Journal of Hazardous Materials, 33 (1993) 229–259
Elsevier Science Publishers B.V., Amsterdam

Risk analysis of the transportation of dangerous goods by road and rail

Grant Purdy

DNV Technica Ltd., Highbank House, Exchange Street, Stockport SK3 0ET, Cheshire (UK)

Abstract

In any debate about the transport of dangerous goods where the effectiveness of existing legislative controls is challenged, 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. This paper gives details of the methodology developed for the analysis of the risks arising from the carriage, in bulk, of toxic and flammable substances by road and rail as part of a major study into the risks faced by the British population from the transport of dangerous substances. This paper concentrates on the novel aspects of the study and in particular consequence and human impact modelling. Models are given for the interaction of passenger and dangerous goods trains taking into account the ability of signals and other systems to detect and stop approaching trains. In the case of road transport, the models allow for the characteristics of different road types and the behaviour of motorists to be simulated. The relative risks of transporting hazardous materials by road or rail are explored and it is shown that the inclusion of motorist and rail passenger populations significantly affects the calculated risk levels. It is concluded that the safe routing of materials with large hazard ranges may be more easily achieved by road. While, the natural separation afforded by the rail system may make this mode more suitable for lower hazard materials. However, it is concluded that 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.

1. Introduction

In recent years the issue of whether or not the transport of dangerous goods by road is less safe than by rail or inland waterway has been raised in Europe. A series of road vehicle accidents in Germany in the late 1980's prompted that

Correspondence to: G. Purdy, DNV Technica Ltd., Highbank House, Exchange Street, Stockport SK3 0ET, Cheshire (UK).
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.

0304-3894/93/$06.00

country's government to implement measures aimed at transferring certain long-haul dangerous good traffic from the road to the railways and inland waterways. This initiative has also prompted the European Community to review the road versus rail safety issue and for member states to consider the need for further legislation dealing with 'safe routing', placarding, driver training and vehicle standards. This legislative activity is, in some cases, being pursued without the benefit of a rigorous study of the risks or benefits involved and much research is now starting to be undertaken in this area. In most cases, methods and models derived for onshore chemical plant risk analysis are now being deployed but those who are undertaking this work soon find that there are crucial differences which need to be respected when the risk from a transport activity is analysed.

This paper is an attempt to express some of those differences; to show where, in the author's opinion, greater care in modelling is necessary and where, conversely, more precise treatments are not warranted. This understanding is based on the experience gained during participation in a five-year study into the transport of dangerous goods in Britain. That study, by a subcommittee of the UK's Health and Safety 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 [1].

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. It also had to allow for assumptions to be easily changed so that the models could be used as 'testbeds' for the gauging the effectiveness of changes to the system of control. The approach was developed by two technical working parties (one for marine, the other for land based transport) on which sat members of the Health and Safety Executive, its contractors, industry, the emergency services and academia.

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. Objectives of the risk analysis

The choice of consequence and impact models and indeed the manner of conducting a risk analysis depends on the eventual use of the results; who will use them and for what purpose. Both the needs of the user and the needs and capabilities of the analyst need to be considered. In the case of the UK Study, it would not have been useful to expend effort developing complex and indepth analyses where, for example, there were great uncertainties in frequency data or the decision making process could not accommodate significant levels of precision. This is one of the most important principles which guided the development of models and techniques for this work, for while we sought methods of analysis which optimised accuracy, this was often at the expense of unnecessary precision.

Similar considerations applied to the types of risk measured and the presentation of the results. Some transportation studies have concentrated on individual risk calculations, presenting the results as contours or risk transect diagrams showing individual risk against distance from the transport route. While such studies may be useful for routing exercises, where a new transport corridor is being selected, unless there is good evidence on the relative distribution of failure events along the route (i.e., 'high spots'), individual risk results can add little to the understanding of risk from a transport operation. The risk numbers produced are normally so small as to be beyond the normal range of human comprehension. Most importantly, this type of treatment fails to address the public's (and the politician's) major concerns; not the risk to individuals, but that to society at large: the risk of a disaster. This involves not only consideration of the potential for transported hazardous substances to cause multiple fatalities but also the likelihood that these might occur because a loss of containment accident coincides in time and space with a human population. Societal risk is therefore not only a more appropriate measure but it also seems to yield more useful results. It leads naturally, via the generation of expectation values (average number of lives lost), to consideration of the need for, and cost benefit, of risk reduction measures. Societal risk analysis does involve many generalising assumptions and averaging but these are not inconsistent with the 'smeared out' nature of the risk associated with transport along a route.

3. 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 consequence 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 somewhat different approach to obtaining the release frequencies for hazardous substances in transit.

One approach possible would have been to use an event tree such as that in Fig. 1. This is similar to that developed by Hubert et al. [2] from French data. This builds on data from all road accidents, and in particular, those involving other goods vehicles, to synthesise a puncture rate for a hazardous goods tanker. However, there is no evidence to suggest that the drivers of hazardous goods vehicles will act in a similar manner to drivers of other vehicles nor that such vehicles will suffer equipment and other failures at the same rate as other similar vehicles containing other bulk materials. The value given to the critical probability associated with 'escalation' to puncture is critical yet very uncertain. Even for countries where good data exist there are always the uncertainties associated with under-reporting.

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 maloperation 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. Over six years, 80 cases of spills due to 'equipment leaks' and four incidents involving substantial spillage following puncture were found. These data suggested a puncture frequency of 6.3×10^{-8} per tank wagon km.

For road transport, 25 incidents were found over a four year period. Analysis of these data yielded a spill frequency of 1.4×10^{-8} per loaded tanker km for large spills (>1500 kg) from collisions etc and 0.7×10^{-8} per loaded tanker km for large spills arising out of equipment failure.

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

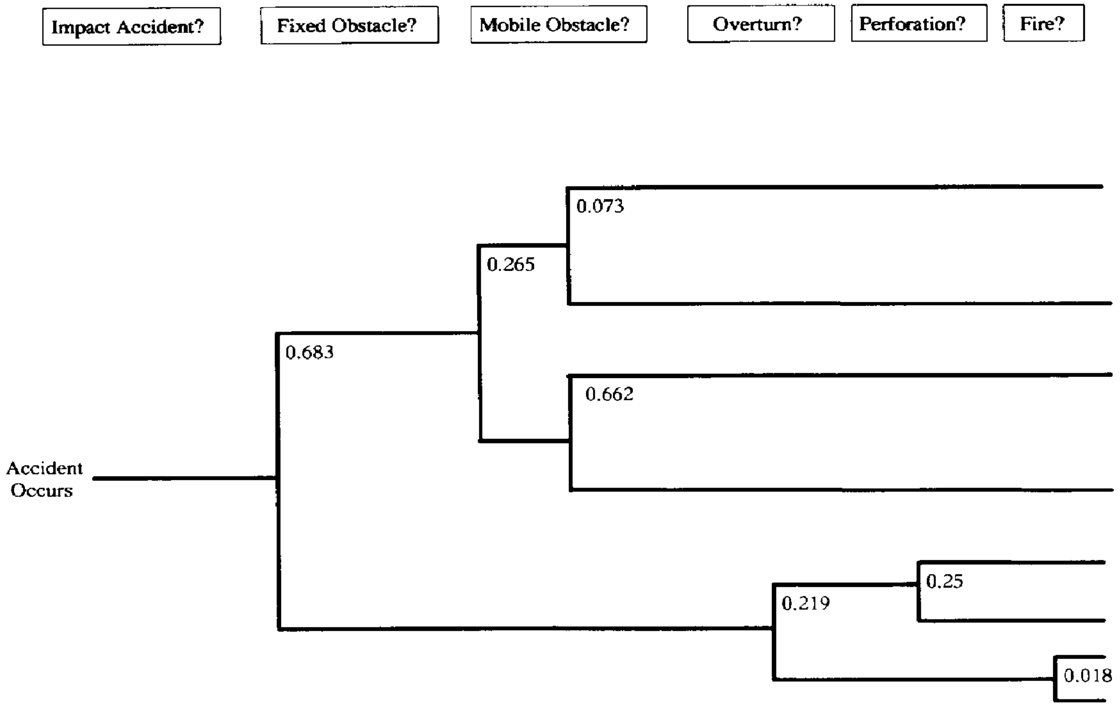


Fig. 1. Incident data analysis after Hubert et al. [2].

statistical techniques from an 'accident free' history provides a useful 'upper bound' check. For transport by rail, the technical working group considered a study by ICI Transport Engineering Division and agreed spill frequencies for ammonia, chlorine and LPG. This study 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 are easily available, it was felt the differences between the design standards and operating practices made these 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.

In summary, the spill frequencies and ignition probabilities listed in Tables 1 and 2 were derived for this work.

Table 1 gives base event frequencies. For flammable events, it is also necessary to consider the probability that a spill will then be ignited and whether this will take place initially or at some later time once a flammable cloud has developed. In some cases it was possible estimate ignition probabilities from accident data, but the under-reporting of spills which have failed to ignite makes these figures unreliable. In most cases, ignition probabilities have to be estimated using synthetic techniques or by expert judgement. This is simplified in transport situations as often the spill-causing event involves sufficient energy to cause ignition, or other sources (for example other road vehicles) are nearby. For the UK study we used the values as listed in Table 2.

TABLE 1

Frequency of spills against cause, substance and transport mode

Substance	Road transport		Rail transport	
	Puncture/ rupture ($\times 10^{-10}$ per wagon km)	Equipment leak ($\times 10^{-10}$ per wagon journey)	Puncture/ rupture ($\times 10^{-10}$ per wagon km)	Equipment leak ($\times 10^{-10}$ per wagon journey)
Motor spirit[a]	190	70	630	–[b]
Chlorine	0.8	36	9	310
Ammonia	4.8	70	25	130
LPG	4.8	52	25	83

[a] For large spills only.
[b] Not considered as such small spills are unlikely to affect members of the public.

TABLE 2

Ignition probabilities for flammable substances

Substance	Type of ignition	Rail		Road	
		Small spill	Large spill	Small spill	Large spill
Motor spirit	Immediate	0.1[a]	0.2[a]	0.03	0.03
Motor spirit	Delayed	0.0	0.1	0.03	0.03
Motor spirit	None[b]	0.9[a]	0.7	0.94	0.94
LPG	Immediate	0.1	0.2	0.1	0.2
LPG	Delayed	0.0	0.5	0.5	0.8
LPG	None[b]	0.9	0.3	0.4	0.0

[a] Derived from historical data.
[b] Derived from: 1 – (Immediate + Delayed).

4. 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 be found which while minimising computational effort does not unduly compromise accuracy. Fortunately in the transport situation there are several constraints which act to limit the range of possible events:

- for multi-compartment tankers, the simultaneous loss of contents from all compartments is extremely unlikely;
- small releases of flammable material are unlikely to ignite or cause hazard as they are rapidly dispersed as the tanker moves and even when stationary, the normal 'open' aspect of a transport situation will aid dilution;
- above a certain hole size, either the release of pressurised, liquefied gas will be so rapid that it can be considered equivalent to an instantaneous release on vessel rupture, or the hole will be sufficiently large to lead to a propagating failure of the pressure vessel;
- in the rail environment, ignited jets of LPG are unlikely to create significant hazard unless they impinge on other LPG tankers which then BLEVE. However, the BLEVE frequency used should normally include such a cause.

For the UK transport study three failure cases were used. These were vessel rupture, a large hole and a nominal equipment leak. Taking such a small number of cases does lead to some coarseness and lack of accuracy in the risk analysis but was justifiable given the limited data available here to suggest how the overall failure rate could be partitioned between difficult failure cases. 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. Sensitivity testing to a 99%/1% split or a 50%/50% split showed that this assumption was not critical. In the case of toxic materials the cloud was assumed to contain 100% of the tanker contents, for LPG twice the adiabatic flash fraction was assumed to enter the vapour cloud.

Particular care is needed to take into account the physical aspects of the spill environment when the consequences are modelled. Factors such as the containment effect of roads and drains can significantly affect the shape and dimensions of the hazard zone. This is particularly true of spills of flammable liquids where the hazard zone is only slightly greater than the area of confinement provided by the road or rail corridor. Furthermore, on the road, surface water drains will limit the size of any liquid pool.

For motor spirit spills we therefore considered two cases: either the tanker remained on the highway or rail corridor in which case the spill was confined by kerbs, drains etc, or the tanker left the road or rail line and was modelled as a circular pool. The pool will (in both cases), if ignited reach a maximum size where the regression rate is equal to the spill rate. Spreading pool expressions such as those given by Shaw and Briscoe [3] can be coupled with a 'drain model' and a fire model [4] to estimate the maximum area of road affected. As the thermal hazard decays rapidly as a receptor moves away from a burning pool, most people who were exposed outside the pool could escape and the area of the pool can be taken as the hazard zone. For example, we calculated that a 25 kg s^{-1} continuous release from a leaking rail wagon (32 te) would produce a pool of radius 24 m. The release would persist for about 20 minutes. If the vapours ignited during this time, the pool size would regress to 12 m. Table 3 shows similar results for road tanker spills.

These results for road tankers take into account loss of the motor spirit into drains and therefore the pool sizes are reduced from their theoretical maximum.

The immediate ignition cases were calculated by assuming that the release occurred over a finite time and that the pool size was the maximum possible after regression. In the delayed case, the pool was allowed to spread to its maximum before ignition took place. These seemed to be realistic assumptions.

The possibility of a 'soft' BLEVE fireball due to heating of a motor spirit tanker in a fire has been considered but does not seem likely. Analysis of the Summit Tunnel Fire incident [5] has shown that even under severe heating conditions, motor spirit tankers will not rupture if three out of four relief valves work or will take at least an hour of prolonged heating if only two operate.

For LPG the type and extent of the hazard depends on the mode of release and whether and when it is ignited. Figure 2 in an example, for continuous LPG releases, of the event trees which can be drawn to rationalise this potential for escalation. Similar trees exist for instantaneous releases of LPG and for spills of motor spirit.

For LPG, standard consequence modelling approaches can be adopted. However, when applied to transportation accidents, certain special considerations apply:

TABLE 3

Motor spirit tanker pool areas

Spill size	Pool area (m^2)	
	Immediate ignition	Delayed ignition
25 kg s^{-1}	314	908
4000 kg	707	1018
8000 kg	1385	1964
12000 kg	2124	3019

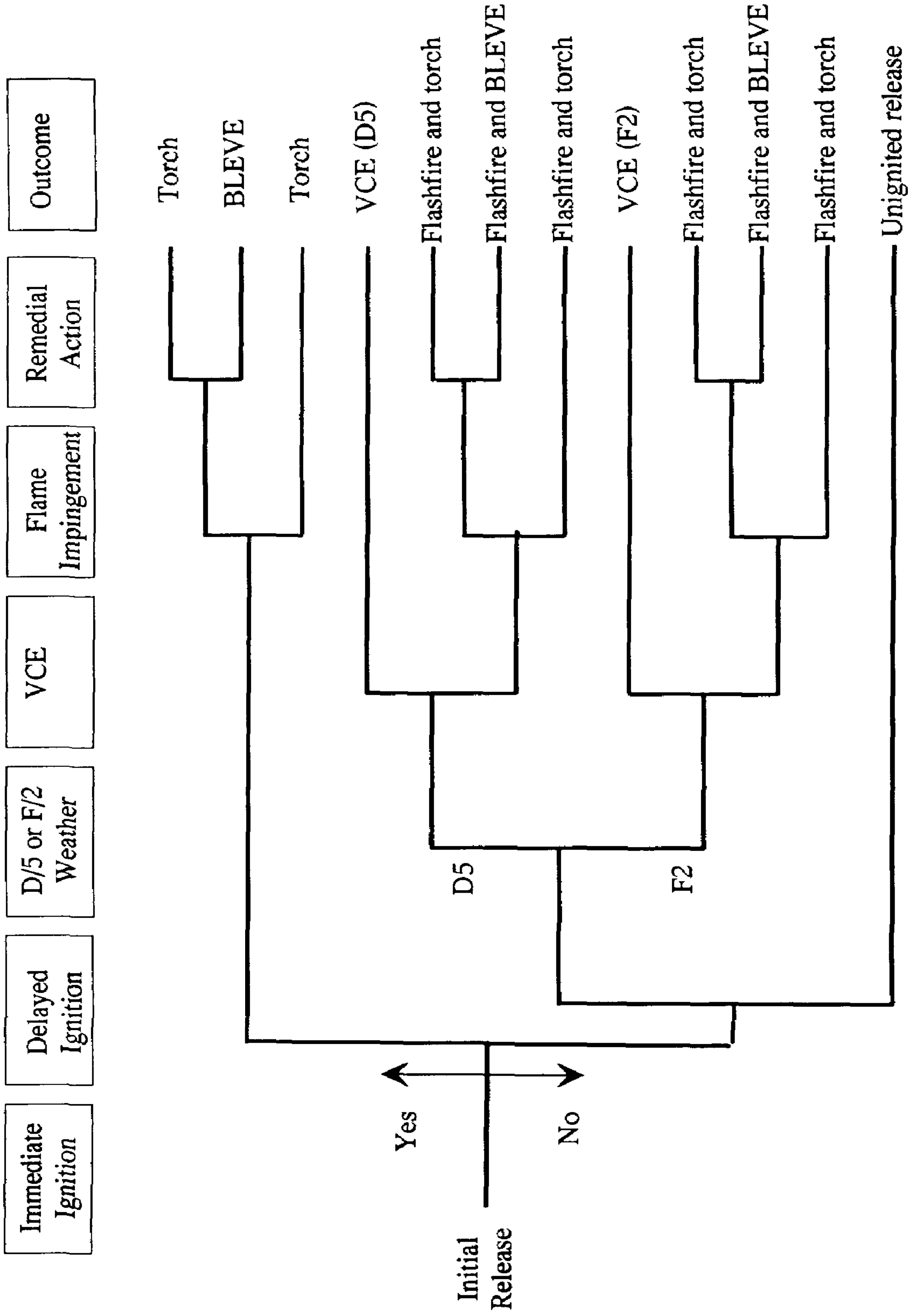


Fig. 2. Event tree for continuous LPG releases.

- for BLEVEs, the resulting fireball will contain a large proportion of the vessel contents as the vessels are always conveyed full;
- BLEVEs are much less likely on the road as one of the primary causes, jet fire impingement from one tanker to another, is highly improbable;
- Vapour Cloud Explosions (VCEs) are very unlikely on both road or rail given the open aspect and limited amount of confinement available. Given the small contribution they will therefore make to the overall risk, a simple consequence model (such as TNT equivalence) is appropriate;
- outside the flammable cloud, the probability of death due to the effects of overpressure from a VCE is low and can be ignored.

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 than a critical 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 for both toxic and flammable gas clouds. The release orientation in relation to the wind direction 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 model.

There is also a strong dependency between the crosswind and downwind extent of the cloud and the level of atmospheric turbulence. This is characterised by the use of appropriate parameters to represent different Pasquill stability categories. For the UK Study, only two categories; D with a windspeed of $5\,m\,s^{-1}$ and F at $2\,m\,s^{-1}$, were used for reasons of computational efficiency. This choice may have had a significant effect on accuracy, and more categories — four or six are usual — are to be preferred for toxic gases. Given the relatively short range of flammable hazard zones, two categories are probably adequate in this case.

The above discussion only applies strictly to above ground, open air releases on a flat, unobstructed terrain. There has been considerable interest recently about the carriage of hazardous materials through tunnels, and the assessment of the associated risks needs special consideration. In the confined space of a tunnel, the spread of the hazardous consequences is very much affected by the air flow and the channelling effect of the tunnel. For example, the blast wave from a vapour cloud explosion could be expected to be transmitted largely undiminished along a tunnel. One of the most serious hazards arises from the hot, often poisonous smoke and products of combustion which can travel significant distances along the roof of the tunnel away from a fire. The UK Study did not pay particular attention to tunnels as they did not constitute a large proportion of any of the routes studied and, in general, the only members of the public who would be affected would be those using the same road or rail tunnel. Further work is required to refine the current analysis methods so that a more accurate estimate can be made of the contribution of tunnels to an overall route risk. At present, few decisions involving the control of dangerous goods through tunnels seem to be based on any form of risk assessment.

5. 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 the 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 in an accident. If only those people who live near the transport route are considered in the analysis, an 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.

5.1 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 in Table 4.

The length of the transport route alongside which each category of population exists can be obtained using computerised techniques for handling census and other demographic information. Much use is now being made of Geographical Information Systems (GIS) to handle such data, although we found

TABLE 4

Off-route population categorisation scheme

Population category	Average density (km^{-2})
Urban	4210
Sub-urban	1310
Built-up rural	210
Rural	20

that a manual technique, using maps, provided a level of accuracy that was acceptable given the many other uncertainties in this work. One refinement of the approach was to note those lengths of track or road alongside which population of the same class exists on both sides, and those where, for instance, the rail line or road has formed a natural barrier and there is one side of urban development while the other is rural. To prevent 'double counting', in the 'one sided' case, for directional hazards — for example a torch flame or toxic cloud — the frequency of the event is halved and, for events with circular hazard ranges such as BLEVE fireballs, the number of fatalities is halved.

It is also 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 there is a residential population within 25 m 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.

5.2 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 Fig. 3 for a dual carriage way road. The zone structure is described in Table 5.

This scheme also 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 and 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. By assuming that 10% of traffic comprises heavy goods vehicles that occupy 20 m of lane length while other vehicle are 4 m long, an average vehicle population of 1.5 gives a Zone d population density of 0.056 m^{-2} for motorways and 0.05 m^{-2} for other roads. Zone d ahead of the accident is essentially clear. For the other carriageway, we have assumed that the curiosity of the motorists produces a density of 0.5 that of Zone d, but in both directions.

This scheme also allowed us to model those events which have directionality, for example a toxic gas release influenced by wind direction and its

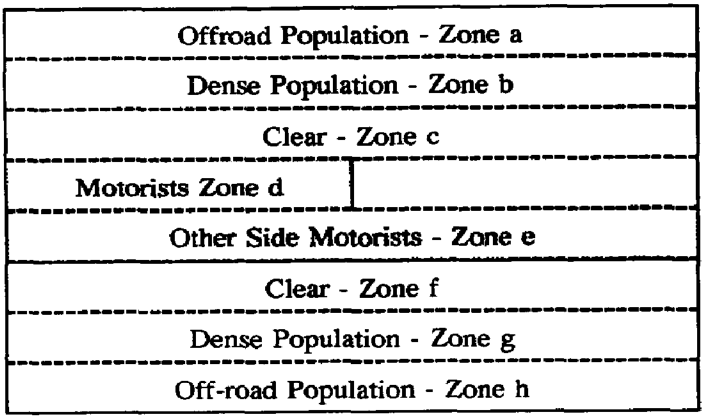


Fig. 3. Population zoning scheme for dual carriage-way roads.

TABLE 5

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

momentum driven phase. There are, of course, an infinite range of possible directions, but these can be reduced to the four cases shown in Figs. 4a and 4b. The cloud is represented as either travelling perpendicular to or along the carriageway. In the along the carriageway case, the plume can either travel in the direction of the affected carriageway or opposite to it. For the perpendicular case, the plume either travels off the road from the accident or across the other carriageway. There is a further complication with instantaneous releases of dense gas where we would predict some gravity driven movement of the cloud up-wind.

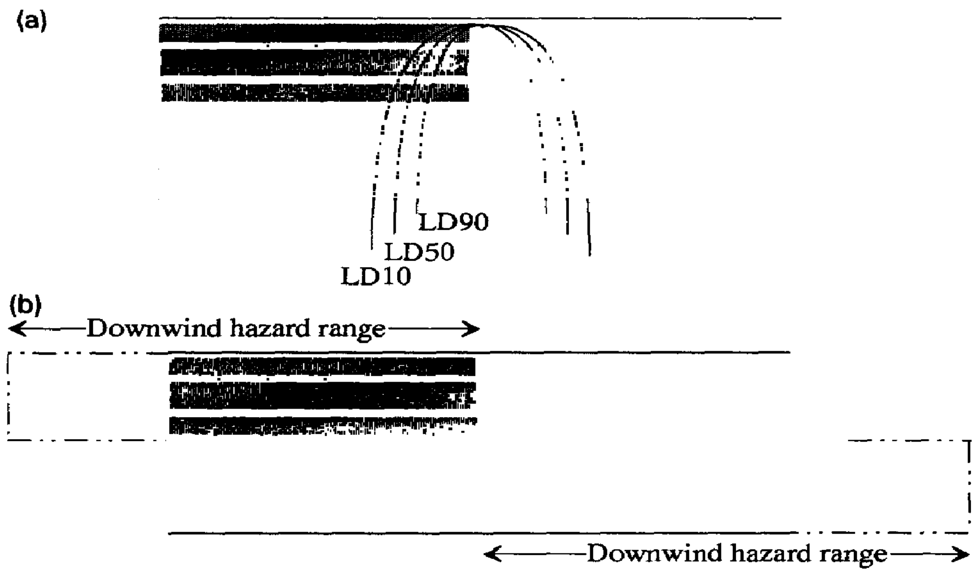


Fig. 4. Model for motorist fatalities, wind across (a) and along (b) carriageway.

5.3 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 injuries which are likely to be fatal. For flammable events we therefore adopted an impact model which had two 'steps':

- within the LD_{50} hazard range, all die;
- between the LD_{50} and LD_{01} ranges 25% of people die;
- beyond the LD_{01} range 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 the impact of overpressure events and thermal events on 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.

5.4 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 log-normal relationship. These have the general form:

$$Pr = a + b\ln(C^{n}t) \tag{1}$$

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 [6] 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 (C(I)) while the gas cloud is present outside:

$$C(\mathrm{I}) = C(\mathrm{O})[1 - \exp(-\lambda t)] \tag{2}$$

where $C(\mathrm{O})$ is the outside concentration, λ is the ventilation rate and t the duration of exposure. This is followed by a decay phase once the cloud has passed but people still remain indoors:

$$C(\mathrm{I}) = C(\mathrm{M})(-\lambda t) \tag{3}$$

where $C(\mathrm{M})$ is the maximum indoor concentration reached. 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 ($\int C^{n}\,\mathrm{d}t$). This can be compared with the probit relationship to give an expected percentage fatalities.

Figure 5 shows some of the potential options 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 this 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 Fig. 6. Therefore, for hazardous event E in weather j, the number of people out-of-doors likely to be killed is:

$$N_{\mathrm{O},E,j} = D_{\mathrm{q}}P_{\mathrm{O},j}[A_{\mathrm{C}1} + A'_1(1-P_{\mathrm{e}1}) + (1-P_{\mathrm{e}2})(0.95A'_2 + 0.7A'_3 + 0.3A'_4)] \tag{4}$$

where $P_{\mathrm{O},j}$ is the proportion of the people who might be out of doors in weather j, $P_{\mathrm{e}1}$ is the chance of escape within concentration C_2, $P_{\mathrm{e}2}$ is the chance of

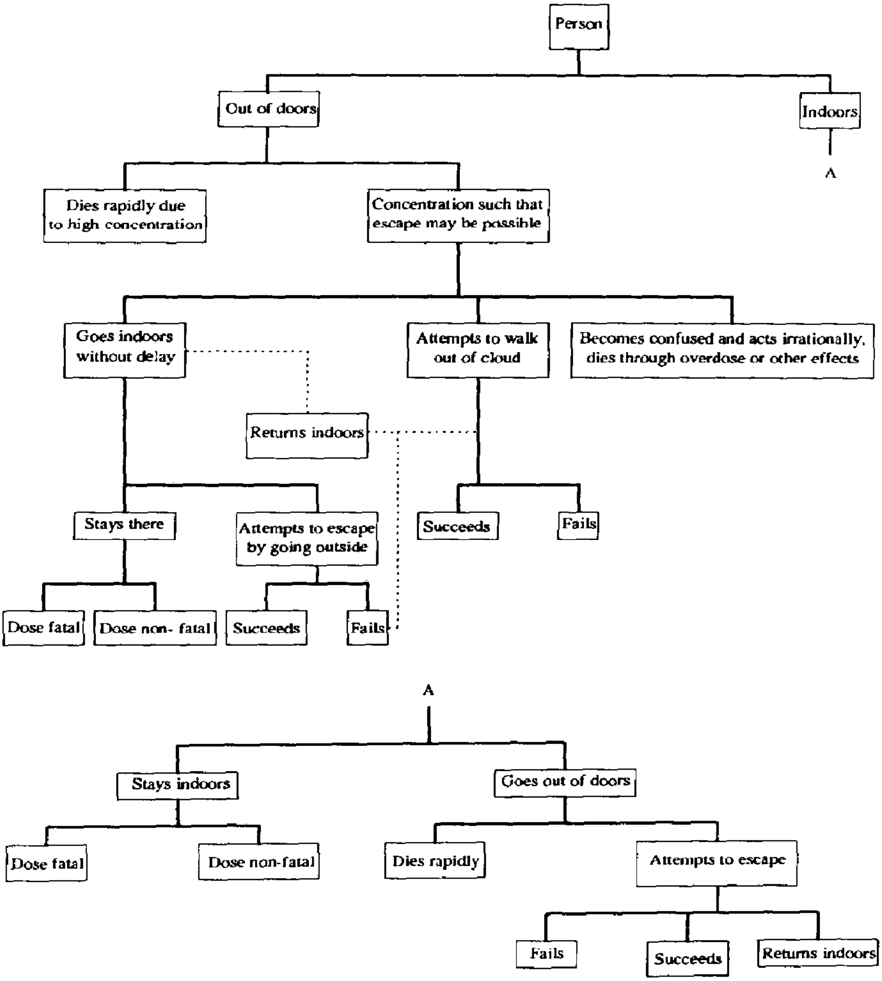


Fig. 5. Range of options available to individual affected by toxic gas.

escape within concentration C_3, area A'_1 is $A_{C2}-A_{C1}$, A'_2 is $A_{C3,90}-A_{C2}$, A'_3 is $A_{C3,50}-A_{C3,90}$, A'_4 is $A_{C3,10}-A_{C3,50}$, and D_q is the population density.

In reality, this expression is more complex as for some releases, $A_{C3,90} \leq A_{C2}$ or even $A_{C3,90} \leq A_{C1}$ and $A_{C3,50} \leq A_{C2}$.

Once people have escaped indoors, they may still be subjected to a fatal toxic load of gas. The number of fatalities indoors therefore comprises those who are already indoors and perish together with the proportion of the 'escapees' who also die. It is given by:

$$N_{I,E,j}=D_q(1-P_{O,j})+D'_q(0.95A_{D,90}+0.7A'_5+0.3A'_6) \qquad (5)$$

where $A_{D,90}$ is the area covered by the indoor LD_{90} isopleth, A'_5 is $A_{D,50}-A_{D,90}$, and A'_6 is $A_{D,10}-A_{D,50}$.

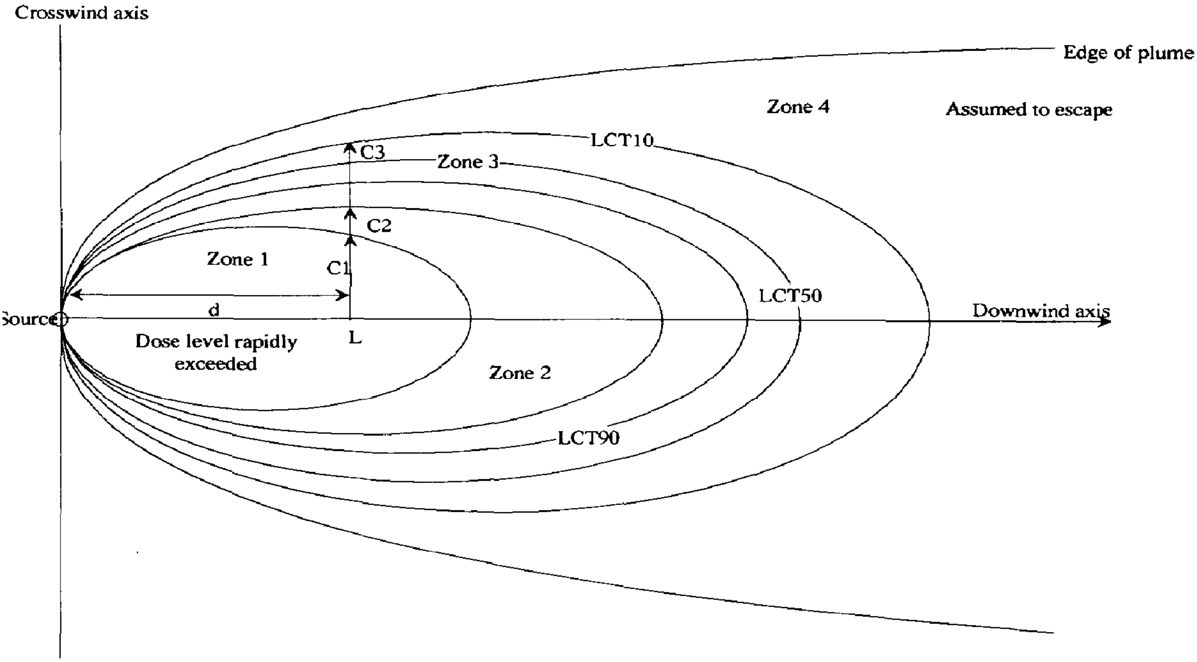


Fig. 6. Model for toxic gas impact.

The proportion of those who escape indoors who subsequently die will depend on whether they escape from $\geq C_1$ concentration, i.e. P_{e2} go indoors, or $\geq C_3$ concentration, i.e. P_{e2} go indoors. D'_q is the average population density of escapees.

For motorists, the protection afforded by their vehicles is very limited. Work by Cook [7] 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 and the expression given above, without the terms for escape, can be used:

$$N_{M,E,j} = D_M[0.95A_{90} + 0.7(A_{50} - A_{90}) + 0.3(A_{10} - A_{50})] \tag{6}$$

where D_M is the motorist population density, and A_x is the area of carriageway (one side) which will experience toxic load LD_x or more. This area is given by:

$$\text{Area } A_x = \text{hazard range to } LD_x \times \text{carriageway width} \tag{7}$$

5.5 Rail users (passengers) interactions

In Britain, the rail network is used for both goods and passenger transport. This raises the possibility that 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 between trains running on the same track. Signalling failure was the cause of one of 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 tanks containing 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, or 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 be understood and adequately represented. Using a combination of fault and event trees, the PASSTRAM model was developed to allow the frequency and consequences of such interactions 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. This model is fully described in the Appendix to this paper.

6. 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 by rail. At present, this trade is conducted by road between these two sites, approximately 100 km apart. However, a change of mode is a realistic possibility.

The route, in the northwest 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 exact breakdown is shown in Table 6.

TABLE 6

Population distribution along study road route

Road type	Population type	Density (km^{-2})	No. of sides	Length (km)
Motorway	Urban	4210	2	0.0
			1	1.0
	Sub-urban	1310	2	1.0
			1	13.0
	Built-up rural	210	2	2.0
			1	17.5
	Rural	20	2	45.5
			1	31.5
Single carriageway	Urban	4210	2	0.0
			1	0.0
	Sub-urban	1310	2	4.0
			1	1.0
	Built-up rural	210	2	4.0
			1	0.5
	Rural	20	2	13.5
			1	1.5

The road tankers which travel this route make 1,743 journeys 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, 81,700 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 West Coast main line between London and Scotland. The passenger train traffic is shown in Table 7.

Using the techniques described above, we have calculated the following levels of societal risk for the different modes in Tables 8 and 9.

TABLE 7

Passenger train traffic on study route

Section	Intercity		Provincial	
	Day	Night	Day	Night
Warrington	47	18	32	3
Kirkham	10	1	125	11

TABLE 8

Societal risk results — Transport by rail

Group at risk	Frequency of N or more fatalities ($\times 10^{-6}$ y^{-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 9

Societal risk results — Transport by road

Group at risk	Frequency of N or more fatalities ($\times 10^{-6}$ y^{-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 Fig. 7 as FN curves.

It can be seen that:

- the risk by rail is approximately five times that by road;
- the risk to rail users is about double that to motorists;
- the risk to off-rail population is approximately 8 times higher than that to the off-road population;
- 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

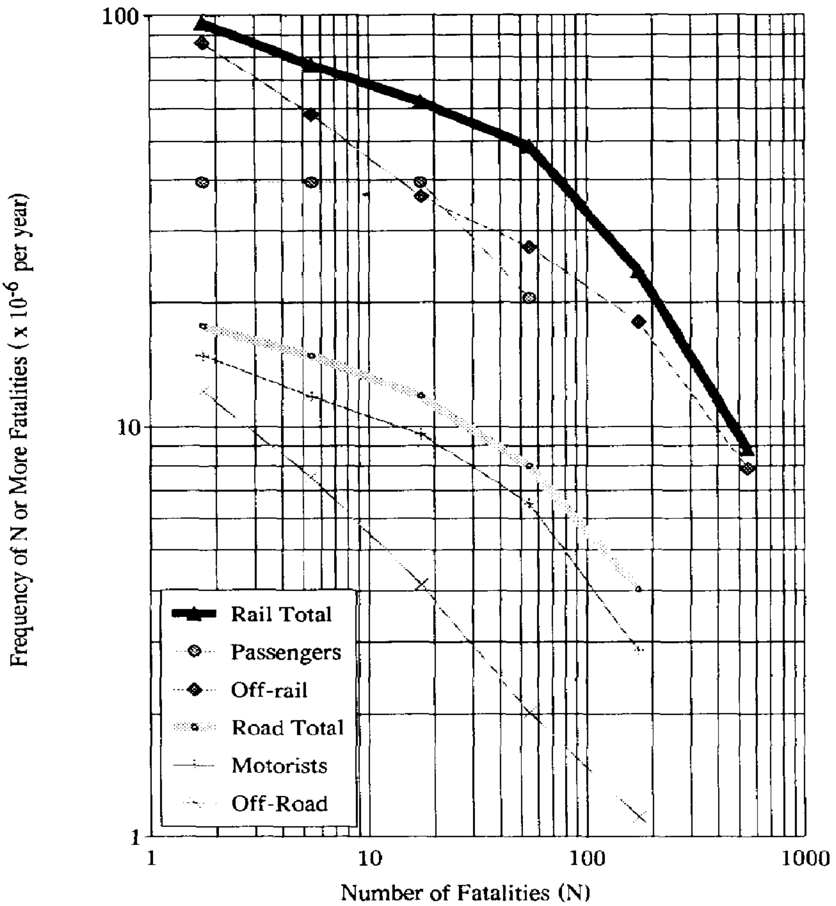


Fig. 7. Societal risk result for road/rail comparison.

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 grounds of safety alone 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.

7. Conclusions

Throughout Europe, concern is being voiced about the transport of dangerous goods and the risks posed to members of the public. Legislators are widening their attention from the problems of fixed major hazard installations to identify 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 we 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.

We have concentrated on the novel aspects of the study and in particular consequence and human impact modelling. In the case of consequence models, we 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 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 transportation 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 have 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 materials with a smaller hazard range, 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.

The potential hazards from the transport of dangerous substances is a very emotive issue; the hazards are brought close to where people live, work and play, and they have no fixed location. This is a case where any risk which is imposed is truly 'involuntary' in that we are unlikely to derive any immediate benefit from the tanker passing our homes, but we can do little to dissociate ourselves from the risks it may present. It is therefore essential that any debate about the level of the risks, their tolerability, and the possible need for risk reduction, is conducted with the benefit of a full understanding of those risks based on a rigorous and appropriately accurate analysis. It is also incumbent on the analyst to consider how best the results of his analysis can be communicated to prevent mis-understanding; this may well influence the manner in which he conducts the analysis.

To ensure consistency and to stimulate quality in such studies, it would seem that some form of code of practice is desirable. This was one of primary conclusions of a recent International Consensus Conference on the Transportation of Dangerous Goods held in Toronto whose participants agreed that the code should consider:

- standards for the definition, measurement and reporting of risk;
- a standard approach to risk analysis for the transport of dangerous goods;
- the need for any results to be compared with observed data to prove realism;
- a standard approach to:
  - (i) release rate and size estimation;
  - (ii) loading and unloading risks;
  - (iii) weather modelling;
  - (iv) inclusion of all affected populations;
  - (v) the use of standardised incident and other databases;
- an explicit statement about the size and sources of uncertainty in any analysis;
- the need to match the complexity and precision of any analysis to the needs and capabilities of the end user;
- criteria for quality review and assurance of the risk analysis process.

Acknowledgements

The author would like to thank the Directors of DNV Technica for their support in preparing this paper, and also would also like to acknowledge the very considerable contributions made to this work over many years by past colleagues in HSE, notably Geoff Grint, Nigel Riley, Linda Smith and Stewart Campbell and by the members of the technical working party.

References

1 Health and Safety Commission, Major Hazard Aspects of the Transport of Dangerous Substances, Advisory Committee on Dangerous Substances, HMSO, ISBN 0-118-85676-6, 1991.
2 P. Hubert et al., Les risques d'accident majeurs dans les transports de maitre dangereuses, Centre d'Etude sur L'évaluation de la Protection Nucleaire, D 114, France, 1985.
3 P. Shaw and F. Briscoe, Evaporation from spills of hazardous liquids onto land and water, UKAEA, Safety and Reliability Directorate, R210, Culcheth, 1978.
4 G.A. Mitzner and J.A. Eyre, Large scale LNG and LPG pool fires, In: The Assessment of Major Hazards, I. Chem. E., Rugby, 1982, pp. 146–164.
5 A. Jones, The Summit Tunnel Fire, IR/L/FR/85/86, HSE Report, Health and Safety Executive, 1985.
6 G. Purdy and P.C. Davies, Toxic gas incidents — some important considerations for emergency planning, In: Multistream, The Subject Group Symposium, I. Chem. E., Rugby, 1985, pp. 257–268.
7 M. Cooke, Risk Assessment Safety: A Case Study of Two Chlorine Plants, Thesis for M.Sc., UMIST, Manchester, 1988.

Appendix

PASSTRAM — *A model to calculate the frequency and impact of hazardous goods events on passenger trains*

Background

In Britain, the signalling system on the railways has been developed over many years to prevent accidents due to the collision of trains running on the same set of tracks. However, in the event of an incident involving a train conveying hazardous goods, the correct operation of the signalling system may not, in itself, prevent passenger trains being affected. It is entirely possible, although unlikely, for releases of materials with long hazard ranges to affect trains properly stopped at signals up the line from the hazardous goods incident.

Normally, a following train would not be allowed into a section of track until the first train has cleared an average 200 yards 'overlap' beyond the next set of signals. However, events with hazard ranges greater than this could impact on trains behind which have properly stopped.

In the event of an incident, the train crew's duty is to protect their train from approaching trains on their track. Many routes in Britain are equipped with automatic 'track circuiting' that detects the presence of a train and will prevent other trains entering that section of track by not clearing the signal protecting that length of track. 'Clips' are also carried which can be applied to nearby tracks to simulate the presence of a train and so provide further protection. In addition, the train crew can place detonators on the rail, can wave red flags to slow approaching trains, and can by walking to the nearest signal post or other means of communication warn. If these safeguards fail, passing passenger trains on adjacent tracks may still enter the hazardous area and become affected. Furthermore, the passenger train (PT) itself may be in collision with a hazardous goods train (HGT) under normal running conditions or after a derailment and this could itself lead to a loss of containment with consequential impact on the passenger train population.

Possible interactions

The range of possible interactions can be rationalised into:

- the collision of a PT and a HGT leading to tank rupture, this includes the case of a previously derailed PT;
- the PT entering a hazard zone after an earlier puncture incident (a 'passing' train or a 'disobedient' train which has passed a 'stop' signal);
- the PT collides with a previously derailed HGT and causes a puncture;
- the PT enters a hazard zone caused by an equipment leak on the HGT; and
- the hazard range from a punctured tanker on the HGT affects a PT properly stopped at signals (an 'obedient' train).

This can be further expanded into six impact cases which take into account directionality:
Case 1 – PT drives into the cloud, the wind is along the track
Case 2 – PT drives into the cloud, the wind is across the track
Case 3 – PT collides with a derailed HGT and punctures a tank
Case 4 – PT collides with HGT and, as a consequence of the collision, a tank is punctured
Case 5 – PT enters the cloud produced by an equipment leak
Obedient long – The PT is stopped at signals but is affected by a HG release nearby, the wind is along the tracks
Obedient perp – The PT is stopped at signals but is affected by a HG release nearby, the wind is across the tracks

The frequency of N or more fatalities — Toxic materials

Cases 1 to 4 above concern the passenger train entering the 'Affected Section of Line' (ASL), the length of track between two sets of signals where the HG incident occurs. In Britain, the length of the ASL will vary between 3/4 and 20 miles. For non-track circuited line, there is an average of five miles between stations or signal boxes. The likelihood of causing passenger train fatalities in Cases 1 to 5 is a function of the spill or puncture frequency, the probability of a particular wind direction, and the probability that given an HGT incident the PT will enter the ASL and, furthermore, will not stop until it is within the hazard range. Figures 8, 9 and 10 show event trees that have been used to derive an interaction frequency for Cases 1 to 5 above. The probability that the PT will enter the ASL (P2) can be derived from quantifying the fault trees shown in Fig. 11 (for track circuited) or Fig. 12 (for non-track circuited line). The value of the top gate probability (G1) is calculated from the probability that the PT will fail to stop at signals (G2, which is a constant for all similar lines) and the probability that a PT will be 'nearby' when the HG incident occurs (E5, which is a function of the PT traffic along that line). For this study we obtained values of G2 of:

- 0.011 for track circuited line;
- 0.22 for non-track circuited line.

Therefore, the frequency of PT fatalities in Cases 1 to 5 are given by:

$$F_{\text{Case 1}} = F_1 P_1 P_2 P_3 P_4 \quad (8)$$

$$F_{\text{Case 2}} = F_1 P_1 P_2 (1 - P_3) P_5 \quad (9)$$

$$F_{\text{Case 3}} = F_1 (1 - P_1) P_2 P_6 P_7 \quad (10)$$

$$F_{\text{Case 4}} = F_2 P_8 \quad (11)$$

$$F_{\text{Case 5}} = F_1 P_2 P_3 P_{10} \quad (12)$$

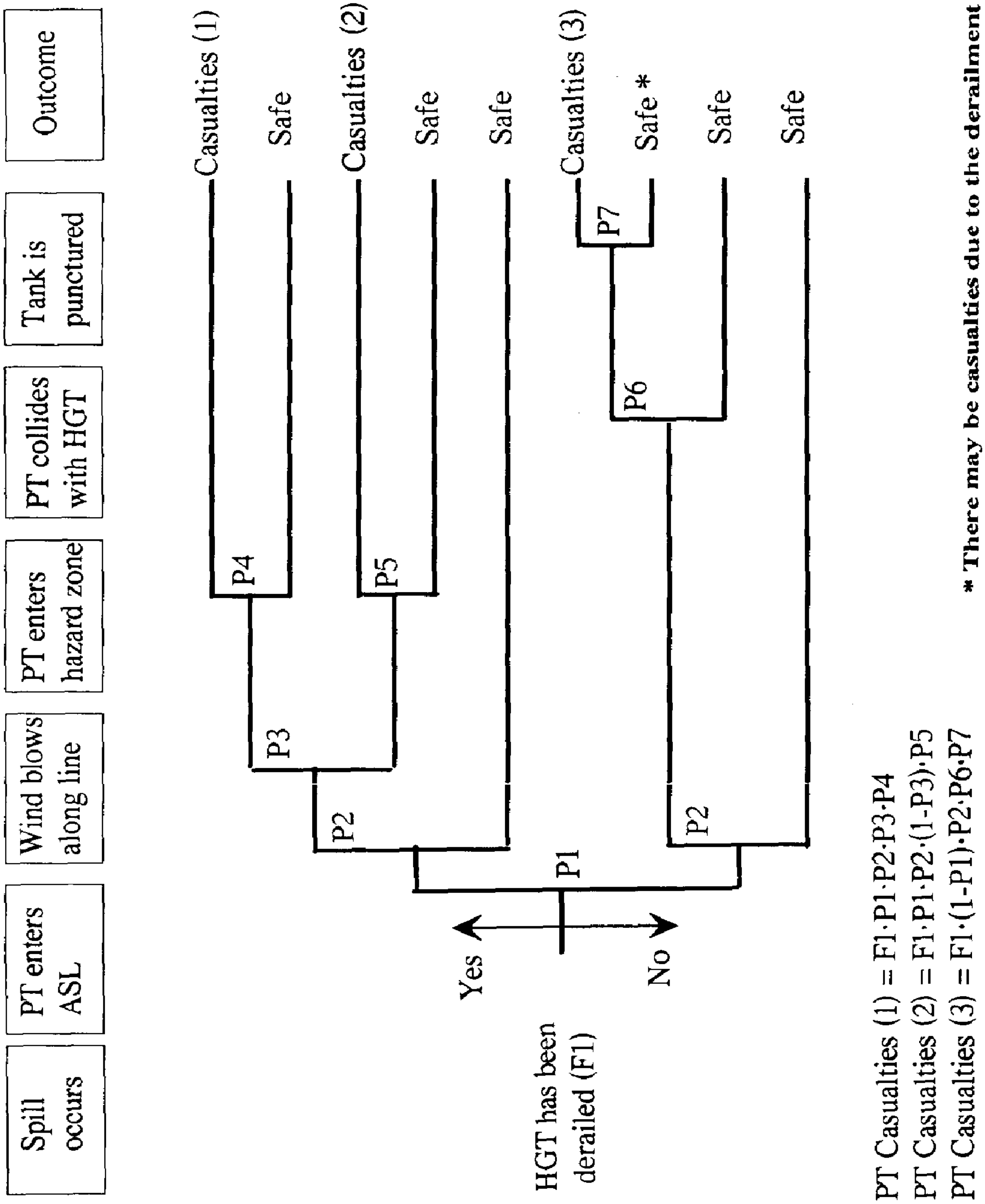
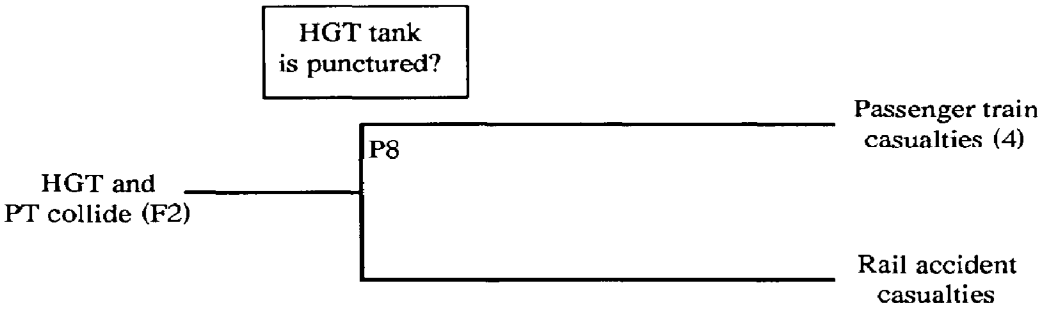
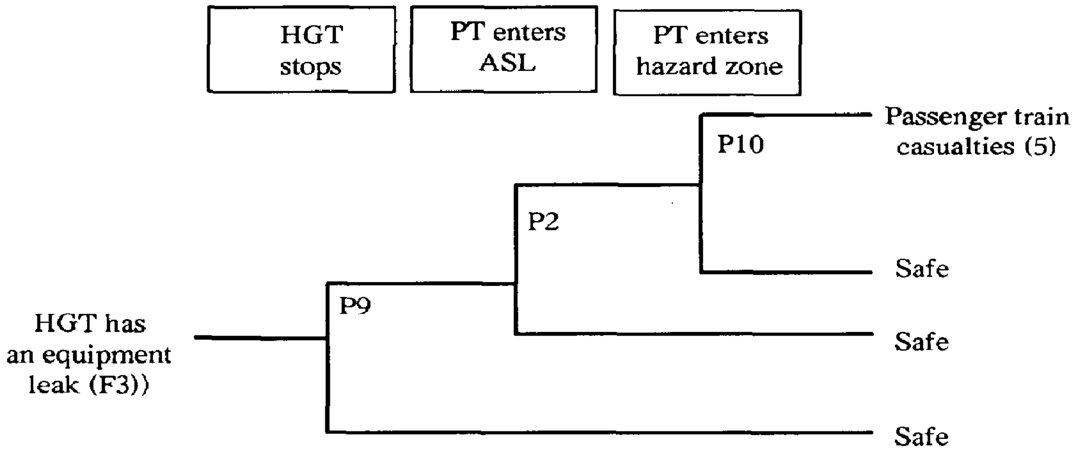


Fig. 8. Event tree for PT interaction with derailed HGT.



PF casualties (4) = F2·P8

Fig. 9. Event tree for running collisions.



PT casualties (5) = F3·P2·P9·P10

Fig. 10. Event tree for PT interaction with equipment leak.

The number of fatalities in each case depends on the proportion of the PT within the hazard range, the outside concentration, the ventilation rate into the train carriage, and the duration of exposure. Rail passengers are effectively 'indoors' and are provided with a measure of protection against the ingress of toxic gases. Modern British trains are, however, provided with mechanical ventilation and the controls are not accessible to train staff (other than the driver) or to passengers. The ventilation rate at 13 air changes an hour is relatively high, and the protection afforded is significantly less than they would experience in a normal house. Train drivers are provided with an extremely high air exchange rate and can effectively be considered as 'out of doors'.

For Case 1, the fraction of the train affected is given by:

$$X_A = L_H / L_T \tag{13}$$

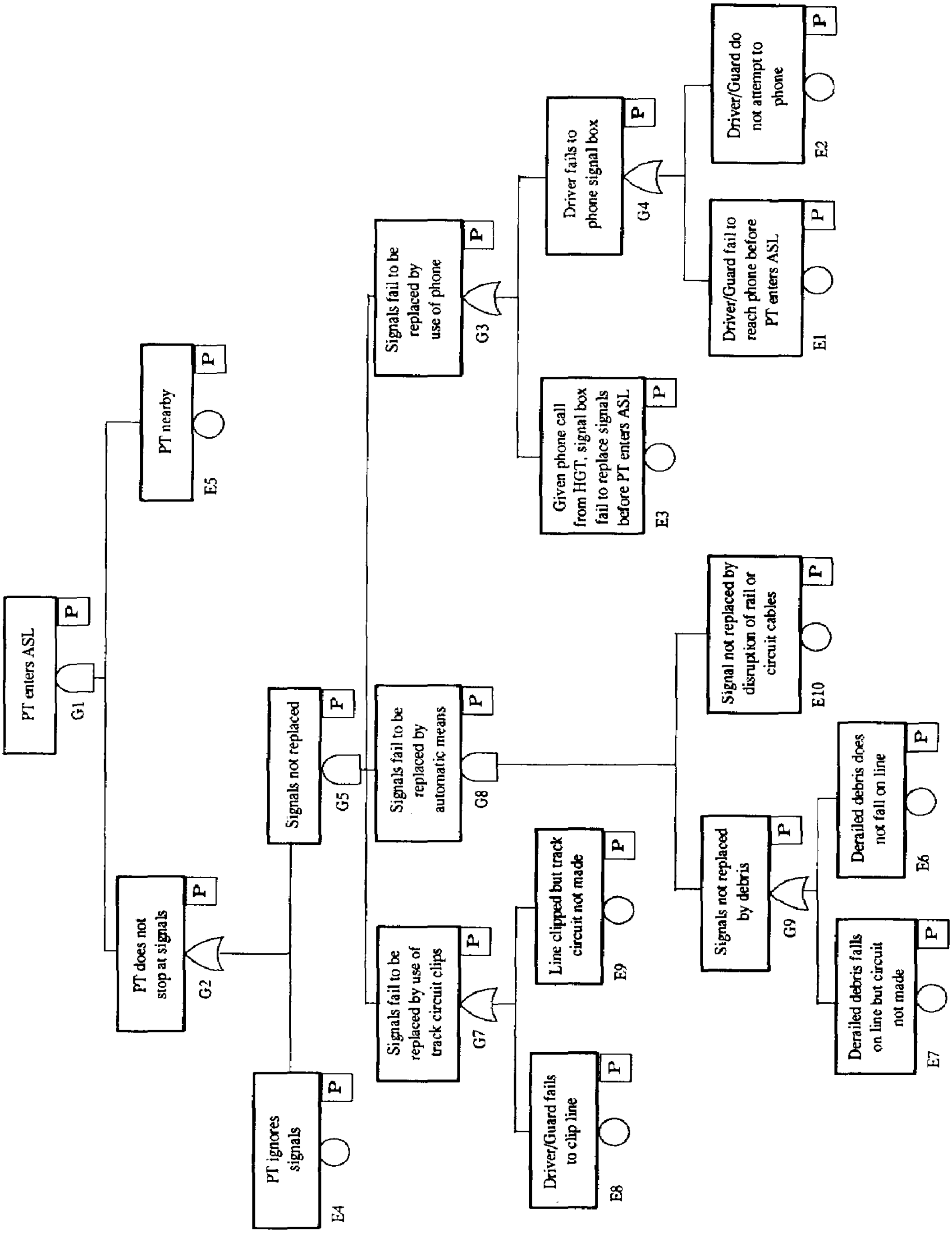


Fig. 11. Fault tree for PT entering ASL with track circuit.

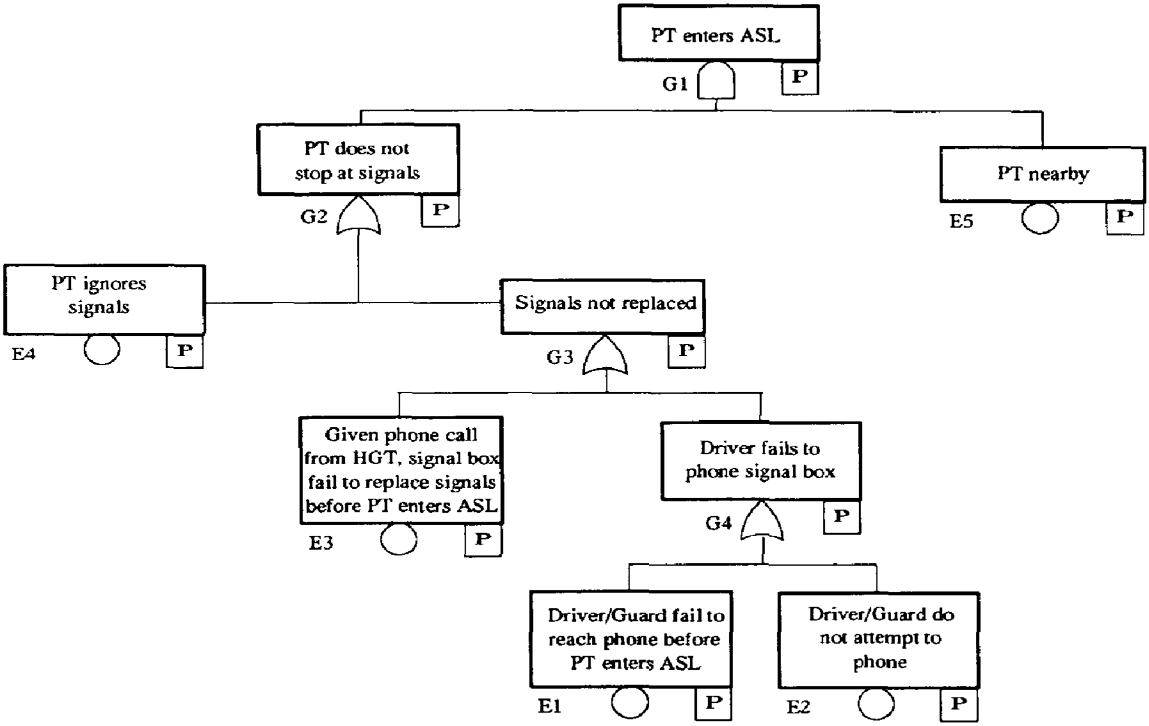


Fig. 12. Fault tree for PT entering ASL without track circuit.

where L_H is the hazard length and L_T the length of the train, and $X_A \leq 1$.

The number of carriages affected (integer) will be given by:

$$N_{CA} = \text{INT}(N_C X_A + 0.5) \tag{14}$$

where N_C is the number of carriages on the train. Using a uniform density (Q_P) of passengers per carriage, for a given level of harm x, the number of people experiencing that level of harm or more will be:

$$N_x = Q_P\{\text{INT}(N_C X_X + 0.5)\} \tag{15}$$

Then, if three hazard ranges of LD_{10}, LD_{50}, and LD_{90} are used, the number of fatalities for event E in weather j is given by:

$$N_{E,j} = 0.95 N_{Ej,\,90} + 0.7(N_{Ej,\,50} - N_{Ej,\,90}) + 0.3(N_{Ej,\,10} - N_{Ej,\,50}) \tag{16}$$

For Case 2, the proportion of the train affected will be:

$$X_A = W_H/L_T \tag{17}$$

where W_H is the width of the hazard zone and the number of passenger fatalities is given by the expression (16) above.

For Cases 3 and 4, the passenger train is actually involved in the incident and that incident is severe enough to lead to puncture of a tank. We would therefore expect the passenger carriages to be very close to or alongside the release. Given the local effect of the train carriages on the dispersion of dense gases, these cases can be treated as for Case 1 by ignoring any tendency for the gas to drift across the rails under the influence of the wind.

The 'obedient train' cases, Cases 6 and 7, can be treated as Cases 1 and 2 but with the 200 yard 'overlap' length subtracted from the hazard range or width, respectively. The frequency of affecting an obedient train with the wind blowing along the tracks (Case 6) is given by:

$$F_{OL}=\frac{F_1P_1P_3(1-G2)E_5L_H}{2(L_L+2L_T)} \tag{18}$$

where L_L is the length of the ASL. Similarly, for obedient trains when the wind blows along the tracks:

$$F_{OP}=\frac{F_1P_1(1-P_3)(1-G2)E_5(W_H/2)}{2(L_L+2L_T)} \tag{19}$$

The frequency of N or more fatalities — Flammable materials

Because of the very small hazard range, the interaction of passenger trains with flammable liquid spills and fires is only likely to lead to a small number of fatalities. This study therefore concentrated on liquefied flammable gases, notably LPG, which have significantly greater hazard ranges. The treatment for toxic gases given above can be extended by the exclusion of some events on the basis of low hazard or low frequency, and by the inclusion of additional events. Excluded are:

- flash fires caused by equipment leaks;
- VCEs in the case of 'non-obedient' trains as the interaction probability is small;
- VCEs in the case of 'obedient' trains as the interaction probability is very low;
- BLEVEs for 'non-obedient', 'passing' trains as the interaction probability is very low.

The cases for LPG interactions are:

Case 1 – PT drives into the flammable cloud, the wind is along the track. Ignition causes a flash fire

Case 2 – PT drives into the flammable cloud, the wind is across the track. Ignition causes a flash fire

Case 3 – PT collides with a derailed HG train and punctures a tank. Ignition of the resulting cloud causes a flash fire

Case 3a – PT collides with a derailed HG train and punctures a tank. Ignition causes a fireball of the tank contents

Case 4 – PT collides with a HG train and, as a consequence of the collision, a tank is punctured. Ignition of the resulting cloud causes a flash fire

Case 4a – PT collides with a HG train and, as a consequence of the collision, a tank is punctured. Ignition causes a fireball of the tank contents

TABLE A1

Ignition probabilities used in PASSTRAM

Event	Probability
Immediate ignition	0.3
Delayed ignition	0.5
Fireball	0.3
BLEVE after flash-fire	0.1

Obedient long – The PT is stopped at signals but is affected by a flash fire caused by a LPG release nearby, the wind is along the tracks
Obedient long, a – The PT is stopped at signals. After being affected by a flash fire caused by a LPG release nearby, it is subsequently affected by a BLEVE. The wind is along the tracks
Obedient perp – The PT is stopped at signals but is affected by a flash fire caused by a LPG release nearby, the wind is across the tracks
Obedient perp, a – The PT is stopped at signals. After being affected by a flash fire caused by a LPG release nearby, it is subsequently affected by a BLEVE. The wind is across the tracks.

Domino events, where fires spread between tank cars leading to several flash fires/BLEVEs, will not extend overall hazard ranges and will only increase slightly the interaction frequencies. For these reasons, they were not considered further.

For flammable events, rail passengers can be considered to be 'indoors' in terms of impact and we have adopted the same assumptions as with 'off-rail' populations; that is:

- 50% of rail passengers within a flash fire (LFL) or fireball radius will die;
- outside the flammable cloud (LFL), rail passengers survive.

Given the special circumstances of the PT/HGT interaction, the ignition probabilities used for the main analysis were judged inappropriate. In this case the ones listed in Table A1 were used.

Event frequencies and the corresponding numbers of passenger fatalities can be calculated in the same manner as for toxic events as described above.