TRANSPORT OF DANGEROUS GOODS THROUGH ROAD TUNNELS: AN INTEGRATED QRA MODEL DEVELOPED UNDER THE JOINT OECD/PIARC PROJECT ERS2

Didier LACROIX Chairman, joint OECD/PIARC Scientific Expert Group ERS2
Research Manager, Centre d'Etudes des Tunnels (CETU),
25 avenue F. Mitterrand, Case n° 1, 69674 Bron Cedex, France

Philippe CASSINI Research Engineer, INERIS,
Parc techn. ALATA, B.P. 2, 60550 Verneuil en Halatte, France

Robin HALL Research Engineer, W.S. ATKINS,
Ashley Road, Epsom, Surrey KT18 5BW, UK

Frank SACCOMANNO Professor of Civil Engineering, University of Waterloo,
Waterloo, Ontario, Canada N2L 3G1

ABSTRACT

The Organisation for Economic Co-operation and Development (OECD) and the World Road Association (PIARC) have joined forces in a common research project on the Transport of Dangerous Goods through Road Tunnels. After a review of current national and international regulations, which has shown their discrepancies, the project is now devoted to risk assessment, decision process and risk reduction measures, in order to recommend appropriate methodologies and standard regulations to tunnel owners and authorities. This paper mainly describes the Quantitative Risk Assessment (QRA) model which was developed by an international consortium of consultants to compare the safety of tunnel routes with their open alternatives and possibly with absolute acceptance criteria. The general approach, the simplifying hypotheses and a general validation performed are described, as well as the principles of the computerised tools, their input and output.

BACKGROUND

Mainly for environmental reasons, the number of road tunnels is quickly increasing in many countries. While most techniques concerning tunnel construction and also safety have been steadily improving, the problem raised by dangerous goods (DG) has not been given a satisfactory answer yet. Although very unlikely, a serious underground accident involving such goods might result in a catastrophe with dramatic consequences on numerous human lives, property and possibly the environment. On the other hand, needlessly banning dangerous goods from tunnels may create unjustified economic costs. Moreover it may force them to drive on more dangerous routes, through dense urban areas for instance, and thus increase the overall risk.

Since its creation in 1957, the Committee on Road Tunnels of the World Road Association (PIARC) has been studying most issues connected with tunnel equipment, operation, safety, including dangerous goods also in the last ten years. The Organisation for Economic Co-operation and Development (OECD), as part of its Road Transport and Intermodal Linkage Research Program (RTR), has studied the safety of road transport of dangerous goods. Further to a joint seminar on Road Tunnel Management, these two bodies decided to pool their complementary skills and experience, as well as the necessary financial support, in order to launch a common research project on the transport of dangerous goods through road tunnels in 1995.

THE JOINT OECD/PIARC RESEARCH PROJECT ERS2

The general purpose of the project is to improve the overall safety of the transportation of dangerous goods by road while facilitating its organisation and preventing unnecessary costs. The output should be recommendations on best methodologies to analyse risks, make decisions, apply them using standard formulations, and implement risk reduction measures.

Financial support is needed to collect the necessary data, develop the methods and models and test them in practice with the final users. Several contributions from member countries have been obtained through the initiative of the RTR Steering Committee of OECD and PIARC. Additionally a substantial part of the Quantitative Risk Assessment (QRA) model development has been financed by a grant from the Directorate General for Transport (DG VII) of the European Commission.

These bodies have created an Executive Committee, chaired by Dr K. Flaate (Norway), to oversee the financial and political issues. A Scientific Expert Group, with members from 14 countries, OECD and PIARC, has prepared the detailed objectives, plans and budget, and is responsible for the general advancement and results of the project. It is chaired by the first author and co-chaired by Mr J. Hart (UK). With the support of OECD secretariat and a Project Manager, Pr H. Knoflacher (Austria), three sub-groups organise and follow up the work of several consultants in charge of various activities as described below.

Task 1: Review of current national and international regulations

Under this task, co-ordinated by Mr J. Hart (UK), current regulations have been reviewed by a Norwegian consultant on the basis of questionnaires returned by 22 countries. It clearly appears that rules and regulations for the transport of dangerous goods in road tunnels vary considerably among countries and within countries. Often countries with few tunnels have more and stricter regulations than tunnel-rich countries.

In a second step, detailed information was gathered in nine countries and analysed. In most cases current decisions are not based on QRA, but several countries intend to implement this approach in the future. A number of problems arising from the existing regulations were identified as well as requirements for new regulations. The two reports are freely available on the internet: www.oecd.org/dsti/sti/transpor/road. Their conclusions have been used to better direct the other tasks of the project.

Task 2: Methodologies relating to risk assessment and decision process

The objectives of Task 2, co-ordinated by Pr. N. O. Jørgensen (Denmark), are to recommend methodologies and propose examples for evaluating the risks induced by dangerous goods transport in tunnels, comparing them with alternative routes and possibly risk acceptance criteria, and proposing decisions using standard formulations.

An inventory and comparison of existing methods were presented at a seminar in Oslo in March 1996 and led the Scientific Expert Group to structure Task 2 as follows:

Technical data on tunnel/routes Traffic and DG transport data	➔ ➔	QRA model	➔ ➔	Risk indicators	➔ ➔	DSM	➔ ➔	choice of alternative

so that the Decision Support Model (DSM), which incorporates political aspects, is clearly separated from the QRA, which is purely technical.

Also, in order to harmonise tunnel regulations, it was proposed to develop a grouping system (GS) for loadings of dangerous goods. Each tunnel would be characterised by the loadings grouping which is allowed through it. These groupings, in small number (3 to 5), would range from all dangerous goods to none. A first proposal on the principle of a GS has been submitted to the interested international bodies and is available at OECD.

Detailed specifications for a QRA model were drafted and submitted to a peer review. Further to an international call for tenders, the QRA development was entrusted to a consortium led by INERIS (France) and including W.S. Atkins (UK) and the Institute for Risk Research (Canada). This activity is fully described in the next section.

At the same time first thoughts were given to the DSM. A Danish consultant reviewed available models and analysed the decision problem. Two types of models are considered as promising and are currently being demonstrated on example cases before a decision is taken on the use of an existing DSM or the development of a new one.

The next step will be to ensure the perfect consistency of the QRA model, GS and DSM: the loadings groupings in the GS must be characterised as well as possible by the accident scenarios included in the QRA model; the authorisation of any of these groupings must be the only possible alternatives for a tunnel regulation in the DSM. This step may include some finalisation of the QRA, GS and DSM.

Task 3: Risk reduction measures (including transport and tunnel operation)

The objective of this task, co-ordinated originally by Mr Tan (Netherlands) and now by Mr Haastrup (European Commission), is to recommend measures well adapted to each specific case, with detailed specifications and an evaluation of the costs and benefits vis-à-vis the associated risks. A first phase has been undertaken by a specialised working group of the PIARC Road Tunnels Committee devoted to dangerous goods and led by Mr Beguin (Netherlands). With the help of a Dutch consultant, they have performed a literature survey, then a first cost and effectiveness ranking of 28 measures on the basis of interviews with tunnel operators. The report will be published by PIARC soon.

A second phase will use and possibly refine the QRA and DSM developed under Task 2. It will aim at quantitatively taking into account the cost and benefits towards risk of measures when deciding on a tunnel equipment and operation.

Task 4: Conclusions and recommendations

The last task, co-ordinated by Mr A. S. Caserta (USA), uses the results of the previous tasks to draw lessons and recommendations. Its objectives are:

- to propose a standard international formulation for tunnel regulations concerning dangerous goods,
- to recommend a general methodology to prepare decisions on authorising or refusing dangerous goods (using the aforementioned loadings groupings if they prove to be effective)
- to recommend appropriate measures to reduce risks.

THE QUANTITATIVE RISK ASSESSMENT (QRA) MODEL

Scope

The purpose of the QRA model is to produce quantitative information about risk levels due to the transport of dangerous goods on given routes, some of them including tunnels. This information, referred to as 'risk indicators', will be used in the DSM to propose decisions which may be based on the comparison of:

- different possible routes to find the safer one,
- the risk level of a route with an absolute acceptability criterion.

Risk is characterised by two aspects: occurrence probability and severity. Severity may be expressed as fatalities, injured people, destruction of buildings and structures, damage to the environment. The number of fatalities has been retained as the most pertinent severity criterion. To characterise the societal risk, the model plots F/N curves which give the yearly frequency F to have an accident with N fatalities or more. It also calculates the individual risk for permanent populations (yearly probability to die from the considered traffic). Injuries and damage to property and the environment are estimated in a qualitative way.

For open sections tools are available. Because of the specific nature of underground accidents, adapted modules had to be developed for the assessment of risk in tunnel sections. It is thus possible to quantify risks for routes including tunnel and open sections.

General Approach

A complete assessment of risks due to DGs would require the examination of all possible meteorological conditions, all possible accidents, sizes of breaches, vehicles fully or partially loaded, etc. Such an assessment is totally impracticable and simplifications are needed. The developed QRA model relies on a methodology based on the following steps:

- Choose a small number of representative DGs
- Imagine a small number of representative scenarios involving these DGs
- Determine the physical effects of these scenarios (for open and tunnel sections)
- Determine the physiological effects of these scenarios on road users and local populations (fatalities)
- Take account of possibilities of escape/sheltering
- Determine the associated probabilities of occurrence.

Computations for scenarios leading to no fatality would be a waste of time. So a set of rather severe scenarios was chosen. They correspond to common types of DGs able to produce fatalities because of various effects: overpressure, thermal effect, toxicity.

Two scenarios are relative to fires of medium and important intensity that could concern heavy goods vehicles (HGVs) without DGs and nevertheless represent a serious risk in a tunnel. The choice of representative DGs and scenarios was operated keeping in mind the future possible ranking of DG loadings in groupings to be used in tunnel regulations. The list of the 10 selected scenarios appears in table 1.

Two different software tools have been developed for computations in the open:

- the Fortran program Rk-DG deals with a 2D grid where population densities and a wind rose are set.
- the spreadsheet-based tool Sk-DG uses a simpler representation: population densities are supposed to be homogeneous within each section, so that wind directions are not needed.

Inside tunnels, only the spreadsheet-based tool Sk-DG is used.

Scenario No.	Description	Capacity of tank	Diameter of breach (mm)	Mass flow rate (kg/s)
1	HGV fire 20 MW (no DG)	N.A.	N.A.	N.A.
2	HGV fire 100 MW (no DG)	N.A.	N.A.	N.A.
3	BLEVE of LPG in cylinder	50 kg	N.A.	N.A.
4	Pool fire of motor spirit	28 tonnes	100	20.6
5	VCE of motor spirit	28 tonnes	100	20.6
6	Release of chlorine	20 tonnes	50	45
7	BLEVE of LPG in bulk	18 tonnes	N.A.	N.A.
8	VCE of LPG in bulk	18 tonnes	50	36
9	Torch fire of LPG in bulk	18 tonnes	50	36
10	Release of ammonia	20 tonnes	50	36

TABLE 1: Main characteristics of the 10 selected scenarios

Modelling of Risk Consequences and Frequencies

In the open, models exist to calculate the consequences of the scenarios. Then probit equations allow the derivation of fatality percentage from physical exposure. These models and probit equations have been used to create contingency tables where calculation results are stored in such a way that the software tools Rk-DG and Sk-DG can use them directly.

In Rk-DG the calculations are performed by interwoven do-loops in order to take into account period of day (with associated traffic and population), direction of traffic, section of route (nature and related frequency of accidents), accident location on this section (discretisation), wind direction, wind velocity. Each calculation provides a number of victims and the corresponding yearly frequency. In Sk-DG, a smaller number of do-loops is necessary. They are operated by spreadsheet macro-command modules.

The probability for a scenario related to a given DG to occur in one year on a 1 km section is assessed according to the following methodology:

- find the yearly frequency for a HGV to be involved in an event (traffic accident, spontaneous fire, loss of containment, etc.) on the route section (function of country, road type, global traffic, HGV traffic),
- find the conditional probability that this HGV transports the given DG (function of traffic composition),
- use the conditional probability to develop the scenario once a HGV with the given DG is involved in an event.

In tunnels, the techniques used for consequence modelling of scenarios in the open do not apply and a specific treatment is needed to derive:

- the zones of the tunnel that will be affected,
- the effects that will go out of the tunnel and create a risk in the surroundings.

A specific spreadsheet tool called hereafter 'pre-conditioner' has been developed. It determines the zones in the tunnel that will be affected by each scenario and the corresponding effect levels. For instance in case of a fire in a tunnel, the spreading of smoke is very dependent of the ventilation regimes. After a delay, the emergency ventilation is generally activated. The ventilation regimes may be very different from a tunnel to another. Even for the same tunnel, the emergency ventilation may vary drastically according to the fire location. The extent, duration and heat release of a motor spirit fire are also very dependent of the drainage provisions.

Because of the complexity of the assessment of the zones affected and the numerous possible cases (one or two bores, longitudinal, semi-transverse or transverse ventilation), the pre-conditioner uses simplified models.

Appropriate measures in a tunnel may reduce the frequency of accidents, their severity, the delays for detection and allow greater possibilities of escape/sheltering. Some of these measures are taken into consideration in the pre-conditioner and the QRA. It is thus possible to explore the influence of mitigation measures on the F/N curves.

Input / Output of the Software

Spreadsheet-based tool Sk-DG. The tool Sk-DG produces the following quantitative outputs for fatalities:

- F/N curves (global and also for each DG involved at least in one scenario),
- expected values (number of fatalities per year).

It also provides qualitative indications on risks of injuries, structural damage in the tunnel sections, environmental pollution.

For the open, the software computations are based on :

- contingency tables in which the shape and extent of the zones of physical effects for the scenarios in the open have been stored,
- contingency tables in which the translation of physical effects into physiological ones has been stored,
- contingency tables in which the elements needed for the yearly frequency assessment have been stored. They are derived from accident statistics issued from France and Canada.

For the tunnel sections, the software computations are based on :

- the aforementioned pre-conditioner which performs a simplified assessment of the physical and physiological effects in a tunnel,
- contingency tables in which the elements needed for the yearly frequency assessment have been stored. They are derived from accident statistics relative to tunnels issued by Canada, France and Norway.

All these contingency tables store input data that have been calculated and validated by the developers and should not be changed. Nevertheless if changes were to be performed, for example use a new probit equation for chlorine, this could be performed inside the contingency tables by an expert user. More generally, expert users may change values in contingency tables so as to:

- modify the physiological effects of the phenomena (change probit equations, etc.),
- modify the way the escape/sheltering possibilities are taken into account,
- modify a scenario (this requires specialists),
- modify default values (traffic composition, ratio of fires not induced by an accident, etc.).

Expert users may also change values in some parts of the pre-conditioner.

The final users will not have such possibilities. The inputs they will have to provide for the spreadsheet-based tool Sk-DG, are: traffic description, route description, distribution of wind velocities if available, indications on weather conditions that may affect the frequency of accidents: fog, rain, etc. Some elements are typically relevant to the site: global traffic, layout of the route, length and nature of each section and must be entered. Other inputs may be omitted and a default value accepted.

Fortran program Rk-DG. Data to be supplied to this software are very similar to those needed by Sk-DG, except that a 2D description of the population density is needed and a wind rose indicating time ratio of wind velocity for 18 (adjustable number) direction sectors is needed.

Tunnel pre-conditioner. Input data are:

- geometry of tunnel (number of bores, layout of lanes, length, cross-section, gradient, camber, drainage possibilities, etc.),
- normal and emergency ventilation regimes (longitudinal, extraction if any),
- delays for activation of the emergency ventilation.

Test cases

A panel of 4 test cases was used during the development to validate the contingency tables and sub-models, clearly feel the difficulty for a final user, help in writing user guides.

For each case, a comparison of risk between a route including a tunnel and an alternative open route was conducted. The 4 tunnels were intentionally chosen to be very different. Figure 1 shows an example of the outputs obtained with Sk-DG for one of the test cases: F/N curves per type of transport (cumulating the risks for all scenarios relative to that transport) and their global contribution.

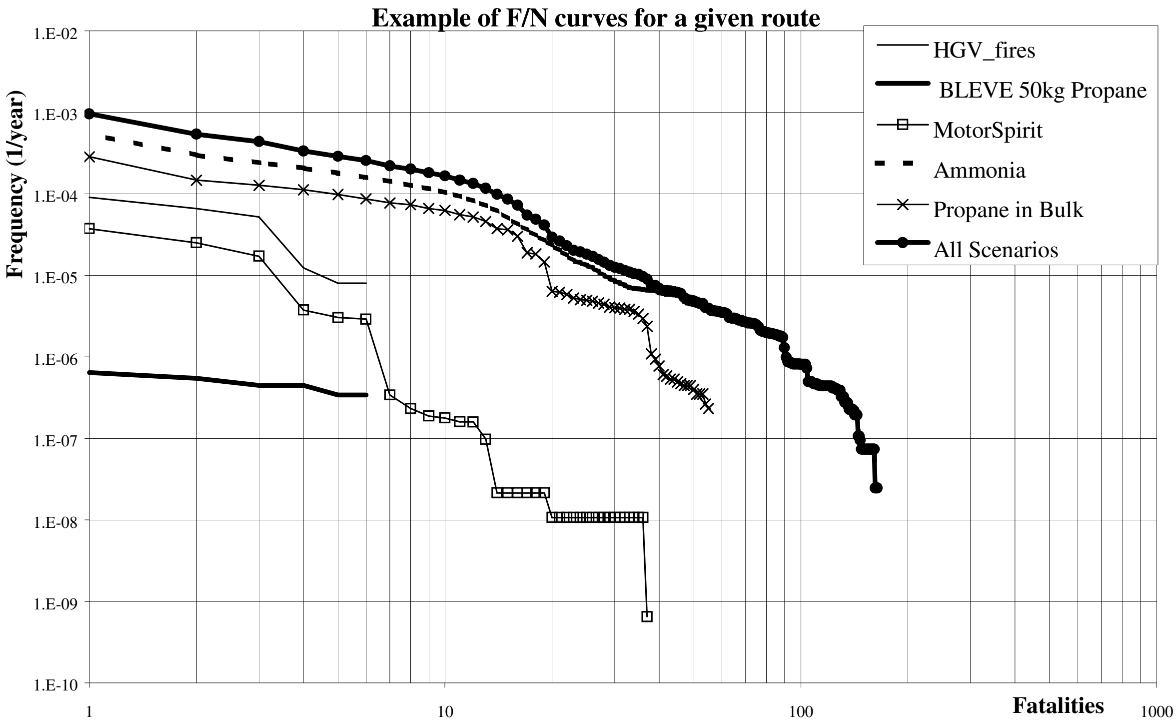

FIGURE 1: Example of F/N curves produced by the QRA model

Validation procedure

A QRA model may calculate systematically biased levels of risk, especially if it is based on a very limited number of DGs and scenarios. This may have limited incidence when comparing two alternative routes, if both have been miscalculated in the same manner. It may lead to wrong conclusions if risk levels have to be compared with 'absolute' acceptance criteria.

Sources of possible error when assessing risk are everywhere. They are present in:

- input parameters,
- physical models used for the consequence assessment,
- statistics available for the probability aspects and derived contingency tables,
- physiological aspects,
- people behaviour and ability to escape,
- emergency procedures.

So it appeared important to check that a correct order of magnitude was reached in the assessment. This has been performed by a comparison between:

- fatalities produced by real accidents available in a database indicating the number of fatalities due to DGs during a few years in France,
- calculations performed with the model for 3 open air sections representing:
  - motorways in rural areas,
  - national roads in rural areas,
  - urban routes,

  each with corresponding surrounding population densities, traffic rates and with lengths proportional to their ratio in the French road system.

Dividing the calculated number of fatalities by the numbers of kilometres and DG vehicles used to run the model leads to a result of:

1.4 . 10^{-9} fatalities due to DGs / (year . DG vehicle . kilometre).

Knowledge of the French DG traffic expressed in vehicle . kilometre per year allowed to derive from the database a mean figure of:

1.9 . 10^{-9} fatalities due to DGs / (year . DG vehicle . kilometre).

So, it appears that the model seems to correctly evaluate the order of magnitude of risk on open sections.

A sensitivity analysis has been performed in order to indicate how the model reacts to different input parameters relative to open and/or tunnel sections. This is useful for the final users: if a parameter does not affect the results too much, it may be determined with less accuracy.

CONCLUSIONS

The joint OECD/PIARC research project ERS2 investigates the most important fields related to the transport of dangerous goods through road tunnels: current and future regulations, risk assessment, decision making, risk reduction measures.

A Quantitative Risk Assessment (QRA) model was developed by international consultants in order to provide risk indicators which can be used in a decision support model to compare a route including one or several tunnels with alternative open routes, and possibly with risk acceptance criteria. The QRA model consists of spreadsheet-based tools and a Fortran program for some finer results. It is aimed at being simple to use, but experts may make changes to take account of specific situations or data. The main outputs are F/N curves and individual risk contours for fatalities. Risks of injuries, damage to the tunnel and the environment are dealt with in a more qualitative way.

The development has included four test cases to try the various sub-models and the user-friendliness. A complementary check is ongoing in several countries: real future users are testing the model on their own cases before it is accepted. A later phase will include a detailed examination of the consistency of the QRA with the Decision Support Model (DSM) and the grouping system (GS) planned for future harmonised tunnel regulations.

The whole research project is expected to be completed in the first half of 2000. All final results will be made available by OECD and PIARC, including the computerised tools. A special session will be devoted to the project at the XXIst World Road Congress organised by PIARC in Kuala Lumpur (Malaysia) in October 1999. Another conference or seminar is envisaged in Europe and North America in 2000-2001.