunnels: Current National and International Regulations* (Report 1), (available on Internet: http://www.oecd.org/dsti/sti/transpor/road/index.htm)

OECD and PIARC (1997), *Transport of Dangerous Goods through Road Tunnels: Current National and International Regulations* (Report 2), (available on Internet: http://www.oecd.org/dsti/sti/transpor/road/index.htm)

PIARC (1999), Tunnel Committee, Road Tunnels, *Fire and Smoke Control in Road Tunnels*, Paris.

PIARC (forthcoming), *Review and Evaluation of Measures to Reduce the Risk related to Dangerous Goods Transport in Road Tunnels (Synthesis of Task 3)*, Paris.

Pons, P. (2000), "Transport of Dangerous Goods through Road Tunnels. ERS2 Project Task 3: Sensitivity Study on 'Native' Measures", INERIS Rap22460_ab.

Saccomanno, F. and P Haastrup (2000), "Influence of Safety Measures on the Risks of Transporting Dangerous Goods through Road Tunnels", paper submitted to the Risk Analysis Conference, February.

Van der sluis, J., D.A. Schreuder, J.M.J. Bos and C.C. Schoon (1998), "Hazardous Material Transport through Tunnels: Investigation into Measures to Reduce the Risk of Transport of Dangerous Goods through Road Tunnels", SWOV Institute for Road Safety Research, the Netherlands, for PIARC Road Tunnel Committee, Working Group 5.

GLOSSARY

BLEVE	Boiling liquid expanding vapour cloud explosion
bps	Best possible scenario score
CCTV	Closed circuit television
DG	Dangerous good
DSM	Decision support model
ERS2	Joint OECD/PIARC research project on the transport of dangerous goods through road tunnels
HGV	Heavy goods vehicle
LPG	Liquefied petroleum gas
Native measures	Risk reduction measures whose effects are included in the QRA model
OECD	Organisation for Economic Co-operation and Development
ORT	Occupant response time
PIARC	World Road Association
QRA	Quantitative risk assessment
QRAM	Quantitative risk assessment model
VCE	Vapour cloud explosion

ANNEX

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