QRA and Decision Making in the Transportation of Dangerous Goods

F. FRANK SACCOMANNO AND KEITH CASSIDY

Lessons learned from the International Consensus Conference on the Risks of Transporting Dangerous Goods, held in Toronto in April 1992, are used to suggest ways through which quantitative risk assessment can be made more practicable for users and decision makers. The discussion focuses on three aspects of the problem: risk uncertainty (in both estimation and process), communication (as related to perspective, criteria for representing risk, and relevance to decision making) and decision support (acting as a guide to cost-effective mitigation).

Quantitative risk assessment (QRA) continues to be at an infant stage of development, plagued by problems of recognition, precision, and credibility. A recent Royal Society report (*1*) laments the deep methodological division regarding such issues as the quantification and qualification of risks, the response of QRA to public perceptions of risk, and the setting of acceptable standards for decision making. According to Blockley (*2*), this division points to the "open-world" nature of risk problems, which Fischhoff (*3*) ascribes to differences in human interpretation and judgment, an inherent attribute of QRA applications in general.

QRA applications in the transportation of dangerous goods are plagued by a number of practical concerns that compromise their usefulness in decision making. Hubert and Pages (*4*) and Saccomanno et al. (*5*) cite a number of inconsistencies in the values assigned by different groups to various components of risk for similar problems. These inconsistencies, it is argued, have contributed to a general loss of credibility in QRA's ability to provide accurate readings of the threats posed. A 1989 Health and Safety Executive (HSE) report (*6*) argues that the views held by members of the public are often at variance with apparent evidence from QRA applications. Covello (*7,8*) has noted that the reasons for this cannot be dismissed as purely "irrational" or "subjective" thinking by the public concerning risk assessment in general, but rather it rests with the ability of QRA to "communicate risk" in an effective and consistent manner. Glickman et al. (*9*) suggest that there is the wider concern that, notwithstanding the question of inconsistencies in the estimates, existing QRA models have failed to express risk in a manner that is responsive to the specific needs of users and decision makers. They argue that QRA should be made more practicable and not necessarily more technically involved. Before proceeding further along the path to "bigger and better models," a momentary halt in progress is advisable to take stock of our current position on the learning curve and map out future directions for QRA model development. Indeed, there may be many learning curves to consider in risk assessment, for example by industry as well as by country.

F. F. Saccomanno, Department of Civil Engineering, University of Waterloo, Waterloo, Ontario, N2L3G1, Canada. K. Cassidy, Major Hazards Assessment Unit, Health and Safety Executive, St. Anne's House, Bootle, England.

In April 1992, an International Consensus Conference on the Risks of Transporting Dangerous Goods was convened in Toronto. One of the basic aims of this Conference was to review the role of QRA in the transportation of dangerous goods and to suggest ways in which the process could be made more meaningful for users and decision makers. It was agreed that this aim could best be achieved by bringing together groups with a wide range of interests and experiences to discuss the issues within the framework of an open forum. Given the complexity of QRA, its multifaceted role, and the diverse interests of those involved, a consensus-seeking approach was believed to provide the most promising avenue for achieving agreement. Similar consensus-gathering approaches applied in the past, most notably in medical research, have proven to be successful in providing insights into resolving problems of some complexity with far-reaching implications for public policy.

The Consensus Conference deliberations produced a number of useful recommendations (also referred to as consensus statements) on how to improve the QRA process and make it more meaningful to users and decision makers (*10*), as follows:

1. QRA must be more responsive to the needs of users and decision makers. Both information requirements and output must be clearly defined and documented.
2. Uncertainty must be fully accounted for in the reporting of risk estimates. Risk and its components must be accompanied by confidence limits. The sensitivity of output to various assumptions concerning parameter values and inputs must be accounted for in the reporting of the risks.
3. Risk measures must be clearly defined. There should be no ambiguity concerning the nature of risks and their perspective, such as individual and societal, or absolute and relative. Risk communication guidelines need to be developed before the analysis begins.
4. Guidelines for decisions and the mitigation of risk must be incorporated into the QRA models. The process must lead to technically informed decisions. Where appropriate, QRA should present output in a form that can be readily used in a cost-benefit evaluation of alternative types of mitigation.

Several of these recommendations are reviewed in this paper with a view to suggesting a "globally acceptable" code of practice for risk assessment as applied to the transportation of dangerous goods.

ROLE OF QRA

Despite a diversity of interests and experience among the participants at the conference, there was general agreement that QRA has three important roles to play (*10*):

1. Provide acceptable and credible estimates of risks;
2. Inform public perception of the nature and importance of these risks, and interpret the technical results; and
3. Provide advice on mitigation in support of the decision-making process.

Many of the conference participants felt that existing QRA models do not fulfil these roles adequately.

The provision of acceptable and credible risk estimates is an attempt to reduce uncertainty in risk estimation, recognizing that, given the nature of QRA, uncertainty can never be fully eliminated. The questions to be addressed are: to whom should these estimates be acceptable and credible? and how is this to be achieved in QRA? A major U.S. National Research Council report (*11*) addressed part of this issue by noting that QRA can be "successful to the extent that it raises the level of understanding of relevant issues or actions and satisfies those involved that they are adequately informed within the limits of available knowledge."

The Consensus Conference considered ways this aim could be achieved by incorporating the analysis of uncertainty into the QRA process and documenting the various assumptions underlying the model and its application to specific transportation of dangerous goods problems (*10*).

The second role of QRA is to communicate risk effectively; that is, to report and interpret the technical results so as to bridge the information gap between the technical analyst and the decision maker or user (who may or may not be a technical person). The Consensus Conference debated the critical issue of whether existing QRA models suitably "inform" public perceptions on the actual threats posed by a given activity. Participants believed that at present QRA models have not contributed adequately to a complete understanding of the risks involved, so that well-informed decisions have not always been possible. This issue has been echoed elsewhere in the literature. As early as 1983, a Royal Society report on risk assessment stated (*12*):

> It follows that the public not infrequently have different perceptions of events from those suggested by the objective statistical assessments made by scientists or other experts (here referred to as QRA). Since policy is rightly directed towards the alleviation of public anxieties, this disparity can lead to large expenditures on safety measures that have low cost-effectiveness or, conversely, to the neglect of serious risks because the public (and by extension the decision makers) happen to be relatively indifferent towards them.

The absence of communication among those involved in QRA development has contributed to much of the misunderstanding on QRA's role and how well existing models fulfil this role. Closely related to the issue of risk communication is the role of QRA in decision support (i.e., as a guide to evaluating alternative risk-mitigation strategies). In this regard, risks should be reported in a manner that suggests an appropriate course of action for specific problems. The role of QRA will be discussed in this paper from these three points of view; namely, risk uncertainty, communication, and decision support for mitigation.

RISK UNCERTAINTY

The nature and degree of uncertainty in QRA varies with the nature of the problem being addressed and how the relevant issues are perceived by the analyst (*10*). Uncertainty in the quantification of risk can take several forms (*6*):

1. "Measurement error" expressed in the formal scientific sense as the range within which a parameter is known to lie with a given level of confidence;
2. Uncertainty in the modeling process;
3. Uncertainty in whether or not there is indeed an effect to be incorporated in an estimate; and
4. Omissions of possible causes of risk because of incomplete analysis, nonquantification of the ways in which human error can arise, and omission of other extreme external causes.

In many existing QRA models, uncertainty is handled in one of four ways:

1. *Use of the so-called "best estimate" approach for all input components of risk.* Frequently, the best estimate is obtained from sample averages extracted from the literature or from observed data;
2. *Erring on the side of safety.* Estimates are made considering the so-called worst-case scenario for each component of risk. The argument is made that even if the final risk estimate is incorrect, the assessment would not compromise safety. The HSE use what is referred to as a "cautious best estimate" approach, which is essentially a combination of the first two of these methods;
3. *Sensitivity analysis to varying inputs.* If risk component values are uncertain, a range of possible input values is obtained for each component and the implications on the final risk estimates are assessed; and
4. *Comprehensive statistical analysis of risk inputs and outputs.*

There are, of course, serious limitations in several of these ways of handling risk uncertainty in the application of QRA. Rimington (*13*) and Haigh (*14*) argue that the use of the most likely estimate or erring on the safe side alone is simply not acceptable, given the high cost of the decisions involved. Sensitivity analysis addresses how a range of values in selected inputs can affect risk estimates, without addressing specifically the reliability of these estimates. As such, the uncertainty issue is not fully addressed in this approach. Another use of sensitivity analysis is to determine whether the changes in the value of inputs make any difference to the resultant outputs. If the output is insensitive to the selected input values, the question is: why worry about the reliability of these input values? Of the previously listed methods for dealing with uncertainty, a comprehensive statistical review of risk and its inputs appears to be the most desirable course of action to take, although the amount of information required to carry out this type of analysis may not always be adequate.

In adopting a statistical approach, Saccomanno and Bakir (*15*) note that two types of uncertainty need to be considered: (*a*) uncertainty in risk estimation and (*b*) uncertainty in the process. The first type of uncertainty is an "uncertainty of knowledge" concerned with the value of the inputs and their parameters. The second type treats risk as a random variable, with a range of possible values tending about the mean. As in any random variable, the values assigned to risk and its inputs can be represented by their unique probability density functions.

UNCERTAINTY IN RISK ESTIMATION

Uncertainty in risk estimation was addressed at the Consensus Conference by considering unexplained variations in a sample of estimates reported by various independent sources studying a common transport problem. This was carried out using a hypothetical corridor benchmark exercise, the purpose of which was to establish controls on the problem being addressed, its underlying assumptions, and the input data used to specify and validate the models (*16*). The corridor benchmark exercise involved the bulk transport of chlorine, liquefied petroleum gas, and gasoline by road and rail over two designated routes (Figure 1). The presence of uncertainty in the application of QRA to the transport of dangerous goods was investigated in terms of five components of QRA (Figure 2):

1. Involvement of the dangerous vehicle in an accident,
2. Occurrence of a breach of containment,
3. Occurrence of release by type and size,
4. Hazard area for different classes of damage, and
5. Number of people killed or injured along a given route section.

Considering the constituents of risk separately permitted a parallel assessment of internal consistency in the QRA models for different phases of the risk-estimation process. Internal consistency was one of the stated requirements for QRA at the Consensus Conference, deemed to be important in producing meaningful and credible results (*10*).

The corridor exercise indicated that despite attempts to control for major sources of uncertainty (i.e., differences in assumptions, data, and model features), inconsistency in risk estimation, as reported by the participating groups, continued to be problematic. Much of this inconsistency could still be traced to differences in assumptions taken by the different groups in their application. Much of this difference could have been reduced through further controls on the application and a more extensive specification of the corridor features (*16*). Indirectly, the corridor exercise confirmed what many of the participants at the conference had stated verbally, mainly that more attention should be paid in QRA applications to the documentation of assumptions and to the reporting of risk estimates. A similar view was expressed by Williams (*17*) in calling for the inclusion of supplementary "qualitative information" in QRA output, and the provision of information in a form that is free of unnecessary technical jargon.

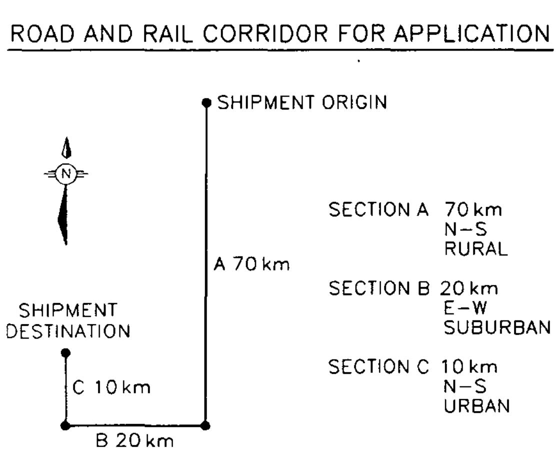


FIGURE 1 Hypothetical corridor features.

UNCERTAINTY OF PROCESS: A DECISION CONTEXT

Although the main focus of the corridor benchmark exercise was to investigate uncertainty in risk estimation, a parallel discussion touched on uncertainty of process and its implications for decision making. An appreciation of uncertainty of process provides a perspective on how risk-tolerance criteria and random variations in risk values can be incorporated into decision making. Risk tolerance refers to a willingness on the part of the public to live with certain risks, in some cases "unacceptable" risks, in order to realize greater benefits. Although these risks may not be negligible, they are perceived as being under some type of control, and hence constantly being reduced.

How does "uncertainty of process" relate to the issue of risk tolerance? Although a given risk may on average be considered to be negligible or acceptable, there may be an "unacceptable chance" that such a risk could in fact attain an intolerable value, given inherent randomness in the process. For example, risks from a given activity may involve on average one or two fatalities per year, but there is a chance that next year a major event may take place that will result in hundreds of fatalities. Notwithstanding the importance of the "average value of risk" in QRA risk estimation, it is the probability of exceeding intolerable values that may be of more concern to decision makers. Although establishing "tolerable levels of risk" is strictly speaking a question of public policy, the Consensus Conference participants expressed a common view that the analyst must be cognizant of this question as it relates to mitigation and the "distribution of risks" (*10*).

RISK COMMUNICATION

A second major role of QRA is the effective communication of the risks involved. Covello (*7*) identified 19 characteristics of risk that must be considered in QRA applications if there is to be sufficient information for evaluating these risks and making appropriate decisions. These characteristics can be grouped under three major headings: (*a*) perspective on risk, which refers to ways in which risks are viewed by users and decision makers within the context of the problem being addressed; (*b*) criteria for measuring risk, which refers to analytical output from QRA; and (*c*) relevance to decision making, which addresses the broader issue of the ability of QRA to advise on an appropriate course of action. This section of the paper focuses on the first two factors; the third factor will be considered in the next section.

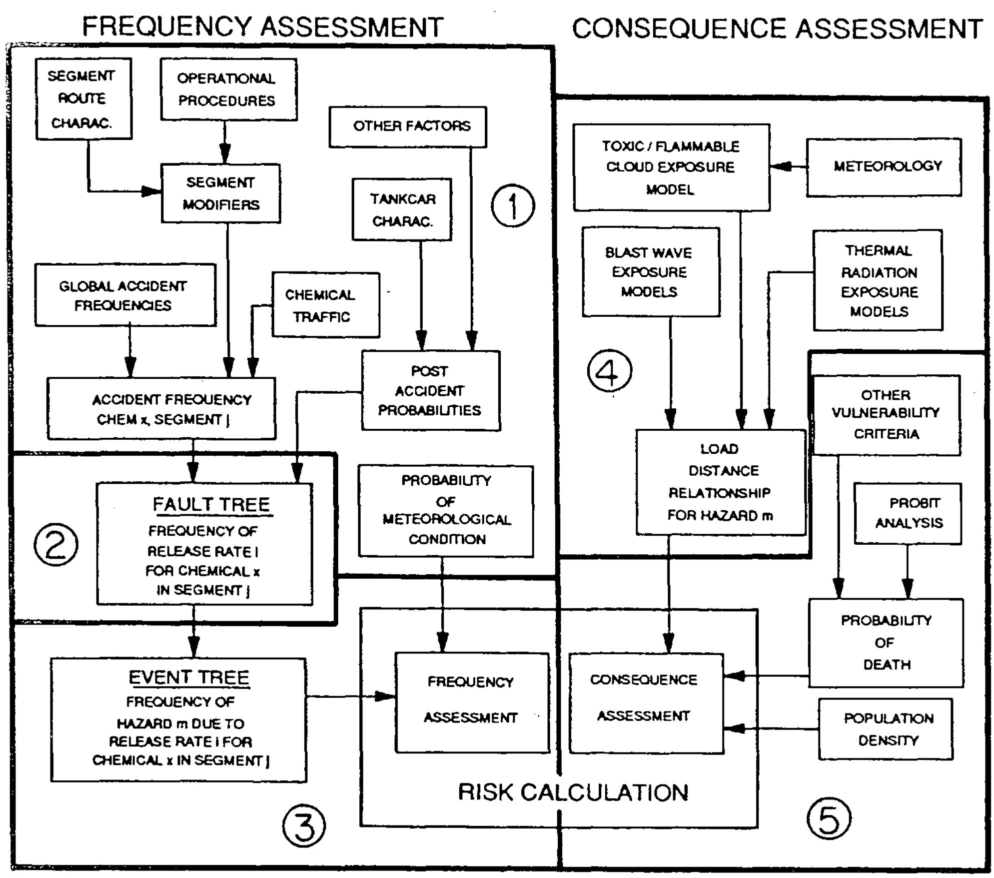
The Toronto Consensus Conference discussed perspective on risk from two points of view: (*a*) individual or societal and (*b*) relative or absolute.

Most QRA models express individual risk as the probability of death (or of receiving a "dangerous dose") per interval of time (usually per year) at designated distances from a given incident involving a specific type of dangerous substance. In transportation, these individual risks are normally represented as equal probability isopleths at various distances from a given incident along the route (Figure 3). Societal risks, on the other hand, refer to the potential threat posed by a given activity to all individuals located within a given hazard area. For the transportation of dangerous goods, this includes all individuals located within a given distance of a threat-producing incident along the route, including both on-route (shared traffic) and off-route population. Societal risks are normally expressed either as an expectation of harm (usually death) or as a plot of the frequency of N or more deaths per year versus the number of deaths. The latter more complete representation of societal risk is referred to as the cumulative *F-N* curve (Figure 4). Societal risk expectation is simply the expected value of the *F-N* curve.

Individual risks for the transportation of dangerous goods are considered to be negligible, because exposure time to risk at any point along the route is normally very brief. Accordingly, QRA applications to the transportation of dangerous goods are normally based on a societal risk perspective. This does not obviate the need to consider also under certain circumstances the individual risks involved; for example, when storage and stop-over time en route are high, with a significant exposure to risk at nearby locations.

Despite a general agreement that *F-N* curves offer the best means of expressing societal risk, Consensus Conference participants suggested a number of ways in which these curves can be better represented:

1. *Extending the range of consequences reflected in the* F-N *relationship.* Several participants suggested that for completeness of reporting, other consequence measures (in addition to fatalities) should be considered because presumably these measures will effect different mitigating responses. These measures can include personal injuries, property damage, and environmental impacts (including the natural environment and health effects) for both short-term (noticeable immediately) and long-term (noticeable after several years) scenarios. Depending on the scope of the environmental effects being considered, the issues can be very



Legend:

1. **Involvement of dangerous vehicle in accident**
2. **Occurrence of breach in containment**
3. **Occurrence of release by type and size**
4. **Hazard area for different classes of damage**
5. **Number of people killed and/or injured along route.**

FIGURE 2 Risk assessment components.

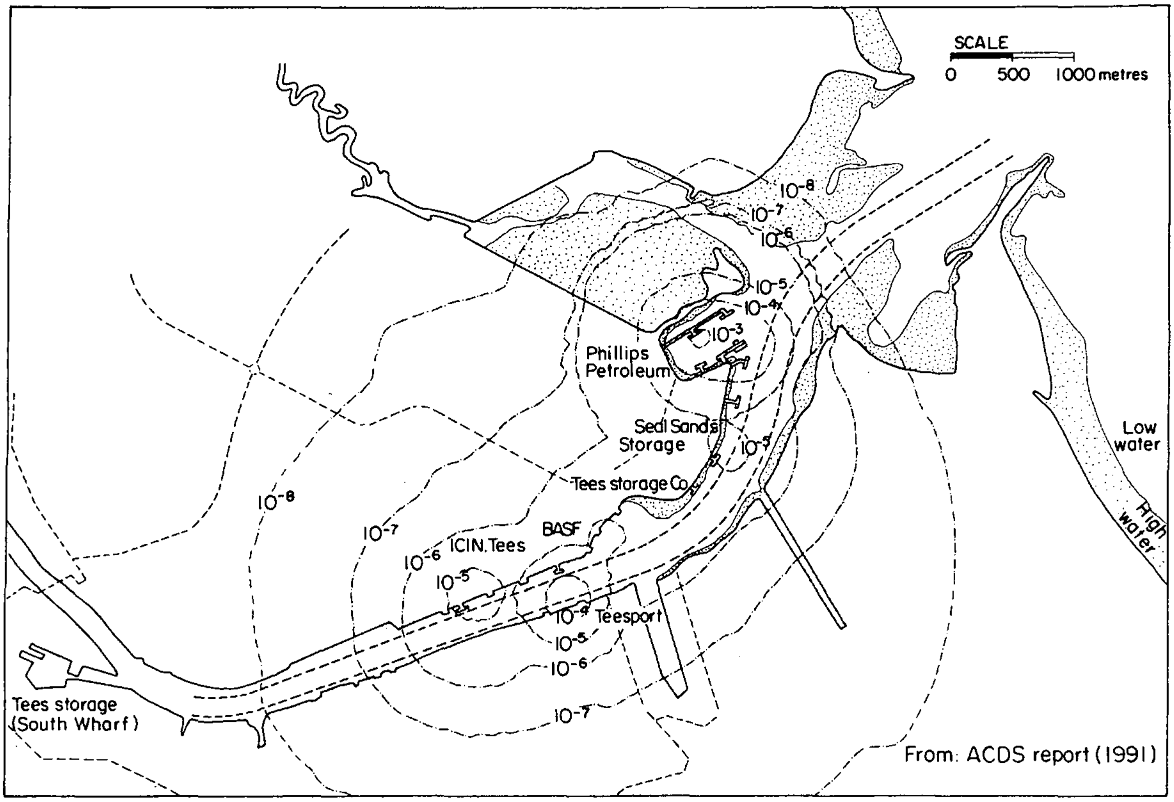


FIGURE 3 Individual risk isopleths (liquefied gas releases at terminal facility). Adapted from ACDS report (*24*).

involved analytically, requiring input from various areas of expertise. As an example of recent initiatives in this area, the HSE and the Department of the Environment (*18*) in the United Kingdom have been exploring ways in which several of these environmental concerns could be incorporated into QRA, based on the 1982 Seveso Directive and the Control of Industrial Major Accident Hazard (CIMAH) Regulations (*19–21*).

2. *Alternative ways of defining risk consequence.* Currently, two types of consequence criteria are used in *F-N* curves for the transportation of dangerous goods: immediate fatalities or "dangerous dose." According to Hurst et al. (*22*), the dangerous dose criterion is a recommended standard, which if exceeded could invite certain controls on development; for example, restrictions placed on certain types of development within a so-called "consultation zone." The HSE-recommended dangerous dose for toxic materials is a function of concentration [in parts per million (ppm)] and exposure time. For liquefied chlorine gas, for example, a dose of more than 108,000 ppm per minute (ppm/min) could give rise to fatalities in the more vulnerable population (*23*). The probability of incurring a fatality in the *F-N* curve requires an additional step in the analysis to translate "exposure to dose" to a "fatality response." To accomplish this, the Advisory Committee on Dangerous Substances 1991 report (*24*) suggests using a probit dose-response formulation, in which the input dose (expressed as a function of concentration and exposure time) becomes an input into a probit expression, with the dependent variable being a measure of the probability of death.

The Consensus Conference did not debate the issue of which criterion better reflects societal risk: fatality/personal injury or

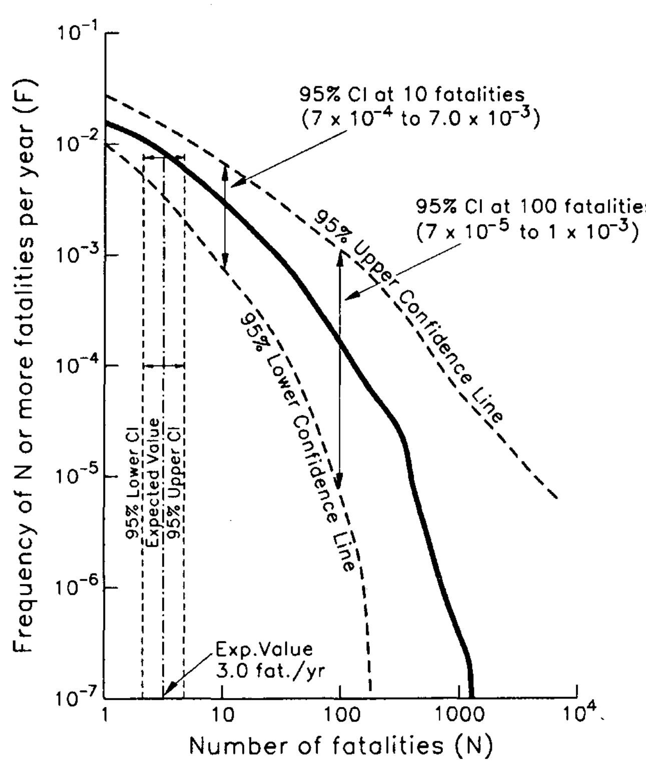


FIGURE 4 Cumulative societal risk *F-N* curve showing confidence intervals.

dangerous dose. However, it was generally recognized that a fatality- (and injury-) based consequence approach may be more readily applied to a further cost-benefit analysis of alternative strategies for mitigation, because techniques already exist for valuing death and injury in discounted monetary terms.

3. *Linking* F-N *curves to mitigation.* The reporting of *F-N* relationships must be linked directly to mitigation. This could include actions taken by individuals in order to avoid the full impact of a potential threat or actions taken by officials in response to incidents that have already occurred so as to minimize their resultant damages. Examples of individual actions include attaining shelter or evacuation. Examples of actions taken by officials include capping or containing the size of the release at the source, advising individuals along the path of potential threat to seek shelter or to evacuate the site, and finally implementing a safe and effective clean-up program.

4. *Including monetary factors.* Decisions are rarely made in the absence of monetary consideration (i.e., the cost of mitigation versus the benefits of risk reduction). According to Rimington (*13*): "Risk assessment is about giving proper structure and weight to any detriments so that we can compare them with the benefits." Many participants at the Consensus Conference echoed this sentiment, suggesting that risk output must be reported in such a way as to permit a thorough cost-effective evaluation of alternative forms of mitigation. This could involve assigning values to deaths, personal injuries, and property damage in the *F-N* curves and assessing the costs of alternative types of mitigation, including emergency response, containment, and clean up, as well as risk avoidance.

5. *Expressing uncertainty in the* F-N *relationship.* Because uncertainty in risk estimation varies with the number of reported cases used in validating the model estimates, the uncertainty associated with very low-frequency/high-consequence events is likely to be greater than uncertainty for high-frequency/low-consequence events. Accordingly, certain regions of the *F-N* curves are more prone to uncertainty than other regions, and this should be taken into account in representing the results. This is illustrated in Figure 4 by establishing confidence limits about each point on the *F-N* curve. The confidence bands associated with low-frequency/high-consequence regions of the *F-N* curve have been drawn wider to reflect a wider band of uncertainty associated with these estimates.

The Consensus Conference acknowledged that imperfect information will always produce risk estimates that are subject to error. The true value of risk will never be known. Confidence bands in the *F-N* curves are helpful to decision makers because they provide a range of values within which the true value of risk (in this case the frequency of N or more fatalities) lies, with, for example, a 95 percent level of confidence. These bands also serve as a basis for comparing uncertain estimates from different sources with values reported elsewhere for similar transportation of dangerous goods problems.

Frequently societal risks in the F-N curves are combined over all consequent damages and expressed as a single expected damage value (e.g., expected fatalities per year). This use of expected value for fatalities and injuries resulting from incidents involving the transportation of dangerous goods has created problems of validation for QRA models and has fostered a belief that these models are unnecessarily alarmist when compared with historical experience. A word of caution is advised in using and interpreting QRA results, based exclusively on the expected value of harm. Because in this measure low-frequency/high-consequence events are lumped together with high-frequency/low-consequence events, the resultant expected value will tend to overestimate risks, when compared with historical data that are normally collected over short periods of time. Many existing data bases include reports on dangerous goods incidents that have taken place over the last 10 to 15 years.

CONCERNING ABSOLUTE AND RELATIVE RISKS

Another question of importance in communicating risk is: should risks in QRA be expressed in absolute or in relative terms? The presence of uncertainty in risk estimation has fostered the belief that absolute risks are simply "abstractions posing as truth" (*10*). A number of participants at the Consensus Conference argued that given this uncertainty, only relative risks have any practical validity in QRA applications. These participants stressed that what is of interest to the decision maker is not the true value of risk, but instead insights gained on the risks involved, whether one activity is safer than another, and the degree to which this is the case. Because only relative risks are required to answer this question, uncertainty in obtaining absolute risks would not be relevant.

Notwithstanding difficulties in obtaining reliable estimates of absolute risk, however, the importance of these measures in certain decision situations should not be underrated. Absolute risks are most relevant in setting priorities on the cost-effectiveness of mitigation and in comparing risks to established tolerance criteria. Relative risks are most relevant when one mitigation option is compared with another and the decision maker is interested in some preferred option without a firm statement as to its costs and benefits or its acceptability vis-à-vis public risk tolerance. When the main focus of interest is actual costs or risk-tolerance levels, then only risks expressed in absolute terms would be relevant in decision making.

QRA AND DECISION SUPPORT

Recognizing that decisions have to be made, the issue that needs to be addressed is how QRA can best aid the decision-making process. QRA is useful for setting priorities, for underpinning an effective risk-management program, for evaluating this program, and also for achieving a better and more public perception of the risk by communicating information about this risk (*14*).

Decision making in a risk environment is a four-stage process: identification of hazards, quantification of risks, assessing the tolerance of these risks in terms of community standards, and developing a cost-effective strategy for their control and reduction. Many QRA models have in the past been confined to identifying and measuring risks associated with different aspects of the transportation of dangerous goods problem: the accident, breach of containment, release situation, hazard area, and casualties involved for different levels of damage. However, at its current state of development, QRA is increasingly being recognized as a process which, although still informed technically, must also reflect inherently economic and political considerations (*6*). To discuss QRA and decision making, the issue of tolerance of risk must first be discussed, because it is tolerance of risk that influences decisions on whether actions need to be taken and the form these actions are to take. In applying risk tolerance to decision making, three factors need to be specified: (*a*) an appropriate risk-tolerance criteria, (*b*) a framework of decisions for different levels of tolerance, and (*c*) the cost and benefits associated with these decisions.

The first factor requires the development of risk-tolerance criteria that are reflective of the public perceptions of risks associated with a given activity and their acceptability. The second factor attempts to formulate a suitable decision strategy on the basis of the previous perceptions on risk tolerance. The third factor is concerned with assigning costs and benefits to the activity being considered and assessing how these costs and benefits are modified by alternative forms of mitigation.

To assist the decision maker in applying QRA, the Advisory Committee on Dangerous Substances (ACDS) report (*24*) suggested an approach for guiding decisions based on comparing risks to established tolerance criteria for advisable action. Three criteria were identified:

1. Risk is so great or the outcome so unacceptable that it must be refused altogether (intolerable);
2. Risk is so small that no further action or precaution is necessary (de minimis);
3. Risks fall between these two states so that they can be reduced to be "as low as reasonably practicable" (ALARP).

How these three "advice regions" were applied in the ACDS report to the national societal risks in the United Kingdom is illustrated in Figure 5. The upper and lower bound ALARP values indicated in this figure have been set for three consequence levels on the societal *F-N* curve in the ACDS report (i.e., 10, 100, and 1,000 fatalities). In general, values of risk from QRA that exceed the upper-bound ALARP values are deemed to be intolerable from a societal perspective. Below the lower-bound ALARP values, societal risks are negligible and do not require further action. Risks in the ALARP region should be reduced as much as is economically practicable. Whether mitigation is advisable is a matter of costs and benefits, supplemented by practical political considerations. As shown in this figure, national societal risks were found to be ALARP at all levels of the *F-N* curve.

Although the application of these criteria may appear on the surface to be straightforward, it is generally recognized that a number of factors act to modify risk-tolerance criteria for different activities and jurisdictions, and this can have serious implications for any suggested advice structure, for example:

1. *National and local interests and customs.* It is generally acknowledged that in some countries the public tolerates certain types of risk more readily than in other countries. Similar discrepancies may take place between different socioeconomic and demographic groups even within the same country or jurisdiction.

2. *Discretionary nature of the risk activity.* This factor distinguishes between risks that are mandated in day-to-day activities and those risks that are discretionary in nature and hence can be avoided simply by lifestyle alterations. (Examples of mandatory

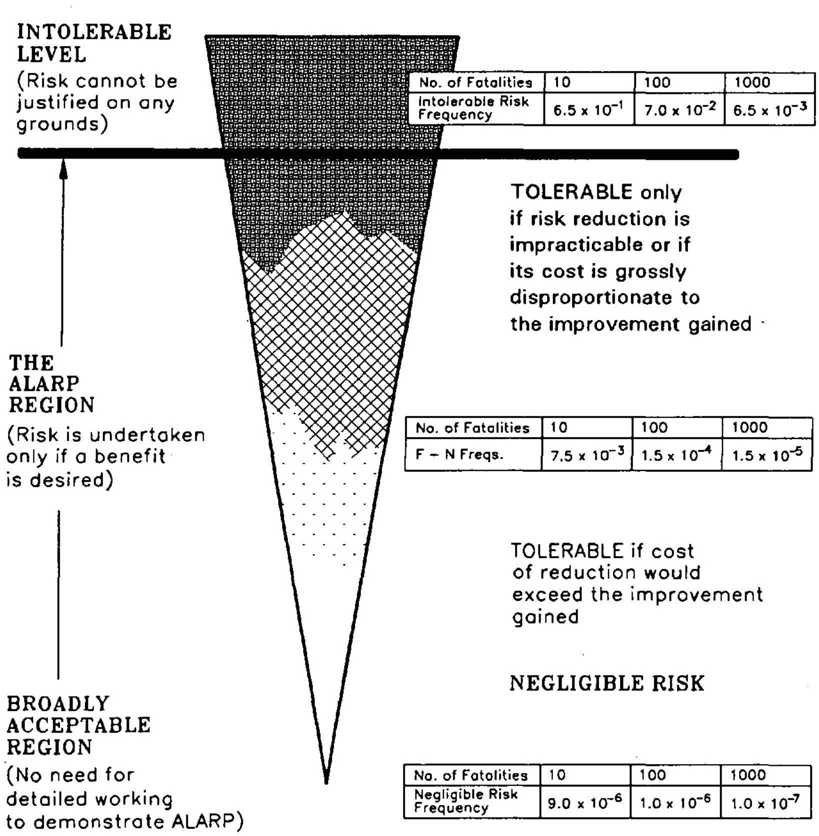


FIGURE 5 HSE risk tolerance criteria for national societal risks in the United Kingdom. From ACDS report (*24*).

risks are work- and ambient-related, whereas examples of discretionary risks are recreational, such as skiing or hang gliding).

3. *Risk history.* This factor considers the past history of risk associated with a given activity. For example, have there been casualties in the recent past associated with the activity and what were the circumstances surrounding these casualties?

4. *Economic consideration.* A number of monetary factors affect tolerance of risk. It is generally recognized that the assignment of costs and benefits to risk and its mitigation varies inherently from jurisdiction to jurisdiction, and from time to time, depending on wider economic issues.

The Consensus Conference acknowledged that largely because of these factors, QRA may not be able to determine the best decision to take on reducing the risks associated with the transportation of dangerous goods and that there is much that needs to be prescribed to the political arena. QRA enables these essentially political decisions to be technically informed.

CONCLUSION

The lessons learned from the Consensus Conference were summarized into a series of consensus statements that were submitted to the participants to elicit their agreement or disagreement. An attempt has been made in this paper to elaborate on these statements with reference to what is known about QRA from the literature, and from discussion at the Conference.

A number of ways in which QRA can be made more relevant to decision makers have been addressed in this paper. However, there are practical limits on what QRA can accomplish in a decision-making context, given the complexity of issues surrounding the risks of transporting dangerous goods. Conclusions regarding limits of QRA are inevitably subjective and political, and depend (among other factors) on the resources available and the questions being addressed. The Consensus Conference could not map out the limits of QRA, a task which is likely impossible to realize. The Conference was instrumental, however, in identifying a number of important issues that need to be considered to make QRA more meaningful to users, decision makers, and the public at large.

ACKNOWLEDGMENTS

This paper was prepared while F. Frank Saccomanno was on sabbatical leave with the Research and Laboratory Services Division of the Health and Safety Executive. The comments and suggestions on this paper provided by Clive Nussey, Nick Hurst, and Mary Trainor of the Research and Laboratory Services Division (Hazard Analysis Section), are gratefully acknowledged. The authors also acknowledge the contribution provided by the various participants at the Consensus Conference, especially Jeff Solway and Lorraine Craig.

REFERENCES

1. *Risk: Analysis, Perception, and Management.* Group Report, British Royal Society, London, England, 1992.
2. *Engineering Safety* (D.I. Blockley, ed.). McGraw Hill, Maidenhead, England, 1992.
3. Fischhoff, B. *Risk: A Guide to Controversy, Improving Risk Communication, Appendix C.* National Academy Press, Washington, D.C., 1989.
4. Hubert, P., and P. Pages. International Discrepancies in the Estimation of the Expected Accident and Tank Failure Rates in Transport Studies. In *Proc., International Consensus Conference on the Risks of Transporting Dangerous Goods* (F. F. Saccomanno and K. Cassidy, eds.). University of Waterloo Press, Waterloo, Ontario, Canada, 1993.
5. Saccomanno, F. F., A. Stewart, and J. H. Shortreed. Uncertainty in the Estimation of Risks for the Transport of Hazardous Materials. In *Proc., International Conference: HAZMAT Transport 91,* Northwestern University, Evanston, Ill. 1991.
6. *Quantified Risk Assessment: Its Input to Decision Making.* Health and Safety Executive, Her Majesty's Stationery Office, 1989.
7. Covello, V. T. *Prospects and Problems in Risk Communication* (Leiss, ed.), University of Waterloo Press, Waterloo, Ontario, Canada, 1989.
8. Covello, V. T. Risk Communication: A New and Emerging Area of Communication Research. In *Proc., International Conference on Risk Assessment,* London, England, Oct. 1992.
9. Glickman, T. S., A. H. Mushkatel, and K.D. Pijawka. The Perceived Risks of Transporting Hazardous Materials and Nuclear Waste: Preliminary Analysis of Case Study Findings and Implications. In *Proc., International Consensus Conference on the Risks of Transporting Dangerous Goods* (F. F. Saccomanno and K. Cassidy, eds.). University of Waterloo Press, Waterloo, Ontario, Canada, 1993.
10. Solway, J. What Is the Risk? *Consensus Report of the International Consensus Conference on the Risk of Transporting Dangerous Goods,* Institute for Risk Research, University of Waterloo, Canada, 1993.
11. *Improving Risk Communication.* National Research Council, National Academy Press, Washington, D.C., 1989.
12. *Risk Assessment:* A Group Study Report. British Royal Society, London, England, Jan. 1983.
13. Rimington, J. D. Overview of Risk Assessment. In *Proc., International Conference of Risk Assessment,* London, England, Oct. 1992.
14. Haigh, R. Risk Assessment: A European Perspective. In *Proc., International Conference of Risk Assessment,* London, England, Oct. 1992.
15. Saccomanno, F. F., and O. Bakir. Analysis of Risk Uncertainty for the Transport of Hazardous Materials. In *Proc., International Consensus Conference on the Risks of Transporting Dangerous Goods* (F. F. Saccomanno and K. Cassidy, eds.), University of Waterloo Press, Waterloo, Ontario, Canada, 1993.
16. Saccomanno, F. F., D. Leeming, and A. Stewart. *Comparative Assessment of Risk Model Estimates for the Transport of Dangerous Goods by Road and Rail.* Health and Safety Executive, Research and Laboratory Services Division, Report N, Sheffield, Yorkshire, England, Dec. 1992.
17. Williams, K. C. Risk Assessment: an Employer's Perspective. In *Proc., International Conference of Risk Assessment,* London, England, Oct. 1992.
18. *Interpretation of Major Accident to the Environment for the Purposes of CIMAH Regulations.* A Guidance Note. Department of the Environment, London, England, June 1991.
19. *Control of Industrial Major Accident Hazards Regulations (CIMAH).* Statutory Instrument 1984/1902, Her Majesty's Stationery Office, 1984.
20. *Directive 82/501/EEC on the Major Accident Hazards of Certain Industrial Activities,* OJ No. L230,5.8.82, Seveso Directive, European Economic Council, 1982.
21. Welsh, S. Assessment and Management of Risks to the Environment. *Institute of Chemical Engineers Symposium Series 136,* 1991, pp. 85–110.
22. Hurst, N., C. Nussey, and R. Pape. Development and Application of a Risk Assessment Tool (RISKAT) in the Health and Safety Executive. *Chemical Engineering Research and Design,* Vol. 67, 1989.
23. Turner, R., and S. Fairhurst. Toxicology of Substances in Relation to Major Hazards. Health and Safety Executive, Her Majesty's Stationery Office, 1990.
24. *Major Hazard Aspects of the Transport of Dangerous Substances.* Advisory Committee on Dangerous Substances (ACDS) Health and Safety Executive, Her Majesty's Stationery Office, 1991.

Publication of this paper sponsored by the Committee on Transportation of Hazardous Materials.