Use of Quantified Risk Assessment in Evaluating the Risks of Transporting Chlorine by Road and Rail

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The Health and Safety Executive (HSE) makes routine use of its computerized quantified Risk Assessment Tool (RISKAT) in order to assess the risks from major industrial hazards. In recent years attention has been directed toward the transport of dangerous substances, and consequently HSE has developed a transportation version of RISKAT. Described is the application of Transport RISKAT to a case study in which the overall risks from a major industrial facility handling chlorine have been assessed. A novel feature of this study is the inclusion of the delivery system into the assessment, and the comparison of two transport modes: rail and road. The proposed switch from rail to road transport significantly reduces the risks from site operations. The study therefore addresses two questions: has any transfer of risks onto the transport system taken place, and if so, are the overall risks reduced as a result of the switch in mode? In addressing these questions, the report concludes that there is a considerable degree of uncertainty in the risk estimates. The effect of variability on the conclusions that can be drawn from the study is illustrated by the use of risk inputs from a number of independent sources.

In 1991 the Health and Safety Commission's Advisory Committee on Dangerous Goods (ACDS) published a report of a major study into the national risks of transporting dangerous goods (*1*). Although concluding that the national risks were tolerable, the report recommended that specific studies should be made of situations in which a concentration of risk from the transportation of hazardous materials is perceived. Such specific studies invariably require the use of quantified risk assessment (QRA) tools in the form of computer codes. For several years HSE has used RISKAT (*2*) to provide land-use planning advice on developments in the vicinity of major industrial hazards at fixed installations. In order to address the ACDS recommendation, HSE has developed a similar suite of codes [Transport RISKAT (*3*)] for assessing transportation risks. The development of Transport RISKAT has been assisted by case work. Described in this paper is the application of the codes to one such case study involving the handling of chlorine by a major industrial facility, together with two options for its delivery system (i.e., by rail or road). The assessment addresses two important issues that have often been neglected in QRA studies.

First, the question of uncertainty in the estimates has been addressed through the use of several data sources, and the implications of any variation in the conclusions between risk estimates produced from each source have been assessed. Second, as a switch in the mode of delivery may have implications for other interacting systems, a more global view of the chlorine delivery system has been taken than would be the case if only the transport risks had been assessed.

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UNCERTAINTY IN QRA

The credibility of QRA's ability to provide accurate predictions of the threats posed by hazardous materials is often undermined by the degree of uncertainty in the estimates. This can be worsened when the findings of QRA are at variance with public perception. One commonly encountered opinion is that rail transport is inherently safer than road. However, although the assumption that rail tankers are less likely than road tankers to be involved in an accident is generally supported by statistical evidence, this perceived safety advantage may be countered by the greater severity of potential consequences because of larger payloads or routing of rail shipments through population centers. In view of such issues, it is important that the assumptions made during the application of QRA and their effects are accounted for in the reporting of risk estimates.

Historically, risk uncertainty has been handled in a number of ways. A "best estimate" approach is sometimes used, in which sample averages are obtained from the literature or from observation. Erring on the safe side is an approach that is biased toward the worst-case scenarios in order that inaccuracy should not compromise safety. HSE adopts a "cautious best estimate" approach to major hazard risk assessment, essentially a combination of the first two philosophies described in this paper. Finally, there are more sophisticated approaches in which the inputs and outputs of a QRA study are subjected to comprehensive statistical analysis.

REGULATORY FRAMEWORK

Fixed Hazardous Installations

The regulatory framework (*4–6*) in the United Kingdom (UK) requires that HSE provide the local authorities with advice on land-use planning around major hazards (*7*). This advice mechanism is triggered when planning applications are made within the consultation distance (CD) of the particular installation, CD being calculated from the notifiable amount of hazardous substance. Developers of new hazardous installations must seek the consent of the appropriate authority.

The criteria used by HSE for providing risk-based advice (*8*) define four development categories with varying sensitivity to risk. The advice to be given on these developments depends on an assessment of the levels of risk as a function of distance and direction from the plant.

Transportation of Hazardous Substances (Rail and Road)

UK regulations specific to hazardous substance transport overland cover the aspects of labeling, vehicle marking, driver training and certification, and the equipment and design of vehicles. The move toward harmonization in the European Economic Community has led to the introduction of dangerous goods transportation and handling agreements (*9,10*). There are no regulations directly concerning the routing of hazardous substance transport.

CASE STUDY

A major industrial facility in the UK (hereafter referred to as "the site") uses chlorine in the manufacture of various products. Currently, this chlorine is shipped overland by rail. Because of operating constraints, the rail delivery system lacks the flexibility required to reduce the lead time for delivery of chlorine to the site. As a result, a large inventory of chlorine is required on site as a backup should it be needed in production.

At this site the notifiable amount of bulk storage of chlorine is large, and consequently the area of land subjected to risk-based development restrictions is considerable. In response to the potential hazard on the advice of HSE, the local authority has imposed a CD of 2.0 km around the plant, which is situated in a highly urbanized region. There are considerable incentives for reducing the CD by lowering the amount of on-site storage of chlorine. To bring this about, the site owners are considering a "just-in-time" system of delivery that more closely matches the requirements of production over time, requiring a switch from rail to road transport. To reflect a much-reduced inventory, a new CD of 1 km has been suggested for the site, reducing the amount of land restricted by 75 percent over the existing zone.

The benefits of reducing the off-site risks as proposed are considerable: 47,000 out of 60,000 residents, 23 out of 29 schools, and 20 out of 25 other sensitive developments will be removed from the consultation zone. There will also be a considerable appreciation in land value because of the reduction in the risk from the site.

Although it is recognized that a just-in-time system of delivery for chlorine will reduce the risks from the fixed installation, the question that needs to be addressed is: are reductions in site risks resulting from a just-in-time system of delivery offset by higher on-route risks associated with a change in the mode of delivery from rail to road?

OBJECTIVES

The case study had four objectives:

1. Carry out a comparative assessment of the on-route risks for transporting chlorine by rail and road to the site;
2. Consider the uncertainty in transport risk estimation by repeating the assessment with several sources of accident and release estimates and to assess the implications of any variability in the risk estimates for conclusions about the relative safety advantages of one mode over another;
3. Carry out a comparative assessment of the risks from site operations before and after the switch in transport mode; and
4. Consider the total risks of site and delivery system with each mode of delivery and assess whether any transfer of risks has taken place. The study of variability (Objective 2) will increase confidence in the conclusions by providing a range of estimates.

In this study, the assessment of the delivery system has included only those risks associated with accident-induced releases of hazardous material.

THE SITE

The site currently consumes some 35,000 tonnes of chlorine/year for the production of various commodities. The handling facility consists of two 150-tonne bulk storage tanks fed from a discharge bay. Pipework from the bulk storage leads to various liquid reactors and vaporizers, which in turn feed a bank of gaseous reactors. The discharge bay holds a maximum of four 28-tonne rail tankers and the reception area another eight. In their initial assessment, HSE has used a total inventory of 360 tonnes to set the CD.

The proposed just-in-time delivery envisages a complete refit. The bulk storage system is to be replaced by one 20-tonne buffer tank, maintained at the 10-tonne level by continuous unloading of road tankers. Unloading operations will mean the presence of one full tanker and one partially loaded tanker on site at any given time. This arrangement allows for a maximum 50 tonne of chlorine on site.

EXISTING AND PROPOSED DELIVERY SYSTEMS

Currently, chlorine is shipped to the plant in 28-tonne pressurized rail bulk tankers. Approximately 8 to 12 tankers/train are shipped three to four times weekly from the supplier to the site. All rail shipments of chlorine take place during the night when passenger traffic on the rail network is negligible.

The existing 319-km rail route, subdivided into 18 sections for the assessment, consists mostly of high-level mainline track. Much of the route is of rural character, with scattered small communities. The route passes through a large town and a large moderately built-up area before entering the highly built-up area containing the site. The maximum allowable freight train speed over much of this track is 100 km/hr, although there may be sections of this route where the maximum allowable speed is lower. The route traverses four railyards. At the rail terminus nearest to the site, the chlorine tankers are shunted onto industrial track for final delivery to the plant.

Specially designed road tankers with a payload capacity of 21 tonnes are proposed for the alternative road supply option. Road shipments would originate from a different supplier to the rail option located nearer to the site. The corresponding road distance is 154 km, subdivided into 14 sections.

The route is motorway (freeway) between Sections 2 and 13. It bypasses urban areas at Sections 4 to 5 and 7. Unlike the rail route, it does not pass directly through population centers until Section 12, when it enters the built-up area around the site.

The average population density varies within 10 km of the route options (Figure 1). Compared with the rail route, the figure shows lower peaks in the population immediately adjacent (nearest 1 km) to the road route, reflecting the tendency for trunk roads to bypass population centers. The motorist population was assumed to be constant along the route and concentrated around an accident site, caused by backing up and "rubbernecking."

COMPONENTS OF RISK ESTIMATION

Illustrated in Figure 2 [adapted from Alp et al. (*11*)] is the structure of quantified risk assessment (QRA) applied to the transport of toxic substances. This structure is the basis of HSE's Transport RISKAT. As in any QRA, the process can be split into three parts: (*a*) identification of hazard type and frequency, (*b*) consequence analysis for each hazard, and (*c*) combination of consequence and likelihood expressed as risk. Hazards associated with the transport of chlorine consist of accident-induced releases during transport and the consequent impacts on nearby population. Heavy gas-dispersion codes are used to estimate the spacial distribution of toxic dose for a range of representative releases and weather conditions. A knowledge of the population distribution and the dose-response relationship (toxicology) allows an estimate to be made of the number of fatalities (or other level of harm) for each event.

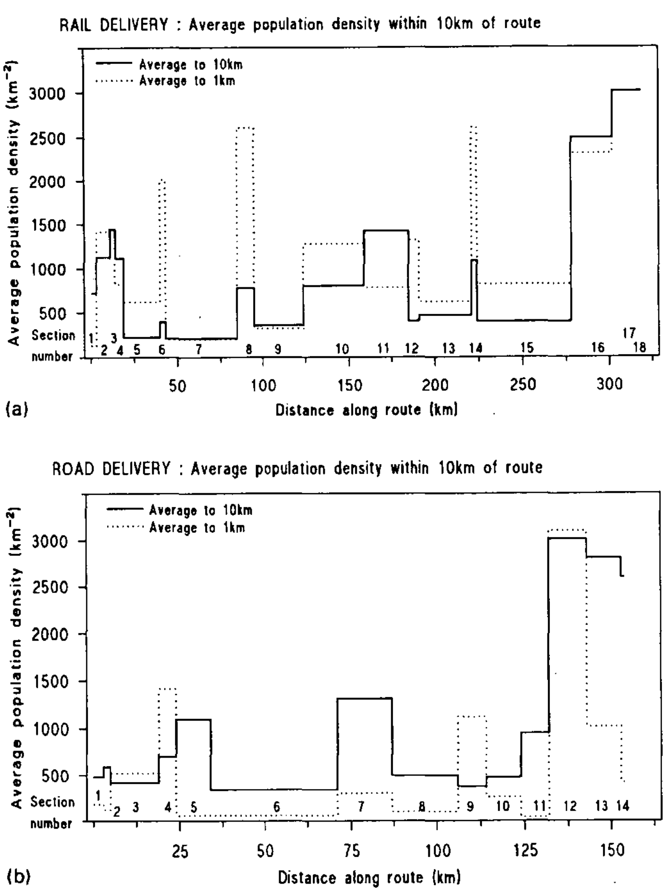

FIGURE 1 Density of population adjacent to (a) rail and (b) road routes.

The assessment of fixed installations has the same structure, although release scenarios are usually more diverse and their frequencies are derived directly from generic data bases.

COMPARATIVE ASSESSMENT OF RISKS

Estimating Release Frequencies: Site

The chlorine plant on site has been assessed by HSE. Loss-of-containment mechanisms were identified for both the rail- and road-supplied plant designs. These ranged from catastrophic vessel failure, vessel holes above and below the liquid level, to various types of pipework failure in the liquid and vapor phases and tanker coupling failures.

The frequencies were obtained from HSE's data base of generic failure rates, used for its static major hazard assessment casework. These data were derived from a number of sources including the historical record and theoretical studies involving such techniques as fault tree analysis supplemented by expert judgment.

Estimating Release Frequencies: Delivery System

The probability of an accident-induced release depends on three constituent factors:

1. *Accident rates involving rail and road chlorine tankers.* These accident rates are expressed in terms of tanker accidents per vehicle km.
2. *Probability of breach of containment (fault rate).* Fault rates are expressed as a percentage of the accidents that result in some form of release.
3. *Probabilities of specific types and sizes of release.* Release probabilities are estimated for catastrophic failure of the tanker containment system and continuous releases result from holes or equipment leaks.

Unlike the case with static major hazards, HSE has not yet developed a policy on failure rates associated with dangerous goods transportation. Therefore to ensure that the implications of variability in the risk estimates are accounted for, this exercise has used failure-rate data from several independent sources.

1. *Institute for Risk Research (IRR), University of Waterloo, Canada.* Road and rail accident rates are based on a statistical analysis of Canadian-reported accident data. Accident rate models (*12*) were calibrated with Ontario accident data. IRR obtained fault and conditional release probabilities for the rail and road transport using a fault tree analysis of chlorine bulk tanker systems for Canadian conditions (*13*).
2. *Averages from a Group of Experts (CONSENS).* To assess consistency in risk estimation for a common set of transport conditions, a group of experts provided "consensus" estimates of accident rates, fault rates and release probabilities for a common transport problem involving the bulk transport of chlorine by rail and road tanker over a 100-km hypothetical route (*3*). Estimates were derived from a mixture of North American and European data. The mean values were used for this assessment.

3. *Health and Safety Commission, Advisory Committee on Dangerous Substances, UK.* These estimates were taken from the study of national risks published in 1991 (*1*). The ACDS frequencies of large releases were derived directly from an analysis of the historical road and rail puncture records. As UK observations of chlorine road and rail tanker breaches were limited in number, U.S. data and UK thin-walled (i.e., nondangerous goods) tanker breaches were analyzed. Engineering judgment was used to account for operational and design differences.

4. *Health and Safety Commission, Research and Laboratory Services Division, UK.* Road accident rate estimates were derived specifically for conditions that match the main delivery characteristics (i.e., articulated trucks, traveling on motorways, and so on). a base of approximately 12,000 individual injury-accident records and traffic flow (i.e., exposure) data for the entire trunk road network during 1991 was obtained from the Department of Transport (DTp). This provided information on the influence of variation in route and vehicle factors on the likelihood of an accident.

5. *British Rail Railfreight Distribution (BRRF).* BRRF supplied an estimate of derailment frequency for all loaded freight wagons.

6. *Loughborough University, UK.* Davies and Lees (*14*) made a study of the UK road transport environment for conveyance of hazardous materials using DTp statistics for 1986. The fault probability was based on attendance by the fire brigade at all incidents involving hazardous materials transport by road.

National Differences

The various sources previously detailed assumed a variety of North American, European, and UK conditions. Studies (e.g., Davies and Lees *14*) have found lower heavy goods vehicle (HGV) accident rates for the UK compared with those in North America. The majority of UK hazardous substance road tankers are fitted with safety-enhancing features such as anti-skid and jackknife systems, which reduce their accident rate compared with the mean for articulated HGVs in general. In the UK there have not been any observations of significant releases of chlorine from road tankers.

There are also basic differences between the North American and UK rail environment, partly stemming from the need for much longer trains in the former case. For instance, long trains require rigid couplers, which may be hazardous in an accident situation. In the UK, the couplers are recessed behind damped buffers, and buffer over-ride protection is fitted to all chlorine tank wagons.

Estimating Hazard Areas for Different Levels of Health Impact

Transport RISKAT incorporates the dense gas dispersion codes DENZ (*15*) and CRUNCH (*16*) for estimation of the toxic dose distribution (hazard areas) that would result from each release scenario for each of a set of representative weather conditions. Stability, windspeed, and windrose profiles were obtained for a weather station in the vicinity of the site. To compute the impact on the population, a probability-of-fatality approach was used, based on a probit relationship (*1*). The code computes hazard areas for both the outdoor and indoor population, the latter via an infiltration model. Motorists are considered effectively outdoors.

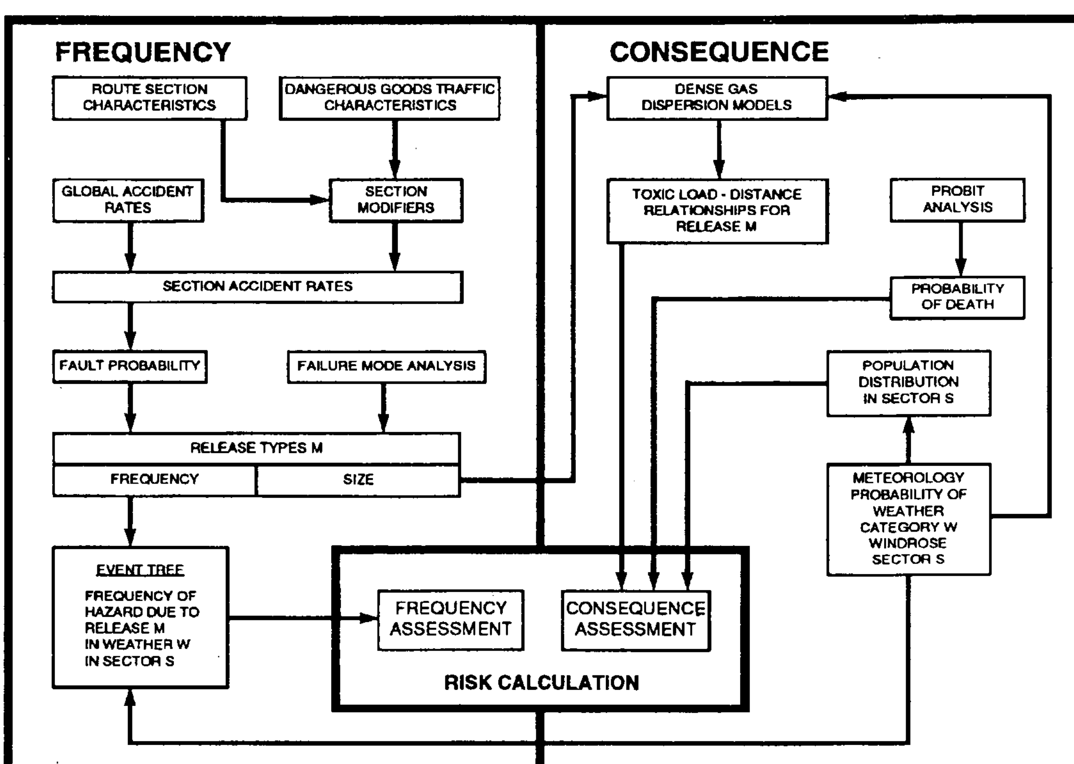

FIGURE 2 Structure of transport-quantified risk assessment.

Individual Risk

Individual risk is defined (*8*) as the risk to which an individual at a particular location is subjected. Because of the mobile nature of transport risk sources, the risks at particular locations are normally de minimus, (i.e., less than 10^{-6} per year) even at distances nearest to the routes, although the risks to unspecified individuals somewhere along the route may be significant. In this exercise, all risks have been expressed from a societal perspective in terms of the expected number of fatalities per year.

Societal Risk Calculation

The number of persons exposed to each representative release can be estimated by matching the hazard areas resulting from each scenario with the population density in the region exposed to the hazard. In this way, an estimate can be made of the mean number killed by each hypothetical release scenario and its probability. Transport RISKAT performs this operation for each route segment in order to calculate on-route risks and over-the-site locality for risks from the plant.

Effect of Population Distribution on Risk Estimation

Societal risk estimation requires the knowledge of how the on- and off-road population is distributed in terms of its density and location. Schemes for estimating this have been developed for static major hazard assessments (*17*). Transport assessments involve much greater areas than static sites. In addition, societal risk estimates are very sensitive to assumptions that are made about the variation of population density with distance. The consequence models need to be sensitive to extreme distributions such as strip developments, where a strip of built-up land exists close to a route and bypasses the section where a sizable clear zone exists between the route and an urban area. In this study, the population contributions were weighted according to their proximity to the routes.

Results

The results are given in terms of three societal risk descriptors:

F-N Curves

These are plots of the number N killed against the cumulative frequency of N or more fatalities that are representations of the spectrum of potential risks. They are useful when "risk aversion" is an issue (i.e., the relationship between tolerability and the scale of the event).

Expectation Value

This is the long-term average number of fatalities per unit time (year). It is constructed by summing the products of all events and their associated probabilities. This can be used in conjunction with the *F-N* curve to compare results from different cases.

Societal Risk Rate

This is relevant to route risks only. It is given by the expectation value divided by the length of route and can be useful in illustrating the variation in risks along a transport route.

Best Estimate, Upper and Lower Limits

In order to aid interpretation of the results, a best-estimate approach has been adopted. This aims to emphasize those risk estimates that have been obtained using inputs that were most appropriate to the case being studied.

Road

The RLSD results were used as the "cautious best estimate" of the risks associated with the road delivery system. This was appropriate because the accident rates were derived from a large, up-to-date data base of accident and traffic records specifically for articulated HGVs on UK motorways, with no distinction made between hazardous materials tankers and other HGVs.

Rail

The ACDS accident rate included both derailments and collisions occurring on the UK rail network, and as the national differences are likely to be greater for the rail environment than that for road, it was thought appropriate to consider the ACDS results "best estimates."

Delivery System

How the societal risk rate (using IRR estimates) varies with route section for the rail and road routes is shown in Figure 3. The range of estimates for each transport mode for the entire routes are shown in the form of *F-N* curves in Figure 4. The expectation values are also given.

Site

F-N curves and expectation values for the site alone are given in Figure 5. Included in the figure are the tolerability limits for specific localities derived by the ACDS in their study of the risks of transporting dangerous substances in the UK. It should be noted that these tolerability curves were derived for certain marine ports included in the national assessment, and great care should be exercised when transferring tolerability criteria from one situation to another. The range of estimates of the total risks from the site and delivery system are shown in Figure 6.

DISCUSSION OF RESULTS

The objective of this study was to estimate relative rather than absolute risks for each mode of transport. The significance of this is that as the same models and assumptions were applied through-

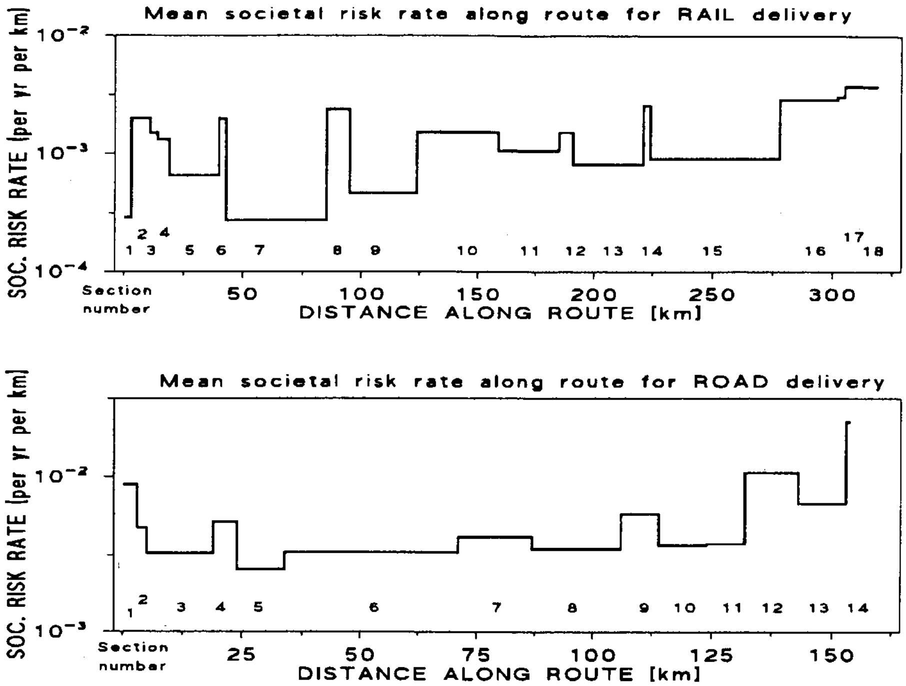

FIGURE 3 Societal risk rates for each delivery system.

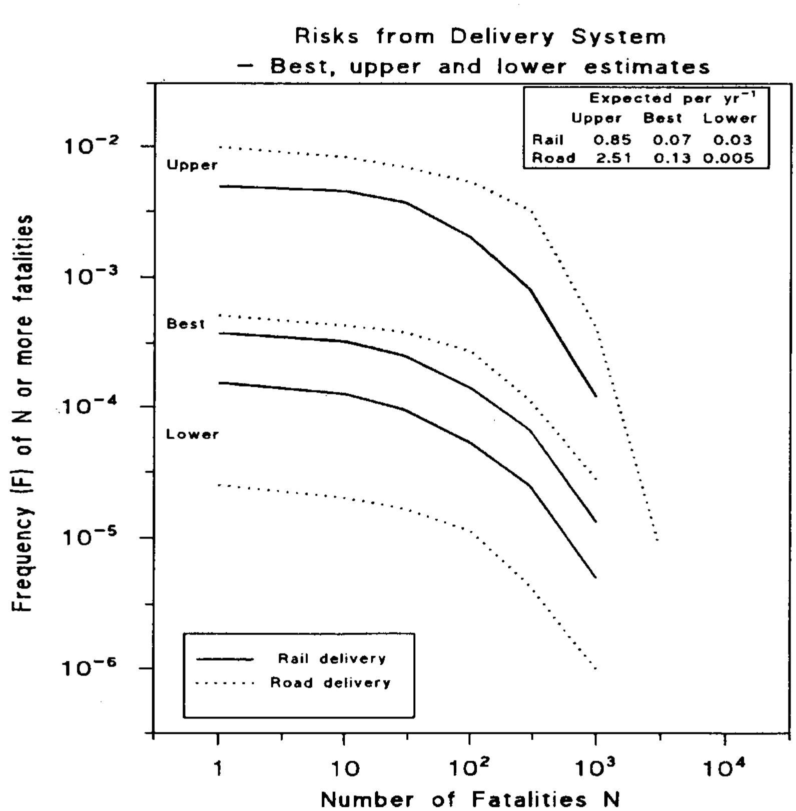

FIGURE 4 Range of estimates of societal risk for each delivery system.

out, the inherent uncertainty will be essentially similar in each case. The results are discussed accordingly.

Route Risks (Delivery System)

Significant differences in the societal risks resulted from variability in the estimates as reported by the independent sources. The estimates for rail delivery range from 0.03 to 0.85 fatalities/year, and the corresponding figures for road span two orders of magnitude from 0.005 to 2.5/year.

The greatest risk estimates for both road and rail were derived from the CONSENS and IRR inputs, which were mostly based on North American conditions. The lowest estimates were derived from the ACDS and BRRF inputs; these were provided for UK conditions.

From Figure 4, the risks associated with each transport mode can be compared. The best estimates are very close, in view of the large variation in the estimates. There is more uncertainty in the estimates for road than for rail, with all the rail estimates being contained within the range of road estimates. As the length of the road route is only half that of the rail route, similar overall risks would seem to indicate greater risks per km for road. The upper estimates indicate higher risks for road.

The motorist population contributed on average about two-thirds of the societal risk because of the road delivery system. This result implies that the model is very sensitive to the assumptions made during the analysis of the impact on the motorist population.

The societal risk rate variations along the route (Figure 3) follow closely the variation of the nearest 1-km population density (Figure 1). This effect is more pronounced with the rail than the road risks because of the large contribution from the motorist population. "Hot-spots" can be perceived along the route (i.e., Rail Section 8, a rail yard in the center of a large town). The results indicate that the model is more sensitive to variations in the population density than in the accident rate.

Site Risks

The risks from the site operations are an order of magnitude lower after the risk-reducing alterations to the design. The expected number of fatalities because of the rail-supplied plant were estimated at 0.2/year, compared with 0.02 for the road supplied "just-in-time" system. The *F-N* curves for both options fall between the ACDS criterion for intolerability at specific localities (*1*) and the negligible line. Note that the transfer of tolerability criteria from one situation to another is a complex issue; the criteria are shown here as a rough guide only.

Total Risks

The total risks of site and delivery system follow a similar pattern to the delivery system alone. The best estimates of the total risks before and after the switch in transport modes are again very close, and there is more uncertainty in the estimates for the road-

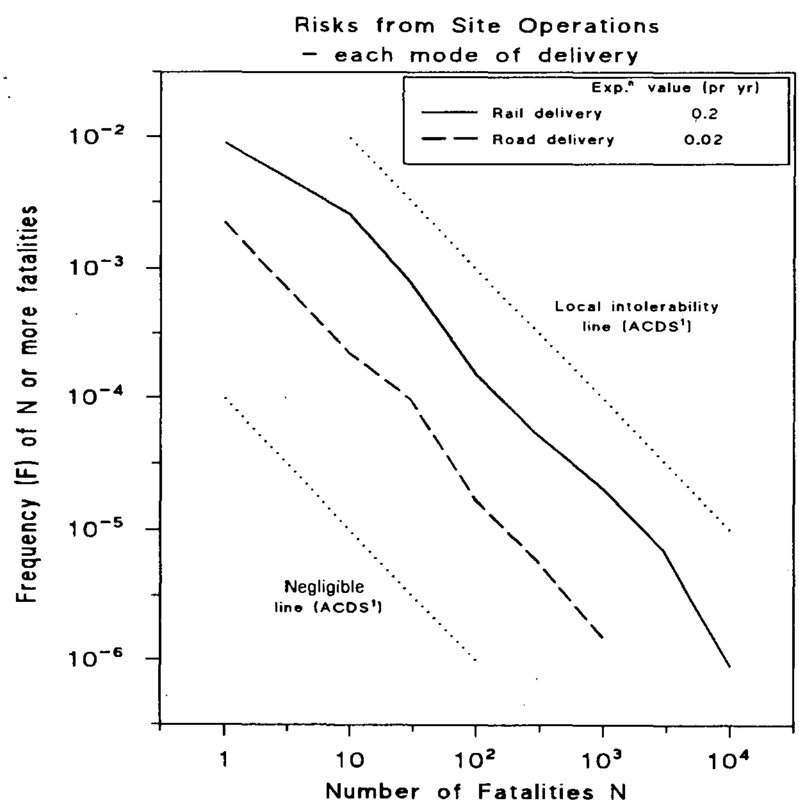

FIGURE 5 Societal risk estimates for site only, before and after change in delivery system.

supplied option. The site risks are lower than the upper estimates for the transport systems, but higher than the lower transport risk estimates. The best and upper-risk estimates support the conclusion that the rail-supplied option is as safe or safer than the road option. A less cautious approach, drawing conclusions from the lower estimates alone, would find the reductions in site risks predominating, with lower risks for the road-supplied option.

Individual Risks

Individual risks to the population resident around the site have been reduced dramatically. This was the basis for the reduction in the consultation zone, which has a radius reduced by 50 percent. Using the "best estimates" of accident and release data, the risks of individuals resident alongside either transport route receiving the LD_{50} (dose giving a 50 percent chance of fatality) have been estimated as lower than 10^{-6} yr^{-1} for distances exceeding 50 m.

CONCLUSIONS

Six sources of accident rate and release probability data were used to estimate risks for road and rail transport of chlorine. The risk inputs from the various sources were derived in a number of ways from a comprehensive statistical analysis of a large number of accidents to engineering judgment applied to the specific details of a small number of actual chlorine releases. Some of the estimates were based on North American data, and some on European and UK data.

Illustrated in the study is the large degree of uncertainty associated with quantified risk assessment applied to the transport of hazardous substances. Depending on the source used for the risk inputs, contradictory conclusions can be drawn. It is likely that some of this uncertainty is explained by national or jurisdictional differences between sources, and on this assumption it was possible to derive "cautious best estimates" of the risks, using those inputs that were most closely tailored to the specific design of the delivery systems.

The findings of this study can be considered in terms of risks to individuals in specific locations (individual risk) or to society in general (societal risk). The switch in delivery mode indisputably results in a highly significant reduction in risks to the population resident in the vicinity of the site.

The best estimates of the societal risks associated with the two delivery system options are not significantly different in view of the degree of uncertainty, whereas the upper estimates are clearly lower for the existing rail-supplied option. The best and upper estimates of societal risks associated with the delivery systems are similar or greater than those associated with the site, and thus the total risks to society from the combined transport and storage operation will not be significantly different after the site modifications. In fact, if the most pessimistic estimates are considered for the delivery systems, risks to society may be slightly increased. Thus, from the societal perspective, the results neither support nor challenge a change in transport mode.

From the perspective of individuals exposed to the risks from the storage of chlorine on the site, the risks have been greatly reduced. This is emphasised by the 75 percent reduction in the

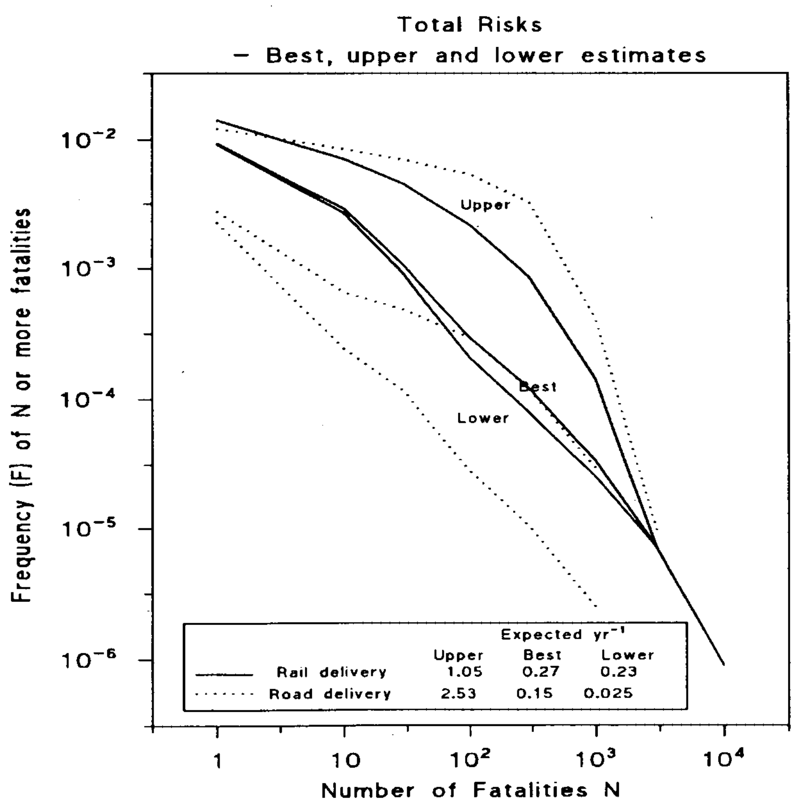

FIGURE 6 Societal risk estimates for combined site and delivery systems.

area of restricted development, which was based on assessments of individual risk. For those alongside the two transport routes, the risks of individuals at specific locations being affected by a release are very low, and in neither route or mode option are the risks significant compared with those from other sources. Therefore, from a consideration of individual risks to the resident populations, the change in mode and accompanying storage alterations should be welcomed.

The study has found that motorists are the main recipients of risks associated with road transport. As both the risk source and exposed populations are mobile, the individual risks will be negligible. However, the chance of a large number of motorists in general being affected by a release will be increased. The significance of this must be related to other societal risks to which motorists are exposed.

Both the societal and individual perspectives are relevant when considering the issue of tolerability. Clearly, no individuals will receive large increases in risk as a result of the change in transport mode. In certain regions (i.e., the site locality) the reverse will be the case. The risks to society in general will not be affected. However, significant increases in risks to one group (i.e., motorists on the road route) have been identified. This implies that dangerous goods-routing decisions should be influenced by considerations of the expected traffic density as well as residential and other exposed populations.

Other issues will also hold weight in the decision-making process. The benefits from the reduction in site risks are great in both economic terms (freeing up land for development) as well as in terms of safety to the large community resident around the site. Political considerations, such as those of public perception and the impetus given to the site alterations as a result of the existing land-planning framework, may in this case outweigh any conclusions drawn from an assessment of risks alone.

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