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Influence of Safety Measures on the Risks of Transporting Dangerous Goods through Road Tunnels

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Abbreviated title: Dangerous Goods Safety in Road Tunnels.

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Abstract

Quantitative Risk Assessment (QRA) models are used to estimate the risks of transporting dangerous goods and to assess the merits of introducing alternative risk reduction measures for different transportation scenarios and assumptions. A comprehensive QRA model has recently been developed in Europe for application to road tunnels. This model can assess the merits of a limited number of “native safety measures”. In this paper, we introduce a procedure for extending its scope to include the treatment of a number of important “non-native safety measures” which can be of interest to tunnel operators and decision-makers. Non-native safety measures were not included in the original model specification. The suggested procedure makes use of expert judgment and Monte Carlo simulation methods to model uncertainty in the revised risk estimates. The results of a case study application are presented that involve the risks of transporting a given volume of flammable liquid through a 10 Km road tunnel.

Keywords:

Safety Measures, Transportation, Dangerous Goods, Road Tunnel, Risk

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Introduction

The transportation of dangerous goods through road tunnels poses special risks to road users and to people residing near the tunnel. Tunnel authorities need to make informed decisions as to whether such transport should be permitted in certain tunnels, and if so, how this can be achieved in a safe and practicable manner. Quantitative Risk Assessment (QRA) models can assist authorities in making these decisions by providing objective estimates of risk that are accurate and applicable to different transportation of dangerous goods scenarios and assumptions [9, 10, 11].

Recently, researchers from the United Kingdom, Canada and France (under the leadership of INERIS) have developed a comprehensive QRA model [6] designed to estimate the risks of transporting dangerous goods in road tunnels and along surface routes for different types of tunnels and types of dangerous goods (DG). The “INERIS model” was developed and evaluated based on road tunnel DG incident data obtained from France [1,2], Norway [3] and the Netherlands [4], as well as other countries in Europe and North America [5].

The primary aim of the INERIS model is to inform decision-makers as to the risk reduction potential of introducing different safety measures and guidelines in specific tunnels. As it currently exists however, the INERIS model can only consider those safety measures that were part of the original model specification (measures that are "native" to the model). Native measures unfortunately, represent only a small fraction of measures that could be of interest to tunnel authorities and decision-makers [6]. This limits the scope of the INERIS model as a practical decision-support tool.

The objective of this paper is to present a procedure for introducing "non-native" safety measures into the existing INERIS model. This procedure formally considers uncertainty in the estimation of the risk, subject to the introduction of different safety measures of interest to tunnel authorities. The procedure described in this paper should enhance the scope and usefulness of the INERIS model, without requiring a re-specification of substantial parts of the original model to include safety measures that were not previously considered.

General Framework

Figure 1 illustrates the framework adopted in this paper for considering changes in the base INERIS model risk estimates subject to the introduction of both native and non-native safety measures. The framework consists of six modules:

1. Define a base case (transportation scenario) for analysis (assumptions, conditions and risk inputs).
2. Estimate risks (probability and consequences) using the INERIS QRA model (for different native input measures).
3. Develop a list of non-native measures of interest to tunnel authorities and decision-makers (based on discussions with experts and members of the OECD working group ERS2)
4. Provide a link between non-native measures and their influence on various risk components in the model. Obtain risk adjustment factors for different risk components.
5. Consider uncertainty in the adjustment factors using Monte Carlo methods.

6. Revise the estimates of risk from the INERIS model and evaluate the cost-effectiveness of the measures being considered.

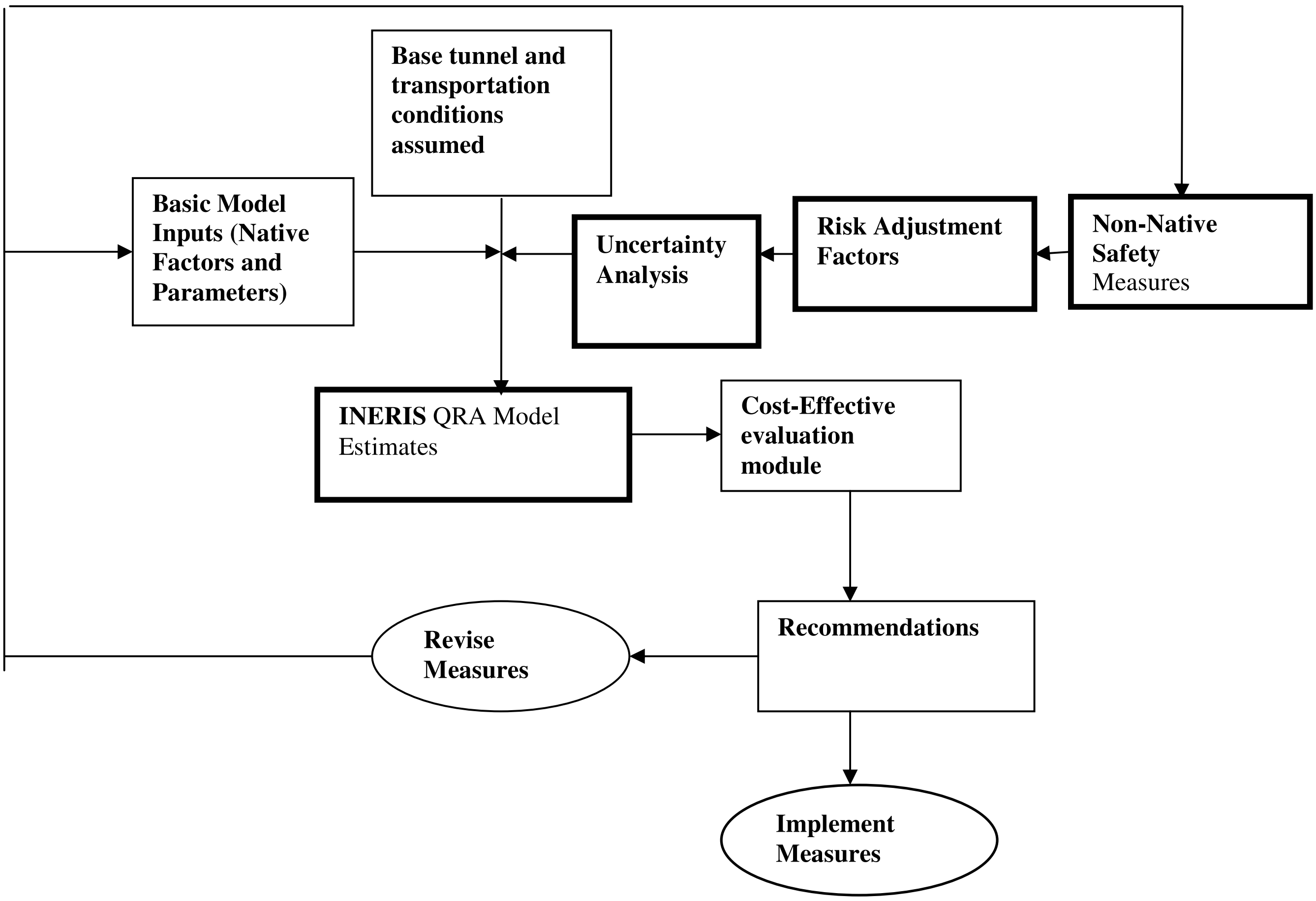

Figure 1: Modifying the INERIS model for non-native measures.

The framework in Figure 1 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 recommendations as to their implementation and/or revision.

The scope of the work discussed in this paper is concerned with: 1) identifying a list of non-native safety measures to consider, 2) classifying risk into its fundamental constituent probabilities and link these to the safety measures being considered, 3) obtaining basic estimates of risk from the INERIS model, 4) adjusting these estimates for individual safety measures being considered, and 5) incorporating a formal treatment of uncertainty in the adjustment factors and demonstrating how this uncertainty affects the cost-effectiveness of the measures being considered.

The treatment of uncertainty in the above framework assumes that risk adjustment associated with specific safety measures can be represented by a unique probability distributions, with a given mean and standard deviation. In this paper, a lognormal distribution was selected to represent the range of values associated with each adjustment factor. The lognormal distribution was selected since adjustment factors are defined continuously over the range of values zero to infinity (i.e. values less than one reflect a reductions in risk, while values greater than one reflect increases in risk). Furthermore, when estimating the effect on risk of specific measures, most risk analysts will tend to err on the side of caution (i.e. underestimating the reduction in risk). As a result, we have assumed that the adjustment factor distribution would tend to be skewed for different safety measures considered. In this paper, we have adopted a lognormal distribution with a positive skew to represent the range of values and their corresponding probabilities for different adjustment factors being considered. We note here that the choice of the lognormal distribution, while affecting the results for this application, does not limit the relevance of the procedure described in this paper for treating uncertainty in the risk adjustment factors where other distributions may be more relevant.

For each adjustment factor, we have assumed a standard deviation equal to 10% of the mean. This assumption is based on observations obtained from a benchmark survey carried out as part of the 1992 Toronto Consensus Conference on the risks of transporting dangerous goods (Saccomanno and Cassidy, 1992). The estimates from the benchmark survey were modified for application to road tunnel transportation, through discussions with the OECD ESR2 working group

The OECD ESR2 working group consists of a number of professionals who are familiar with the tunnel operations associated where DG are involved and with the general concept of QRA model applications. A survey was devised to solicit opinion on the likely effect of selected measures on tunnel risks for different types of tunnels and DG. The results of this survey were compiled and introduced as "most likely value" for each adjustment factor as it reflects its impact on risk. An average standard deviation equal to 10% of the mean was used for most adjustment factors to reflect uncertainty in the factor estimates as obtained from each of the group members. In a few instances, where variation in the estimates was found to be higher than normal (as in the case of the effect of controls on allowable tunnel speeds), we used a standard deviation equal to 20% of the mean adjustment estimate.

The combined effect on the overall risk estimate of changes in the values of different adjustment factors was determined using Monte Carlo simulation methods. A random sample of adjustments was generated from the lognormal distribution, with an assumed mean and standard deviation. These values were then applied to their corresponding risk component estimates, using an appropriate joint probability expression for risk. The risk expression provides a mapping for the combination of uncertainty in the adjustments factors of interest for different safety measures.

In this paper we used the software package "Crystal Ball©" to generate random samples of risk adjustments for different safety measures and risk estimates. Crystal Ball© is a spreadsheet based computer package developed by Decisioneering, Inc. [7] to carry out a Monte Carlo simulation on uncertain variables. For each variable Crystal Ball© provides a menu of different probability distributions. The user specifies the appropriate distribution based on the assumed behaviour of the variable being considered. Crystal Ball© calculates multiple scenarios of a model by repeated sampling of values from the distribution for each uncertain variable. In this analysis, we have assumed all factors reflect a lognormal distribution.

Sample values of input variables were combined using MC methods to yield joint risk probabilities for different safety measures being considered. A number of useful statistics are obtained from Crystal Ball© which describe the resultant risk distribution, for example, means, variance, skewness, percentiles, confidence intervals, etc. The risk component distribution obtained from Crystal Ball© is obtained by combining the samples of risk inputs using simulation and a given joint risk expression.

Input Assumptions

Much of the variability in input estimates as obtained from different sources can be accounted for by different assumptions underlying each transportation of DG scenario. A first step in obtaining consistent estimates of risk is to ensure that these estimates apply to a common set of assumptions and transportation scenarios. Variability that remains unexplained after controlling for a given scenario is ascribed to uncertainty in the estimates.

Table 1 summarises the different types of transportation scenarios, which can be considered by the INERIS QRA model [6].

Table 1: Input conditions and categories.

Factor	Categories			
Tunnel Class (3 categories)	**Grand**	Autoroute	Urban	
Length (3 categories)	**>10 km**	500-1000m	<500m	
Tunnel zone considered (3 categories)	**In tunnel**	Transition in Tunnel	Before Tunnel	
No of bores (2 categories)	**1**	2		
Lanes per direction (3 categories)	**1**	2		
Traffic volume (3 categories)	**High**	Medium	Low	
Average traffic speed (2 categories)	**> or =100 km/h**	<100 Km/H		
Weather (2 categories)	**Good**	Adverse		
Type of DG (4 categories)	DG1	DG2	**DG3**	DG4

Bolded values represent inputs used in this application..

The INERIS model provides estimates of risk for four classes of DG :

DG1 Pressure liquefied gases that are toxic and non-combustible

DG2 Pressure liquefied flammable gases

DG3 Flammable liquids

DG4 Toxic and corrosive liquids

In this paper, we have limited our analysis to the bulk transport of flammable liquids (DG3). We have also assumed a DG volume of 60,000 one-way shipments per year along a 10Km stretch of Grand Tunnel. This yields an annual exposure of 0.6 million truck vehicle-kilometres of DG over the entire length of tunnel. The tunnel in question is assumed to be single bore with one lane in each direction. The risks are estimated for the “in-tunnel section”, such that differences in risk at tunnel transition zones (entrance and exit) are not considered. The INERIS model is able to consider different sections of the tunnel transport, such as, before entrance, entrance, transition, in-tunnel and exit.

Risk for the transportation of DG is a complex process, with a wide spectrum of probability and consequence events. To simplify the discussion in this paper, we have limited our treatment to a few major risk outputs, as illustrated in Figure 2. These are the risks for which estimates are obtained subject to the introduction of specific safety measures.

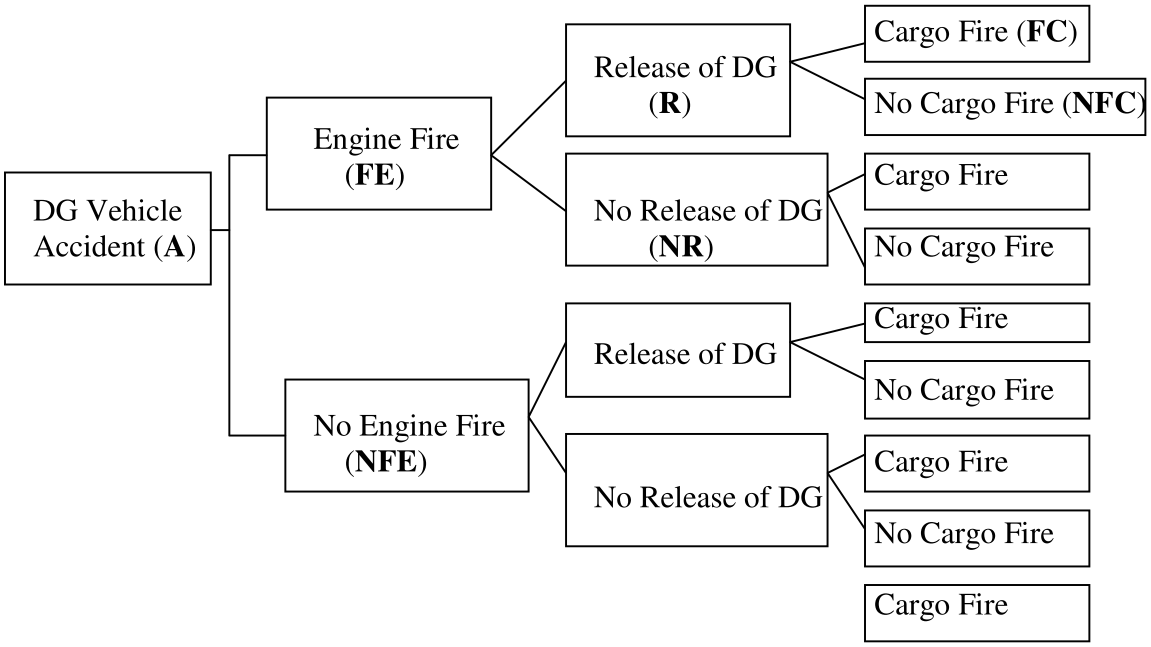

Figure 2: Event tree of basic risk components considered in this application (tree considers DG accident initiating event)..

In the above framework, cargo fires and non-fire events are estimated in terms of:

- With and without releases of DG
- With and without engine fires
- With the prior occurrence of a DG-HGV accident

A similar event tree was developed for non-accident events (**NA**), where all subsequent events are repeated as per fires.

The risk component probabilities along each branch in Figure 2 are expressed as joint probabilities of all preceding branches and the expected values are obtained by multiplying the joint probability for risk by the expected exposure along the tunnel for DG3.

For example, the expression for engine fire (FE) was of the form:

$$\begin{aligned} P(FE) = P(FE/R \cap A)P(R/A)P(A) + P(FE/NR \cap A)P(NR/A)P() + \\ P(FE/R \cap NA)P(R/NA)P(NA)P(FE/NR \cap NA)P(NR/NA)P(NA) \end{aligned} \tag{1}$$

where

FE = engine fire

R, NR = release and non-release of DG

A, NA = accident and non-accident

Each term in equation 1 represents a separate branch of risk output tree in Figure 2. A similar expression was developed for the other risk components of interest in this paper, namely, cargo fires, no cargo fires, releases with and without engine fires and all of these with and without accidents.

The base estimates in the existing INERIS model are summarised in Table 2 for different components of risk [6]. These estimates were obtained from three different sources: a) estimates as documented in the literature, b) consensus of opinion by various experts, and c) some analysis of empirical data for Europe and North America. Some brief remarks have been included in Table 2 to explain the rationale behind each estimate as adopted in the INERIS model.

Table 2: **Basic risk component estimates for given transportation scenario given an accident.**

Term (Event Tree)	**Term Description**	**Base Estimate**	**Comment**
With accident involving DG-HGV			
$P(A)$	Expected no. of DG-HGV accidents per year	0.05	Assumed exposure 0.6 million veh-km per year
$P(FE \mid A)$	Engine fire given a DG-HGV accident	0.10	
$P(R \mid FE \cap A)$	Release given engine fire and accident	0.05	
$P(FC \mid R \cap FE \cap A)$	Cargo fire given release with engine fire and accident	1.00	Conservatively assumed to be one.
$P(FC \mid NR \cap FE \cap A)$	Cargo fire given no release, engine fire and accident	0.00	Without release cargo cannot burn.
$P(FC \mid R \cap NFE \cap A)$	Cargo fire given release, engine fire and accident	0.10	One case in ten will ignite from other sources than FE.
$P(R \mid NFE \cap A)$	Release given no engine fire with accident	0.01	Lower than the same case with FE.
$P(FC \mid NR \cap NFE \cap A)$	Cargo fire given an accident without release and engine fire	0	Without a release cargo cannot burn.
Without accident			
$P(FC \mid R \cap FE \cap NA)$	Cargo fire given release, engine fire and no accident	1.00	Less than or equal to the same case given an accident.
$P(R \mid FE \cap NA)$	Release given engine fire and accident	0.01	Must be lower than with accident.
$P(FE \mid NA)$	Engine fire given no accident	0.005	Must be much lower than FE given A.
$P(FC \mid NR \cap FE \cap NA)$	Cargo fire given engine fire with no release and no accident.	0	Without a release cargo cannot burn.
$P(FC \mid R \cap NFE \cap NA)$	Cargo fire given release no engine fire and no accident	0.10	One case in ten will ignite from other sources than FE.
$P(R \mid NFE \cap NA)$	Release given no engine fire and no accident	0.0001	Spontaneous release from leaking valves.
$P(FC \mid NR \cap NFE \cap NA)$	Cargo fire given no release, no engine fire and no accident	0.00	Without release cargo cannot burn.

Non-Native Safety Measures

In this paper, adjustments introduced for specific non-native factors have been applied to the INERIS base model base estimates from Table 2 for the same set of underlying assumptions and transportation scenarios.

The ESR2 working group suggested a number of relevant non-native safety measures, which could be of interest to tunnel authorities. These measures, as listed in Table 3, were expressed in terms of precise actions that could be evaluated by experts [8].

Table 3: OECD working group tunnel safety measures

Code in Paper	OECD identification	Description
O1	M4	Change of speed limit of 20 km/h
O2	M5A	Change of distance between moving vehicles from 10 to 100 meters
O3	M5B	Change of distance between stopped vehicles from 1 to 50 meters
O4	M6	Change from/to prohibition to overtake
O5	M7A	Change from system without escort to system with escort behind in normal traffic conditions
O6	M7B	Change from system without escort to system with escort behind and before
O7	M7C	Change from system without escort to system with escort with only DG in the tunnel tube
C1	M8	Change from system with no automatic identification system to one with
C2	M11A	Change from no lighting to standard lighting for the country in question
C3	M11B	Change from standard lighting to maximum lighting for emergencies
C4	M11C	Change from standard lighting to also marker lights for evacuation
O8	M12	Chance from no automatic incident detection system to one with
D1	M13	Change from nothing to adequate fire resistant structure
E1	M14	Change from nothing to adequate fire resistant equipment
D2	M15	Change from nothing to adequate explosion resistance
D3	M17	Change from porous to non-porous asphalt
E3	M18	Change from no emergency phones to phones every 100 meter
E2	M19A	Change from nothing to fire extinguishers every 100 meter
E4	M19B	Change from nothing to water supply every 200 meter
E5	M20A	Change from nothing to fire detection sensors
C5	M21	Change from no CCTV to a Closed Circuit TV system
C6	M22A	Change from nothing to emergency radio communications
C7	M22B	Change from M22A to also public broadcast
C8	M22C	Change from M22B to also mobile phones;
E7	M25	Chance from normal emergency services to special emergency teams at tunnel portals;
	M26A	Change from nothing to red/green signals at 500 meter intervals;
	M26B	Change from M26A to variable message signs at each end
E8	M27	Change from no action plan to a standard action plan with exercises;

A total of 28 measures were suggested to reflect five broad types of safety controls, i.e. tunnel design, incident detection, traffic control, traffic regulation and emergency response.

For the purpose of this paper, we have represented each broad type of safety control by one of the 28 safety measures. These include:

1. Case D1: Change from nothing to adequate fire resistant tunnel structure.
2. Case O1: Change in speed limit (reduction of 20 Km/H)
3. Case O5: Change from no escort to escort behind the DG vehicle.
4. Case C5: Change no CCTV to CCTV
5. Case E1: Change from nothing to adequate fire fighting equipment.

The rationale for considering these representative measures and their likely affect on risk is discussed below. According to the ESR2 working group, the introduction of these measures is likely to affect risk in the following ways:

Case D1: Change from nothing to adequate fire resistant structure

This measure has very limited effect on accident frequencies, toxic releases or explosions.

Fire resistant tunnel structures will have a significant effect on smoke movement (i.e. life safety effects) in addition to their structural protection properties. The protected surfaces absorb heat more slowly, so the smoke is hotter and more likely to stay stratified.

Fire resistant structures are used in the Netherlands for all underwater tunnels. In all cases, ducts (especially fresh air/smoke extraction ducts) need to be fire protected. Rock tunnels are generally unaffected.

In the QRA model, since the effect of people is the main concern of the model, a relatively large hole size was assumed for the motor spirit pool fire scenario, leading to a relatively short pool fire duration and consequently limited damage to the tunnel structures.

Case O1: Change of speed limit of 20 km/h

The measure of changing the speed limit is one that is easy to implement, though a key issue is compliance. The change of the speed limit of 20 km/h is tentatively assumed to result in an effective speed reduction of 10 km/h. There is no consensus on the resulting effect on the accident frequencies. In fact there is a considerable uncertainty due to several factors.

First of all it is known that the accident rates are linked more to the speeds distribution, i.e. speed differences between the vehicles travelling in the same direction. In other words if the traffic flow is homogeneous (laminar flow) the accident rate decreases. Thus if a speed limit change lowers the speed of some vehicles, while others keep the previous speed, an increase in the accident rate may be occur. It is thus important to impose speed limits for all cars, and not only for heavy goods or for Dangerous Goods vehicles.

Secondly there is a balance between two contradictory effects with reducing speed limits: On the one hand, reducing the speed increases the travel time, that is the duration of presence in a dangerous zone increases; on the other hand, enforcing speed limits is able to lower the accident rates.

Regarding the smoothing of the traffic flow, experiences from Holland indicates that stationary known control points, only influences driver behaviour on a short distance of the road before and after the fixed point control. To obtain a positive result, it is necessary to control efficiently the speed (for example through automatic speed control devices) and to have a very limited tolerance. This may be relevant for the tunnel cases in the future.

Given these comments, change in the speed limits with enforcement is expected to be one of the most effective measures.

Case O5: Change from system without escort to system with escort behind normal traffic

Escorting of dangerous goods through a tunnel can be implemented in different ways. For example, other vehicles may be not be allowed in the tunnel during escorting; alternatively, such as at the Dartford tunnel, a gap is imposed between normal and DG traffic, and the escort vehicle travels behind.

Escort vehicles carry fire-fighting equipment, with people who know how to use it, plus communications equipment. Early response and identification is possible.

The effects of escorting DG are expected both on frequencies and on consequences. Regarding frequencies, accident rates are expected to be reduced. Visual checks of vehicles before entering tunnel is one of the contributory factors for this. In addition, escorting will ensure early enough detection to prevent the risk from escalating, because of the presence of fire fighting equipment and trained personnel in the escort vehicles. As well as there being less chance of a serious accident, the number of people in the danger zone will be reduced.

The costs related to such a measure are high (especially running costs), but they can be covered by toll charges. This is the case, for example, at the Dartford tunnel in UK and the Fréjus tunnel between France and Italy.

Intermediate measures are also possible, such as truck checking without escorting. There are issues involving available space and the difficulty of implementation on motorways. Another intermediate measure involves ‘announced’ (prior notice) transport of dangerous goods. A tunnel in Norway works this way.

Case C5: Change from no CCTV to a Closed Circuit TV system

Closed circuit TV is mostly relevant where there is a control room linked to the tunnel, with manning 24 hours a day. In this case, a number of TV screens is shown in the control room, with continues view of the tunnel. Some systems include fever screens than cameras with a TV image, which shift sequential between the cameras.

Such systems allow the operators to detect unusual conditions in the tunnels, for instance stopped vehicles, while for instance smoke cannot be detected easily by CCTV.

Another issue is that the operator naturally does not watch the TV screens continuously with the same alertness.

However once an alarm has been sounded, the operators can get an overview of the situation faster than in situations without the CCTV.

Case E1: Change from nothing to adequate fire resistant equipment

The assurance that the equipment in the tunnel, i.e. lighting, fire extinguishers, emergency phones etc, is protected against fire will have very limited effect on the accident probabilities, since only a major fire would normally interrupt such facilities.

Rather, a fail-safe principle should be considered when designing all tunnels systems, so that if the systems are destroyed in one place, there should not be an impact on other areas. This principle applies to lighting, communications (especially emergency communication devices), CCTV.

Ventilation devices may also be fire-protected, as is the practice in the Netherlands. Redundancy could also be used to help provide fail-safe operation.

Adjusted Risk Estimates

Table 4 summarises the adjustment factors for each of the five safety measures and each of the fifteen risk estimates considered in this paper (as per Figure 2 and Table 2). These factors express the percentage change in risk for the given tunnel application which "in the opinion of the ESR2 working group" results from the introduction of each safety measure.

As discussed above, the adjustment factors in Table 4 have been assigned a unique lognormal distribution, with the mean being equal to the estimates and a standard deviation equal to 10% of the mean. The exception to this assumption is speed controls, where standard deviation was set equal to 20% of the mean.

To reflect uncertainty in the adjustment factor estimates, a sample of 20,000 random numbers was generated for each risk input. These samples were combined using the relevant risk joint probability expression to yield the adjusted risk estimate subject to the introduction of a given safety measure. These are the probability of a DG vehicle accident per year, probability of a spontaneous engine fire per year, probability of a DG release per year and the probability of a cargo fire per year. Crystal Ball© was used to combine the input samples and obtain an output distribution for risk with a number of useful statistics.

Table 5 summarises several statistics for each risk estimate and safety measure, including means, 10th and 90th percentiles, and probability of exceeding the base case estimate from the INERIS model. The relative merits of introducing different safety measure can be compared graphically with the risk estimates for the base INERIS model estimates. This is illustrated in Figure 3 for each measure considered in this paper. To simplify the analysis, we have only shown in this Figure the estimates of the means from Table 5. A similar graph can be obtained for any one of the statistical indicators generated by the simulation.

Table 4. Summary of adjustment factors estimated and used for each of the four risk components as a function of the risk reduction measure evaluated.

Event	**Probability**	**Basic model estimates**	**Base case**	**D1**	**C1**	**O1**	**O5**	**E1**
Prob of HGV accident (A)	P(A)	0.05	1	1	1	0.9	0.75	1
Prob of Spont Fire (FE) given A	P(FE/A)	0.1	1	1	1	0.95	0.98	1
Prob of Release (R) given FE and A	P(R/FE+A)	0.05	1	1.05	0.98	0.95	0.9	0.99
Prob of Cargo Fire (FC) given R, FE and A	P(FC/R+FE+A)	1	1	1.05	1	1	0.9	1
Prob of Cargo Fire (FC) given NR, FE and A	P(FC/NR+FE+A)	0	1	1	1	1	1.1	1
Prob of FC given R and NFE and A	P(FC/R+NFE+A)	0.1	1	1	0.98	1	0.8	1
Prob of R given NFE and A	P(R/NFE+A)	0.01	1	1	1	0.85	1	1
Prob of Cargo Fire (FC) given NR, NFE and A	P(FC/NR+NFE+A)	0	1	1	1	1	1.1	1
Prob of Cargo Fire (FC) given R and FE and NA	P(FC/R+FE+NA)	1	1	1.05	1	0.99	0.9	1
Prob of R given FE and NA	P(R/FE+NA)	0.01	1	1	0.98	1	1	0.99
Prob of FE given NA	P(FE/NA)	0.005	1	1	1	1	1	1
Prob of Cargo Fire (FC) given NR+FE+NA	P(FC/NR+FE+NA)	0	1	1	1	1	1	1
Prob of Cargo Fire (FC) given R, NFE and NA	P(FC/R+NFE+NA)	0.1	1	1	0.98	1	1	1
Prob of Release (R) given NFE and NA	P(R/NFE+NA)	0.001	1	1	1	1	1	1
Prob of Cargo Fire (FC) given NR, NFE and NA	P(FC/NR+NFE+NA)	0	1	1	1	1	1	1

Discussion of Results

The above results suggest that D1 (introducing a fire resistant structure) and E1 (access to fire resistant equipment) have had little or no influence on the various risk probabilities when compared to the Base Case (no change). This result was expected since these measures are designed to reduce the damages associated with DG events rather than reduce their likelihood of occurrence. Safety measure C5 (introducing a CCTV system along the tunnel) has had a negligible effect in reducing the chance of cargo fire. The largest risk reduction effects are those resulting from O1 (reduction in the maximum speed limit) and O5 (introduction of escort vehicle for DG shipments). The use of escorts has had the most desirable effect on reducing all components of risk, i.e. the accident, engine fire, release and cargo fire.

Uncertainty in the estimates of the adjustment factors affects the some of the conclusions obtained from this analysis. For example, we found measure O5 (introduction of escorts behind the DG vehicle) to be most effective in reducing DG vehicle accidents, fires and releases in tunnels. However, there is a 5%, 5%, 0% and 5% chance that the base case means is exceeded for accidents, engine fires, releases and cargo fires, respectively, even after escorts are introduced. Given the cost of introducing escorts in tunnels, some authorities may view the above probabilities of exceeding the Base Case to be too high to warrant implementation of this measure… this despite the fact that "on average" risks are reduced as a result of this measure.

From an analysis made for other measures (not reported in detail in this paper), it was concluded that the following safety measures have little if any influence of risk probability:

D2	Change from nothing to adequate explosion resistance
C3	Change from standard lighting to maximum lighting for emergencies
C4	Change from standard lighting to marker lights for evacuation
O3	Change of distance between stopped vehicles from 1 to 50 metres
E6	Change from normal emergency services to special teams at portals

Further investigations are underway regarding the remaining measures.

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

Table 5: Risk component estimates means, 10th and 90th percentiles and probability of exceeding Base Case

	Unit	Base Case			D1				C5				O1				O5				E1			
	per X years	Mean	10%	90%	Mean	10%	90%	P X>base	Mean	10%	90%	P X>base	Mean	10%	90%	P X>base	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%	4.5	3.4	5.7	25%	4.0	3.5	4.5	5%	5.0	4.4	5.6	45%
Spontaneous fires	1000	9.7	8.3	11.3	9.7	8.3	11.3	45%	9.8	8.4	11.2	45%	8.5	6.4	11.0	25%	7.2	6.1	8.3	5%	9.7	8.3	11.3	45%
Release	10000	8.4	6.9	10.0	8.5	7.0	10.0	55%	8.4	6.9	9.9	45%	6.6	4.8	8.5	10%	4.9	4.1	5.8	0%	8.4	6.9	10.2	45%
Cargo fires	1000	1.3	1.0	1.6	1.3	1.1	1.6	50%	1.3	1.0	1.5	40%	1.0	0.7	1.3	10%	0.6	0.5	0.8	5%	1.3	1.0	1.6	45%

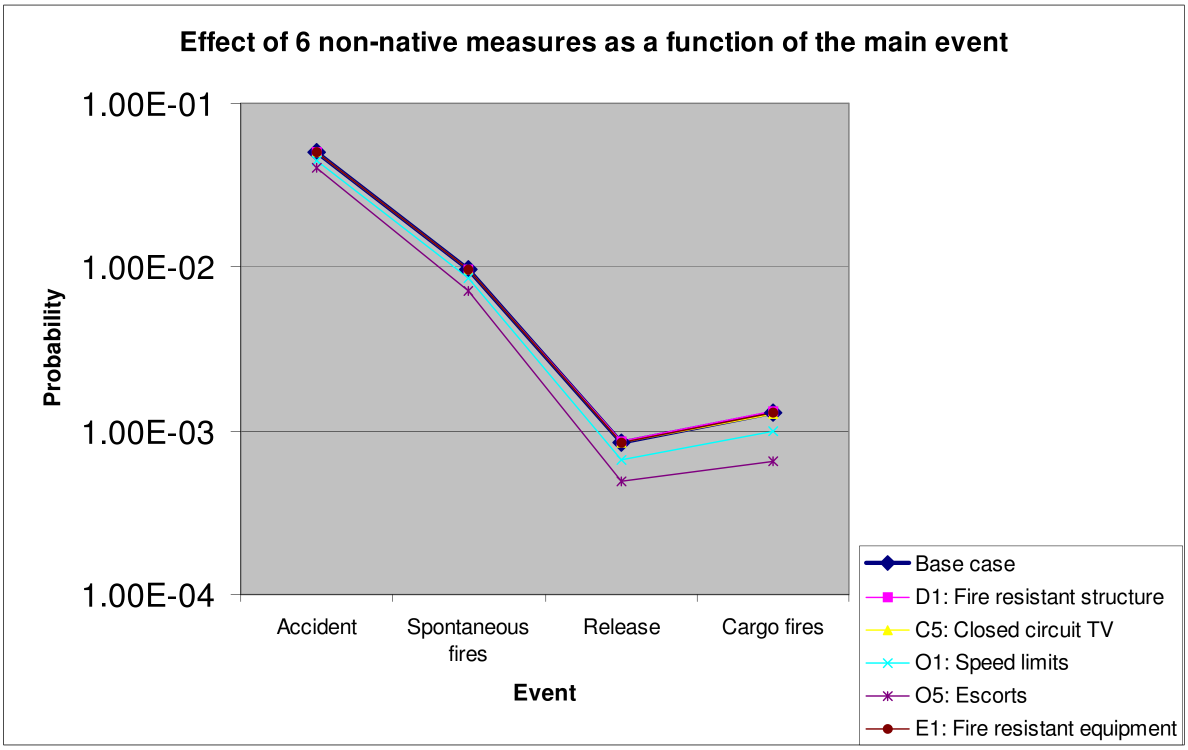

Figure 3: Risk component means for different safety measures and the base case.

Conclusions

The procedure outlined in this paper permits an extension of the existing INERIS QRA model to include safety measures that were not part of the original model specification. This was done without obtaining new data or involving re-specification of major parts of the existing model. This initial application of the procedure to a specific tunnel and DG type has produced some promising results. These results provide useful information to decision-makers on the relative merits of the safety measures being considered. As such, the procedure has without a doubt enhanced the usefulness of the existing QRA model as a decision-support tool.

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