# THE MEASUREMENT OF RISK FROM TRANSPORTING DANGEROUS GOODS BY ROAD AND RAIL

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## 1. INTRODUCTION

In recent years the issue of whether or not the road transport of dangerous goods is less safe than rail or inland waterway transport has begun to emerge in European transport circles. A series of road vehicle accidents in Germany in the late 1980's prompted that country's government to implement measures aimed at transferring certain long-haul dangerous good traffic from the road to the railways and inland waterways for safety reasons. This initiative has also prompted the European Community to review the road versus rail safety issue.

Last year (1991) saw the publication by the UK's Health and Safety Commission (HSE, 1991) of the results of a 5 year study into the transport of dangerous goods in Britain. That study, by a sub-committee of the Commission's Advisory Committee on Dangerous Substances, considered the risks to the British population from the carriage of dangerous goods by rail, road and by sea in the light of the present regulatory and voluntary controls and the need for and possible nature of additional controls.

This was the first occasion when the risk to a nation from the transport of hazardous materials had been measured to such a degree and the study involved considerable research in order to develop suitable methods of analysis. Further research was also needed to understand the results which the analysis produced. While studies looking at the risks from transporting hazardous materials have been and are being carried out elsewhere (and all these were reviewed), none of these methodologies were found to be fully appropriate for the UK study. In general this was because:

- elements of the methodology could be considered 'obsolete';
- they had been developed to reflect a transport system or a system of regulatory control that was somewhat different to that in the UK;
- they had been developed specifically to investigate one aspect of transportation, for example, the safe routing through a city area, and did not have wider applicability.

For these reasons a 'new' approach was necessary: specific to the British situation, which sought to minimise uncertainty while providing 'transparency' of the risk calculation process so that the decision makers could understand and have confidence in the results.

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[1] The views expressed in this paper are the author's and do not necessarily represent those of DNV Technica or of the Health and Safety Executive

This paper is concerned with the work of a technical working party for land-based transport and the modelling associated with the transport of non-explosive substances in bulk (called 'the UK Study' throughout the rest of this paper). While the techniques of analysis were developed in the context of the British situation, many of the lessons learnt and insights gained have much wider application. The paper especially addresses the question of whether it is safer to convey hazardous substances by road or by rail.

## 2. FREQUENCY ANALYSIS

For those countries or regions with a history of hazardous goods accidents, consulting the historical record is normally the first step in any study of risk. Indeed, if enough incidents have (unfortunately) occurred, the modelling of the possible consequences and impact of such events may be of secondary importance. In Britain, however, we have suffered few such incidents. Those that have occurred have normally involved flammable liquids and no person has yet died as the consequences of a leak from a damaged tanker (road or rail) holding liquefied flammable or toxic gases such as LPG or chlorine. For this reason, the UK Study adopted a some-what different approach to obtaining the release frequencies for hazardous substances in transit.

An analysis of the available UK data on rail and road incidents involving tankers containing hazardous materials showed that releases could occur from two sources, firstly by puncture or rupture following collision, roll-over or derailment, or secondly, from failure or mal-operation of the tanker equipment. For the rail mode there was sufficient data on 'thin walled' wagon accidents to generate a frequency for punctures and equipment leaks directly.

While motor spirit spill frequencies could be obtained directly from this analysis, there are no incidents recorded in the UK where properly designed road or rail tankers for pressurised liquefied flammable or toxic gases have been punctured. For these it is therefore necessary to adopt a synthetic approach to deriving appropriate spill frequencies; a rate generated by statistical techniques from an 'accident free' history provides a useful 'upper bound' check. For transport by rail, the technical working group used an analysis by ICI Transport Engineering Division to give spill frequencies for ammonia, chlorine and LPG. This analysis considered the historical accounts of puncture of 'thin walled' wagons and estimated in each case the conditional chance of failure if the vessel concerned had been a 'thick walled' LPG/Ammonia or Chlorine containing vessel.

Although data on US rail incidents is easily available, it was felt the differences between the design standards and operating practices made this data inapplicable to the British situation. However, for road transport, the differences were less important and could be identified with some confidence. Because of this, US road data could be used and, by appropriate modification to exclude those events which could not or were unlikely to occur in Britain, spill frequencies were derived. Fault tree analysis was used to develop the possible causes and events which could lead to equipment leaks. These were then used to derive appropriate equipment spill frequencies for both rail and road transport of LPG, ammonia and chlorine.

## 3. CONSEQUENCE ANALYSIS

As with all forms of such quantified risk analysis, the selection of a representative set of failure cases and assignment of the corresponding spill sizes/rates are the most important steps to producing an accurate characterisation of risk. An optimum set of cases has to found which while minimising computational effort do not unduly compromise accuracy. Fortunately in the transport situation there are several constraints which act to limit the range of possible events.

For the UK transport study, one hole size together with total vessel rupture and a nominal equipment leak rate were used. Taking three release sizes only is judged to be on the borderline of what is acceptable for this type of study but the selection was driven by the limited data available on how to partition the base puncture frequency between different hole sizes. In the absence of any corroborative data, it was assumed that 10% of the releases from pressure vessels were instantaneous and could be modelled as the entire loss of contents. In the case of toxic materials, the cloud contained 100% of the tanker contents, for LPG twice the adiabatic flash fraction was assumed to enter the vapour cloud. Sensitivity testing to a 99%/1% split or a 50%/50% split showed that this assumption was not critical.

The risk from released toxic gases such as ammonia and chlorine is very dependent on the accuracy of the dispersion modelling. As societal risk is to be calculated, the crosswind extent of the cloud is as important as the downwind hazard range. The societal risk estimation involves the calculation of the numbers of fatalities from the areas of land which experience more that a criteria toxic load. The use of simple gaussian models which do not allow for negative buoyancy effects such as cross and up wind spreading will therefore produce inaccurate (likely to be optimistic) results. The release orientation in relation to the wind can be an important consideration and the modelling of the initial momentum driven jet seem important pre-requisites to the use of an accurate dense gas dispersion code.

## 4. IMPACT ANALYSIS

While the modelling of consequences and the estimation of frequencies are important components of the risk analysis approach, of equal importance is the estimation of the number of people who will be killed or injured by a particular hazardous event; Societal risk places equal emphasis on both the frequency of occurrence and number of fatalities. However, we find that this aspect of analysis has been little developed elsewhere and it was given particular attention in the UK Study. In particular, it seemed important to us to include all the population who may be affected by a dangerous goods incident. This includes motorists on a road where an incident occurs or members of the public travelling as passengers on trains which become involved on the rail. If only those people who live near the transport route are considered in the analysis, a very incomplete picture may be presented of the risk and its major contributors. This could lead to erroneous conclusions about the nature of and benefits from risk reduction strategies.

### 4.1. Off Route Population Density Measurement

For long transport routes, the population distribution along the route has to be characterised by a limited number of population categories, each representing an average situation. For the UK study we chose the four categories shown below:

Table 1. Off-Route Population Categorisation Scheme

| POPULATION CATEGORY | AVERAGE DENSITY ($km^{-2}$) |
|---|---|
| Urban | 4210 |
| Sub-urban | 1310 |
| Built-up Rural | 210 |
| Rural | 20 |

The length of the transport route along side of which each category of population exists can be obtained using computerised techniques for handling census and other demographic information.

It is important to take into account the natural separation that occurs between off-route populations (typically residential) and the road or rail line. In Britain, there are very few locations where population comes within 25m of a rail line and so when the impact of an event is being calculated, this 25 m 'swathe' must be excluded. This approach also acts to 'screen out' small, low consequence events from the analysis.

### 4.2 Off-road and Motorist Population Modelling

In the road situation there is a smaller but nevertheless important separation between the road and the off-road population. The width of the separation depends essentially on the class of road. It may be only the width of a pavement on an urban, single carriageway road but it may be much larger for a motorway. Furthermore, there are large sections of some routes where 'ribbon development' in a narrow strip alongside the road produces a very high population density (for example shopping areas) with open, low population density land beyond. To accommodate all these situations and to encompass the variation in the on-road, road user population density, a zoning scheme was developed. This is shown in Figure 1 for a dual carriage way road. The zone structure is described in Table 2:

Table 2: Population Zoning Structure For Roads

| ZONE | NAME | DESCRIPTION |
|---|---|---|
| a | Off-route population | This is similar to that used in the rail study but may be 'depleted' if there is ribbon development. |
| b | Dense population | This allows for a high population density immediately adjacent to the road. |
| c | Clear Zone | Motorways and Dual Carriageway roads are likely to have a significant gap between the road edge and the population. |
| d | Motorists, Accident Side | Road User population which 'backs-up' behind the accident. |
| e | Motorists, Other Side | Road user population on other side of carriageway. |
| f | Clear Zone | Same as Zone c. |
| g | Dense population | Same as Zone b. |
| h | Off-route population | Same as Zone a. |

This scheme allowed us to model the response and density variations in the motorist population following an accident involving the release of hazardous material. We find that even at night, on main roads and especially motorways and dual carriageways, traffic rapidly builds up behind an accident leading to a very high population density on that carriageway. On the opposite carriageway, the traffic slows down due to the 'ghoul' effect; again increasing the population density.

This scheme also allowed us to model those events which have directionality, for example a toxic gas release influenced by wind direction and its momentum driven phase. There are, of course, an infinite range of possible directions, but these can be reduced to the 4 cases shown in Figures 2a and 2b.

### 4.3 Human Impact Measurement - Flammable Substances

For flammable and explosive events, we find that consequence models predict a fairly sharp cut-off between the point where people exposed will suffer very serious and likely to be fatal injuries. For flammable events we therefore adopted an impact model which had two 'steps':

- above the $LD_{50}$ hazard range, all die;
- between $LD_{50}$ and $LD_{01}$ 25% of people die;
- beyond the $LD_{01}$ all survive.

Where the $LD_{50}$ and $LD_{01}$ are very close together, this can be simplified to a single step where everyone inside the $LD_{50}$ hazard range dies. This is particularly true for Motor Spirit where only those within the pool fire are assumed to die.

This approach is only true for overpressure events and thermal events to people out-of-doors. For non-continuous thermal events such as flash-fires, people indoors are assumed to survive; even if their homes catch on fire.

For motorists, it can be assumed that vehicles provide very little protection against fires and explosions. Those in cars are effectively trapped and escape from the road is not easy in congested traffic.

## 4.4 Human Impact Measurement - Toxic Gases

To allow for the accurate representation of the variation in human susceptibility and to enable the implementation of the zoning schemes for on and off-route populations, it was necessary to use a graduated approach to dose-effect modelling for toxic gases. The normal manner of doing this is to use 'probit' equations which seek to represent that variation in the percentage of a population that will die against a received 'toxic load' assuming a long-normal relationship. We used three levels of impact, $LD_{90}$, $LD_{50}$ and $LD_{10}$ for this study and assumed that the proportion of the population that will die in the area between $LD_X$ and $LD_Y$ will be (X+Y)/2%.

It has been shown (Purdy and Davies, 1985) that going or being indoors provides considerable mitigation against the effects of toxic gases. The impact on people indoors can be calculated by using a simple gas infiltration model which allows for the exponential build up of concentration indoors while the gas cloud is present outside and a decay phase once the cloud has passed but people still remain indoors. The integration of these expressions with respect to time with the concentration raised to a power n (taken from the probit equation) yields a toxic load ($\int C^n.dt$). This can be compared with the probit relationship to give an expected % fatalities.

Many options are available to a person who is affected by a toxic gas. For people out-of-doors this can be rationalised into a simple model:

- at or above a concentration ($C_1$) a person will be unable to take any action and is likely to die;
- below this concentration, down to $C_2$, there is a chance that he or she can escape indoors. $C_2$ can be set so that chance is (say) 0.2;
- below that concentration there is a higher probability of escape but of those who remain outside the proportion who die is given by (X + Y)/2 where the area falls between the $LD_X$ and $LD_Y$ hazard ranges.

This model is shown in Figure 3. For motorists, the protection afforded by their vehicles is very limited. Work by Cook (1988) shows that the 'Ram' effect of the car, even without a fan switched on provides a very high level of ventilation. Therefore we have assumed that these people are effectively out-of-doors.

### 4.5 Rail Users (Passengers) Interactions

In Britain, the rail network is used for both goods and passenger transport. This raises the possibility that a one or more passenger trains may interact with a hazardous goods incident causing fatalities on the passenger train. Most other studies have failed to consider this 'extra' population but our work shows that they can make a significant contribution to the risk and that steps to prevent and minimise such interactions need to be considered.

On British Rail, the signalling system is principally concerned with preventing collisions by trains running on the same track. Signalling failure was the cause of one the UK's most serious transport incidents involving a hazardous substance. This occurred at Eccles, near Manchester in December 1984 when a passenger train ran into the back of a 14 wagon goods train hauling 'gas oil'. Three tanks ruptured forming pool fires and a 'fireball' which caused three fatalities and 76 injuries.

Despite this incident, we would expect such collisions to be rare events and, in the case of flammable liquids, to cause, at worst, only a few fatalities. Events involving LPG and liquefied toxic gases have the potential to cause many more fatalities and our analysis has mainly considered the interaction of passenger trains with incidents involving rail wagons of these materials. These materials have long range effects which could affect a passenger train properly stopped by the signalling system, the so called 'obedient' train. Moreover, there is a possibility, although more remote, that the passenger train might collide with the hazardous goods train and cause the release, might collide with a previously derailed train or might, as this is specifically not prevented by the signalling system, be affected as it attempted to pass by the scene of a hazardous goods incident on an adjacent line.

This is a complex study which requires that the signalling and emergency systems on British Rail to be understood and adequately represented. Using a combination of fault and events trees, the PASSTRAM (Purdy,1992) model was developed to allow the frequency and consequences of such interaction to be calculated for a route that involves sections along which different passenger train types, of different frequencies and passenger numbers travel at different times of the day.

## 5. CASE STUDY - A COMPARISON OF TRANSPORTING CHLORINE BY ROAD AND BY RAIL

To demonstrate the use of the models described in this paper and to bring out many of the points made above, we have carried out calculations of the societal risks associated with the transport of the same annual tonnage of chlorine between two locations by road or rail. At present, this trade is conducted by road between these two sites, approximately 100 km apart but a change of mode is a realistic possibility.

The route, in the north west of England, is at present served by road tankers several times a day. This one route constitutes a significant proportion of the national annual tonnage of chlorine transported by road in Britain. The journey is 103 km long, of which 80 km is motorway, and the rest is mostly single carriageway. The route travels past, but not through, three large towns and only about 1 km of the route has 'urban' population on at least one side with 19 km with suburban population on one or both sides. Most of the rest is rural.

The road tankers which travel this route make 1,743 journey a year carrying 17.5 te each time.The alternative delivery by rail would require 1,052 29 te tankers a year. The rail route is about 97 km long but passes through 3 major towns with populations of 176,000, 81,674 and 126,000 respectively. The route includes 6 km of urban and 20 km of sub-urban population. Most of the route is also used extensively by passengers trains; part is the main West Coast main line between London and Scotland.

Using the techniques described above we have calculated the following levels of societal risk for the different modes:

Table 3. Societal Risk Results - Transport by Rail

| | FREQUENCY OF N OR MORE FATALITIES ( x $10^{-6}$ $yr^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 10 | 30 | 100 | 300 | 1000 |
| Passengers | 39.5 | 39.5 | 39.5 | 10.6 | 0.0 | 0.0 |
| Off-rail Population | 105.0 | 47.8 | 27.8 | 26.8 | 11.9 | 5.2 |
| Total | 107.3 | 68.0 | 56.8 | 41.5 | 13.6 | 5.7 |

Table 4. Societal Risk Results - Transport by Road

| | FREQUENCY OF N OR MORE FATALITIES ( x $10^{-6}$ $yr^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 10 | 30 | 100 | 300 | 1000 |
| Motorists | 16.7 | 10.5 | 8.8 | 4.8 | 1.7 | 0.0 |
| Off-road Population | 15.5 | 5.9 | 2.9 | 1.4 | 0.9 | 0.0 |
| Total | 19.0 | 13.6 | 10.3 | 6.2 | 2.6 | 0.1 |

These results are also shown in Figure 4 as FN curves.

It can be seen that:

- the risk by rail is approximately 5 times that by road;
- risks to rail users is about double that to motorists;

- risks to off-rail populations are approximately 8 times higher than those to off-road populations;
- the road risk is dominated by that due to motorist involvement.

These results are due to a common factor in British transport systems; most of our rail system was built over 100 years ago and was intended to go from town to town while most of our major roads have been built over the last 20 years and have been specifically routed to take traffic away from centres of population.

It would be possible to construct a route which would be more favourable to rail, but in reality the historical legacy of our transport systems will always tend to produce lower risks for the transport by road of materials with long hazard ranges. The risks from the transport of these substances will be lower if the route followed avoids centres of population and this is more easily achieved in Britain by road rather than rail. Substances with a shorter range effect such as motor spirit, should normally be more safely transported by rail since there is already a very worthwhile separation between the rail line and people who live nearby and passenger train involvement is likely to be restricted to direct collisions when, at worst, only a few passengers may be affected.

It is clear that in Britain it is not possible to say that transport of hazardous substances by rail is safer than by road or, indeed, vice versa. However, there seems to be no case on safety for the British Authorities to enforce modal transfer. This contrasts with the situation in other countries such as Germany where legislation now requires transfer to rail for longer journeys.

## 6. CONCLUSIONS

Throughout Europe, concern is being voiced about the transport of dangerous goods and the risks posed to members of the public. Legislators are shifting their attention from the problems of fixed major hazard installations to addressing what is the most appropriate means to control the risk from hazardous materials in transit.

It is very important that there is a full understanding of the magnitude of the risks involved and the causes and major contributors so that properly informed decisions can be made. In this paper I have described the methodology that was developed as part of a major study into the risks faced by the British population from the transport of dangerous substances.

I have concentrated on the novel aspects of the study and in particular consequence and human impact modelling. In the case of consequence models, I have suggested that the choice of model and the depth of the analysis must be driven by an understanding of the overall uncertainties of the risk analysis and the contribution each element makes to that uncertainty. Where it matters, the most accurate models are appropriate; for less sensitive elements, a more simple and less rigorous approach may be more justifiable. The final arbiter of the degrees of complexity and precision necessary is the end user; in this case a decision making body. The analysis methodology must be sufficiently transparent so that the results can be understood and used with confidence.

The modelling of human impact has been a feature of this paper reflecting the need perceived by those conducting the UK Study to be more rigorous in the treatment of this aspect of hazardous goods risk analysis. Other workers have not dealt with this in such detail before but our work has shown that the inclusion of motorist and rail passenger populations can significantly affect the calculated risk levels and can therefore have a profound effect on any conclusions which are drawn on the need for further legislative controls and the nature of those controls.

In support of these points and to demonstrate the use of the models that were built, the relative risks of transporting chlorine by road or rail has been explored in a realistic case study. From this it can be concluded that the safe routing of materials with large hazard ranges may be more easily achieved by road. For lower hazard materials, the natural separation afforded by the rail system may make this mode more suitable. However, in Britain, there appears to be no evidence to support, on safety grounds, a general transfer of hazardous goods from road to rail or the reverse.

## 7. ACKNOWLEDGEMENTS

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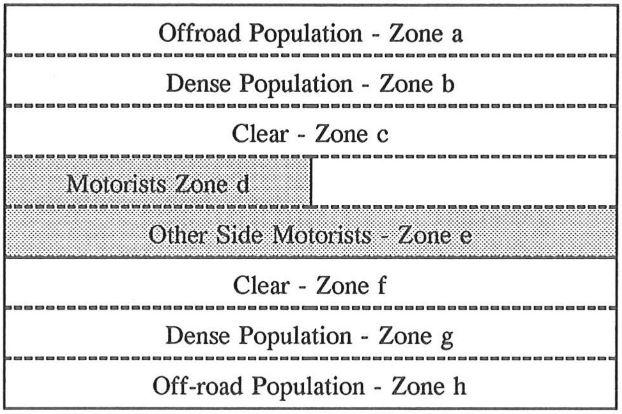

Figure 1. Population Zoning Scheme for Dual Carriage-way Roads

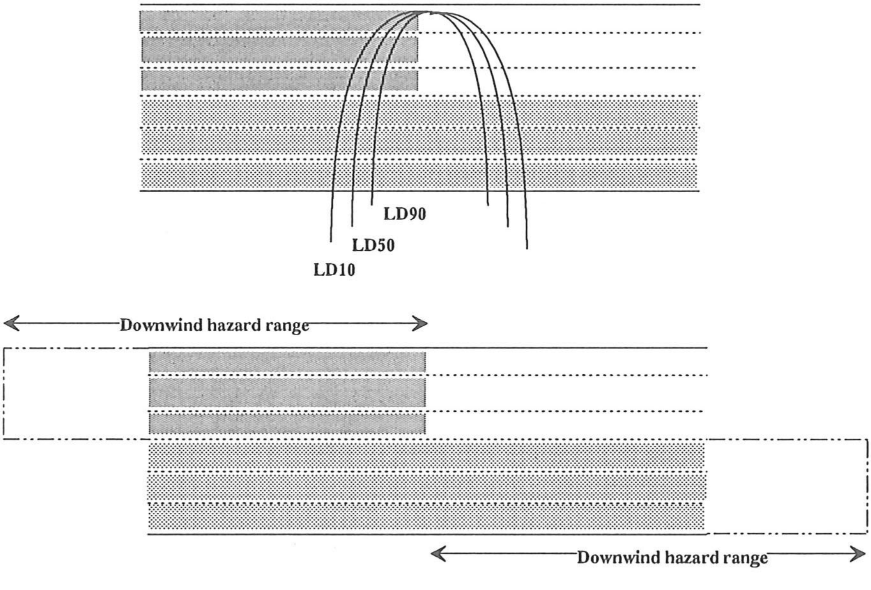

Figure 2 (a) and (b). Model for motorist fatalities, wind across and along highway

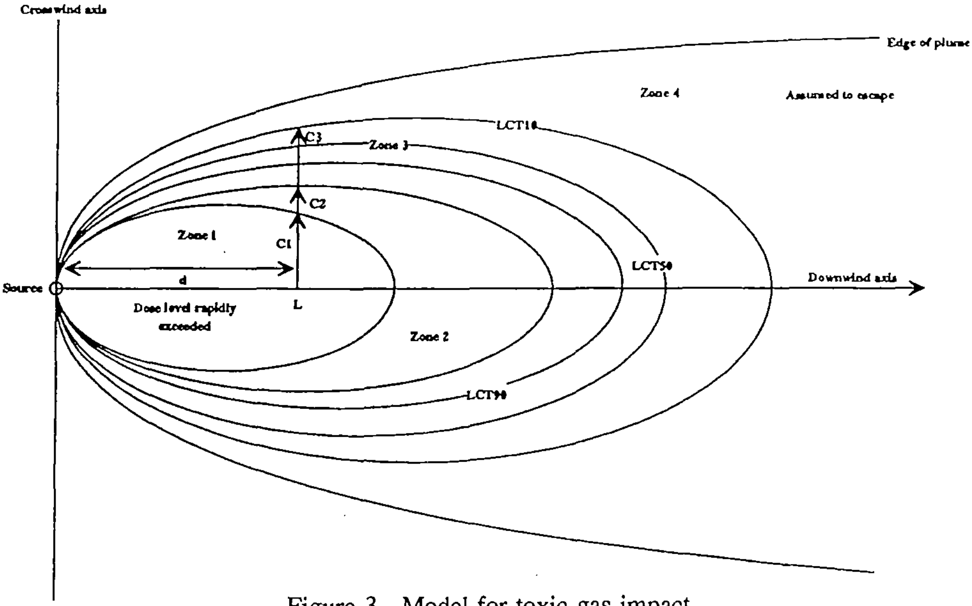

Figure 3. Model for toxic gas impact

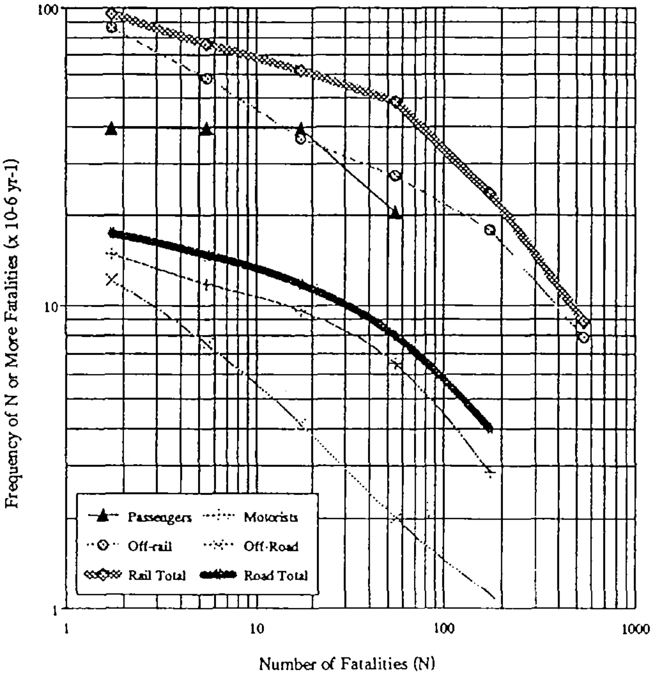

Figure 4. Societal Risk Result for Road/Rail Comparison